A Holistic Framework for Improved Energy Performance in Marine Manufacturing Plants

A thesis presented in fulfilment of the requirements for the degree of

Doctor of Philosophy

by

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Abstract

While the marine industry provides one the most energy-efficient modes of transportation (OECD, 2010), activities of manufacturing plants in this industry, including shipyards and marine equipment manufacturers, are highly energy intensive and environmentally polluting. For instance, a ship is a giant structure consisting of various systems of which construction require very diverse shipyard manufacturing processes such as cutting, bending, blasting, and welding, and so on. Similarly, manufacturing of various machinery and equipment such as marine engines and marine propellers and other onboard equipment and components involve energy-intensive processes such as melting and machining. All the systems and processes are required to be powered using large amounts of energy.

Improved energy performance is of great importance for marine manufacturing plants in terms of their business competitiveness because the marine industry represents one of the world`s most open and competitive markets (Stopford, 2009). In such a fiercely competitive market, business factors such as cost-cutting, and good corporate image are imperative to be successful. Also, increased awareness of the effective energy management practices in their production systems will undoubtedly strengthen the ability of marine manufacturers to compete effectively in the open marine market through increased greener corporate image and reduced energy costs. As well as for their benefits, an overall effort from marine manufacturing industries will also contribute to global and national efforts in fighting climate change.

Bearing the above motivational reasons, the present study aims to develop a holistic framework for improved energy performance in marine manufacturing plants and to demonstrate the applicability to a typical marine equipment&component manufacturing plant in Turkey. The developed framework consists of the critical energy management themes of Energy Efficiency, Renewable Energy Use, and Demand Response Participation, which together form a holistic energy management framework incorporating all critical aspects of improved energy performance in a manufacturing plant. The application of the proposed framework requires performing a detailed energy audit and a techno-economic feasibility analysis for renewables-based microgrid application with demand response.

In this research, a real application case study of a Turkish marine component&equipment manufacturing plant is chosen and exemplified to demonstrate the applicability of the developed energy management approach. A detailed energy audit was conducted in the manufacturing plant selected to identify energy saving potentials, of which implementation would reduce the energy consumption of the plant and increase energy efficiency. At the same time, a dedicated power measurement campaign on energy consuming systems of the plant was performed to collect appropriate data to use in the microgrid feasibility analysis, which explored the techno-economic potential of integrating renewable energy use and demand response participation.

The main findings of the proposed framework in the research has demonstrated that there exists a considerable energy efficiency improvement potential within a marine manufacturing plant through the application of various technical and organisational energy saving potentials that can be identified conducting a detailed energy audit. In addition, it has been found that a noteworthy level of power self-sufficiency can be achieved for the plant by exploiting the onsite renewable energy sources through the application of a microgrid. The contribution of demand response participation, with measures such as such peak shaving and grid arbitrage through energy storage to the economic feasibility of the microgrid investment, is found to be remarkable.

This research can be seen as one of the first attempts in the area of energy management in marine manufacturing, which makes the current research novel. A significant contribution has been made in addressing the importance of improved energy performance and energy management issues among marine manufacturing plants such as shipyards and marine component/equipment manufacturers. Creating an increased awareness towards the importance of effective energy management and culture, it is envisaged that this study can be utilized by manufacturing plants of the marine industry to improve their energy performance. The developed methodology was successfully applied to a real case, this success can be translated into another case in similar nature by tailoring the developed methodology to the particular needs of other cases.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Eren Uyan

Contents

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Last but not least, I would like to express gratitude to my parents, my uncle, and my sisters for their endless support and encouragement throughout my life.

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Nomenclature

item	description	unit
ρ	actual air density	kg/m^3
ρ_o	air density at standard temperature and pressure	kg/m^3
T_o	lapse rate	K/m
z	altitude	m
g	gravitational acceleration	m/s^2
Qc	conduction heat loss	kW
t	cooling water temperature	^oK
T	molten metal temperature	^oK
R	heat resistance of refractory lining	$kW/^oK$
SC	specific capacity	$m^3/min/kW$
I	current	A
U	voltage	V
PF	power factor	non-dimensional
Vf	volumetric flow rate of free air	m^3h^{-1}
NL	number of leaks	non-dimensional
T_i	average temperature of the air at the compressor inlet	oC
P_1	line pressure at leak	kPa_a
P_i	atmospheric pressure	kPa_a
C1	isentropic sonic volumetric flow constant	$s^{-1}K^{0.5}$
C_2	conversion constant	sh-1
C_d	coefficient of discharge	non-dimensional
D	leak diameter	mm
C_3	conversion constant	mm^2m^{-2}
PL	power loss from an air leak	kW
k	specific heat ratio of air	non-dimensional
N	number of stages	non-dimensional
E_a	compressor isentropic (adiabatic) efficiency	non-dimensional
E_m	compressor motor efficiency	non-dimensional
S	salvage value	€
C_{rep}	replacemet cost	€
R_{rem}	remaining life	year
R_{comp}	lifetime of component	year
E_{tot}	total amounts load which a micro-grid served	kWh/year
$E_{grid, sales}$	amount of energy sold to the grid	kWh/year
U_{hub}	wind speed at hub height of wind turbine	m/s
U_{anem}	wind speed at anemometer height	m/s

$Zhub$	hub height	m
$Zanem$	anemometer height	m
z_o	surface roughness length	m
ln (..)	natural algorithm	non-dimensional
Y_{PV}	rated capacity of PV array	kW
f_{PV}	derating factor	%
G_T	solar radiation incident	kW/m2
$G_{T,STC}$	incident radiation at standard test conditions	kW/m2
AP	temperature coefficient of power	%/°C
T_c	PV cell temperature	°C
$T_{c,\ STC}$	PV cell temperature under standard test conditions	°C
T_a	ambient temperature	°C
$T_{c,\ NOCT}$	nominal operating cell temperature	°C
$\eta_{mp,\ STC}$	electrical conversion efficiency	%
τ	solar transmittance	%
α	solar absorbance	%
h_{sd}	discharge static head	m
h_{pfd}	discharge pipe friction head	m
h_{fld}	discharge fitting losses head	m
h_{fud}	discharge furnace systems losses head	m
h_{ss}	suction static head,	m
h_{pfs}	suction pipe friction head	m
h_{fls}	suction fitting losses head	m
f	friction factor	non-dimensional
L	length	m
D	diameter	m
Q	flow rate	m^3/h
A	area	m^2
υ	viscosity	m^2/s
ε	roughness	mm
K	resistance coefficient	Non-dimensional
H_a	absolute pressure	m
H_{vp}	absolute vapor pressure of the water at the pumping temperature	m
kWp	peak power of a PV system or panel	kilowatt-peak

Abbreviations

AC	Alternating Current
ANLB	Average Number of Light Bulbs
APD	Average Power Demand
BB	Battery Bank
BEP	Best Efficiency Point
BF	Ballast Factor
CAP	Compressed Air Production
CCT	Coordinated Colour Temperature
CG	Centralized Generation
CNC	Computer Numerical Control
CO_2	Carbon Dioxide
COE	Cost of Energy
CRI	Colour Rendering Index
DC	Direct Current
DCV	Demand Controlled Ventilation
DG	Decentralised Generation
DG	Diesel Generator
DR	Demand Response
EC	European Commission
ECSP	Energy Cost Saving Potential
EE	Energy Efficiency
EnMS	Energy Management System
EPI	Energy Performance Indicator
EPSRC	Engineering and Physical Sciences Research Council
EPW	Energy Plus Whether
ESP	Energy Saving Potential
ERP	Emission Reduction Potential
EU	European Union
GA	Grid Arbitrage
GC	Grid-Connected
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
GM	General Motors
HID	High Intensity Discharge
HOMER	
HVAC	Heating Ventilation Air Conditioning
IPCC	International Panel on Climate Change
ISO	International Standards Organisation
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
LED	Light-Emitting Diode
LF	Load Factor
MRR	Material Removal Rate
NDC	Nationally Determined Contributions
NS	Number of Shifts
NPSH	Net Positive Suction Head
NPV	Net Pre Sent Value
PBMG	Purpose Built Manual Grinding
PDCA	Plan-Do-Check-Act
PESP	Primary Energy Saving Potential
PV	Photovoltaics
PV	Present Value
RE	Renewable Energy
RES	Renewable Energy System
RR	Relative Roughness
SC	Specific Capacity
SCADA	Supervisory Control and Data Acquisition
SEC	Specific Energy Consumption
SME	Small and Medium Enterprises
TDD	Tubular Daylighting Devices
TLFX	Total Luminius Flux
TOSB	Tayland Organize Sanayi Bolgesi
TOU	Time Of Use
TPES	Total Primary Energy Supply
TSMS	Turkish State Meteorological Service
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VFD	Variable Frequency Driver
VOC	Volatile Organic Compounds
WEC	World Energy Council
WEC	World Energy Council
WMO	World Meteorological Organization

Dedication

Anatolia is the land of self-sacrificing and long-suffering people, who devote themselves to their children's lives. This thesis is dedicated to two of those Anatolians:

my mum and dad.

1

Introduction

1.1 INTRODUCTION

The main objective of Chapter 1 is to make an introduction to the thesis for the reader by presenting the background and motivation of the thesis in Section 1.2, aims and objectives of the research presented in the thesis in Section 1.3, and structure of the thesis presentation in Section 1.4. Finally, Section 1.5 gives a summary of the Chapter.

1.2 BACKGROUND AND MOTIVATION OF THE THESIS

Energy is perhaps the most important socio-economic asset in the development, maintenance, and survival of any nation. This is to maintain the status-quo for developed countries and to survive or to establish and catch up the developed nations for the developing countries` survival. However, the world is today facing a preeminent energy challenge because of the excessive consumption of fossil fuels since the Industrial Revolution. The energy challenge can be described within the following two dimensions: Climate Change and Energy Security. On the one hand, combustion of fossil fuels releases large amounts of Greenhouse Gases (GHGs) which are the main cause of **global warming and climate change**, on the other hand, fossil fuels, which are unequally distributed over the Earth, are non-renewable energy sources and have been depleting. This results in an **energy security** problem which creates highly volatile energy prices. The energy challenge is therefore the hot topic of the current World agenda to be addressed not only by the major stakeholders but also by both political circles and academia. Hence huge international efforts are being spent to tackle this challenge.

This challenge is also referred as energy trilemma, a term coined by the World Energy Council (WEC), to express the difficulty of ensuring secure and affordable energy supply and meeting rising energy demand while reducing GHGs emissions (Gunningham, 2013; WEC, 2015). The three dimensions of the energy trilemma can be listed as follows (and shown in Figure 1-1) (Gunningham, 2013; WEC, 2015):

- Energy security (for stable and affordable energy supply).
- Economic competitiveness (for cost of energy).
- Environmental sustainability (for reduced environmental impacts, i.e. GHGs emissions).

In today`s energy systems with dominant dependence on fossil fuels, each dimension demands competing objectives and balancing them which present a great challenge.

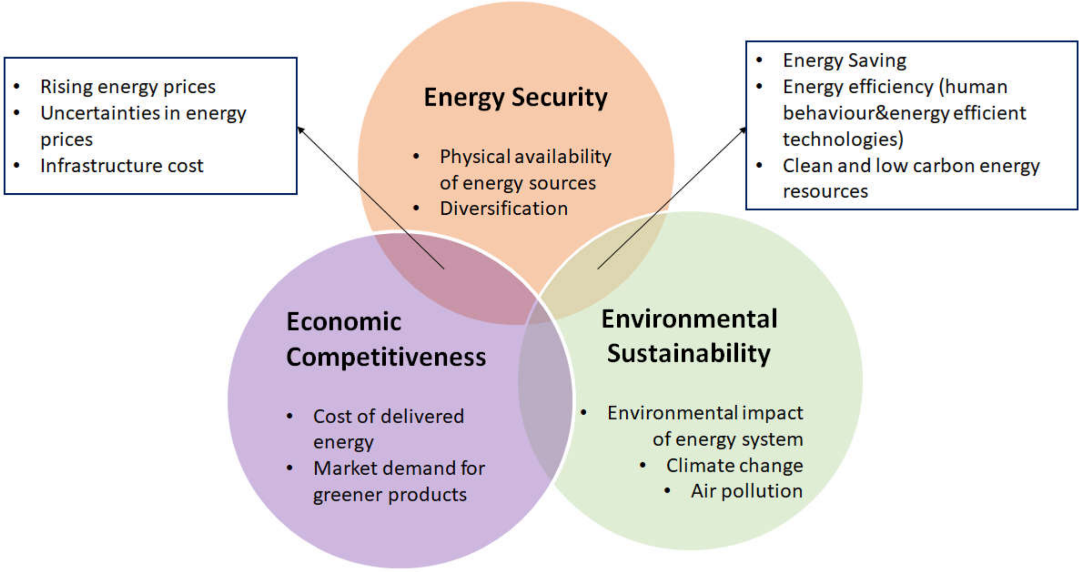


Figure 1-1: Energy trilemma (adapted from Ang et al., 2015)

To deal with the above described complex energy challenge, a paradigm change at every aspect of the World economy, which is called as **low carbon transformation,** has been emerging not only in the developed world, but also in the developing countries, particularly the fast-growing economies with limited domestic energy sources.

A low carbon economy is an economy characterised by activities which emit reduced levels of carbon dioxide into the atmosphere (Levy, 2010). Both the generation and consumption of the energy have a bearing upon the energy challenge and are under the effect of the emerging low carbon transformation. Therefore, both energy generation and using sectors relate to the problem. Amongst the main consumer sectors of the world`s global energy, the power generation, industry, and transport sectors are the major stakeholders with close interrelation amongst them and hence requiring special attention. Within the industry sector, manufacturing has been and still is the dark horse of many nations' industries as well as being one of the top energy consuming sectors.

In this respect, the major paradigm changes have been being witnessed in two major energy consumer sectors. The first one is in **power generation sector: from more centralised generation (CG) to distributed, i.e. decentralised generation (DG)** which facilities deployment of microgrids and onsite generation for local users in a country and reduces the country`s transformation and distribution losses pertaining to CG. What is more, DG also enables the integration of renewables into power system because renewable energy generators such as wind turbine and solar PV modules are DG devices because of their nature. This aspect of DG enables the power end-users, such as manufacturing plants, to generate their own electricity based on low carbon energy sources such as wind and solar. This will not only reduce the dependence and stress on the national power grid but also contribute to deferral of costly new generation or capacity upgrades in central plants emanating from the increasing power demands. Thus, this paradigm change has multifaceted benefits such as increased use of renewables, reduction of transmission and distribution losses and associated environmental impacts and avoiding projected capacity upgrades. In this respect, increased penetration of distribution generation is beneficial from national perspectives as well as from the perspectives of major power consuming sectors such as manufacturing sector.

The second paradigm shift is **in manufacturing sector in the form of "low carbon manufacturing"**, which creates a challenge for manufacturing plants to minimise their environmental burdens, particularly to decarbonize their production processes, while sustaining and improving their competitiveness. This is particularly true for those energy-dense manufacturing enterprises operating in globally competitive business areas such as marine sector and for those located in fast-growing developing countries dependent on outsourced energy to power their economies due to their limited domestic energy sources, such as the case of Turkey which intensely faces the energy challenge.

Indeed, maritime and offshore related marine manufacturing plants requires special attention in terms of the above defined energy challenge and low carbon manufacturing transformation. This is because of the fact that shipping is the life-blood of the world economy because intercontinental trade, the bulk transportation of raw material, and import and export of food and manufactured goods would not be possible without shipping (ICS, 2017). Today 90% of the world`s goods are shifted by shipping (ICS, 2017), which is the most efficient means of transportation. The prospects for the industry`s growth is expected to continue to be strong owing to its growing efficiency as a transportation mode and increased economic liberalisation (ICS, 2017) as well as the continuing globalisation of emerging economies. In addition to these, ¾ of the earth's surface is covered by the world's oceans, which are a vast source of various resources as well as food and energy. Huge areas of the oceans with various natural resources, various minerals, alternative energy form, offshore oil and gas production, and renewable hydropower are still waiting to be explored. In line with the growing World population which will result in growing energy and resource demands, it is expected that traditional shipping including naval aspects and ocean industries such as fisheries, maritime transport, tourism, offshore oil and gas production as well as emerging activities such as marine renewable energy including ocean energy, aquaculture, seabed mining, and marine biotechnology (WB and UN, 2017) will grow. All these activities are linked to marine manufacturing plants and increase in them will lead to increases in manufacturing of marine systems. At this point, marine manufacturing plants such as shipyards and marine equipment manufacturers are an indispensable part of the marine industry, which is one of the most open and competitive sectors of the global economy. Besides, it is also well-known fact that the marine manufacturing plants are high-density energy consumers as considerable amounts of electricity is required to power the manufacturing systems so that it is affected by the above-defined energy challenge and faces the challenge of Low Carbon Manufacturing paradigm shift. Therefore, the marine manufacturing industry, as a high-density energy consumer, will benefit more from effective energy management to save energy and improve its efficiency.

As stated earlier, the enterprises located in fast growing developing countries, particularly those ones dependent on outsourced energy to power their economies due to the limited domestic energy sources and located geopolitically at critical part of the world, are affected by the energy challenge more. The most outstanding epitome of these countries is Turkey. In recent years, with its fast growth rate, Turkey has become one of those countries at the cross-section of two major continents as well as being close neighbours to the countries who are rich in classical energy sources (oil and gas) but also politically volatile. This has made Turkey to rely heavily on her neighbours and hence vulnerable from the energy security point of view which requires close review of Turkey’s own energy sources and effective energy management. The challenge for Turkey, like many alike countries, is to maintain the security of affordable and stable energy supply while meeting the GHGs reduction plans dictated by binding international climate change agreements such as Paris agreement. In other words, maintaining an appropriate balance between meeting growing energy demand at an affordable cost and stable manner and achieving significant carbon reductions are very conflicting with today`s fossil-based carbon intensive energy systems and perhaps it is the most challenging task for Turkey.

While the above paragraph reflects Turkey’s current energy status in general, as far as the efficient use of the energy sources in industry is concerned, the Turkish Manufacturing Sector plays a vital role in Turkey`s energy problems as a major primary energy and power consumer. Due to their significant contribution to overall energy consumption of Turkey, the Turkish Manufacturing Sector is often addressed in national climate change and energy policies such as the 2023 Energy

Vision as described in Chapter 2. Increasing energy efficiency of manufacturing plants and reducing their dependence on the national grid by employing onsite generations or microgrids to be more self-sufficient in terms of power generation can contribute to Turkey`s national energy aims. Considering the fact that Turkey`s energy demand is growing fast in parallel to her growing economy, there will be need for costly capacity increases and upgrades. A collective energy performance improvement effort from the Turkish manufacturing industry will help Turkey minimising new capacity upgrades and investments. Within this framework, the Turkish manufacturing industry is expected to have their fair share in Low Carbon Transformation of Turkey.

Amongst the major modes of Turkish manufacturing industry, the Turkish marine manufacturing industry has a very important potential to be more efficient. Having surrounded by three closed seas and with her own active marine fleet and industry until the last economic down turn, Turkish shipbuilding industry has been one of the fastest developing sectors in the world after South Korea and China shipbuilding industries. In fact, Turkish shipbuilding industry is still the most attractive backyard for many European ship owners being at their close proximities as opposed to Korean and Chinese ship yards. Currently Turkish yards, including the naval, are still the major stakeholder sites for major mega yacht builders and owners as well as smaller size of commercial vessels.

The Turkish government also recognizes the above stated potential of the Turkish Shipbuilding and associated marine industries and hence in providing them with attractive incentives, e.g. providing building sites at Organisational Industrial Development regions around Marmara Sea (Kocaeli, Tuzla, Yalova regions) with long term leases. While these incentives recently have been taken up by number of Turkish manufacturing SMEs, the establishment of good management culture for the effective energy efficiency of these manufacturing plants and its implementation appears to be missing and hence requiring major input.

As a matter of fact, the Author of this thesis has been fortunate to be sponsored by the Turkish Government to conduct research in the general field of marine manufacturing. Having explored the state-of-the-art in Chapter 2 within the framework of the above observations, the Author is confident that there is a clear gap to introduce and hence establishment of the good energy management culture in fast developing Turkish marine manufacturing sector as the main motivation of the Author and the thesis.

In order to provide a solution for the above identified major gap there is a need to investigate the state-of-the-art approaches/methodologies that can be applied to individual or combined plants which can be in non-marine or within the marine manufacturing sector. The methodologies should involve accurate determination of energy consumption by careful auditing, that of saving, efficiency, self-sufficiency and cost-effectiveness that will all contribute and form the good energy management culture.

Within the above framework, this PhD thesis study is motivated to address at the improved energy performance within the following two major contexts:

- Marine manufacturing industry
- Concerning Turkey

1.3 RESEARCH AIM&OBJECTIVES

1.3.1 AIM

Based on the above background and motivation, the aim of this research is to develop a holistic framework for improved energy performance in marine manufacturing plants and to demonstrate the applicability to a typical marine components&equipment manufacturing plant in Turkey.

The above aim is achieved through developing a holistic energy management framework incorporating energy management themes of energy efficiency, renewable energy use, and demand response particiation and applying it to a good representative marine manufacturing plant. The application of the proposed energy management framework requires performing a detailed energy audit and a techno-economic feasibility analysis for renewables-based microgrid application with demand response. In order to apply the proposed energy management framework, an energy intensive marine manufacturing plant in Turkey was chosen. A detailed energy audit was conducted in the chosen manufacturing plant in order to identify energy saving potentials, of which implementation would reduce the energy consumption of the plant thus increase the energy efficiency. At the same time, a dedicated power measurement campaign on energy consuming systems of the plant was performed to collect appropriate data to use in the microgrid feasibility analysis, which explored the techno-economic potential of integration renewable energy use and demand response participation.

1.3.2 SPECIFIC OBJECTIVES

In order to achieve the above described aim of the thesis, following research objectives are specified and addressed in the following chapters of the thesis:

1. To perform a state-of-the art review in the field of global energy challenge and industrial energy management to show the need for the present study and identify the research gaps that this thesis intends to fulfil.
2. To develop a holistic energy management framework that will help manufacturing plants improve their energy performance, with a specific emphasis on marine manufacturing industry.
3. To choose a good representative marine manufacturing plant, which belongs to a typical Turkish marine manufacturing industry SME, to apply the develoed holistic energy management framework.
4. To conduct a detailed energy audit in the chosen marine manufacturing plant to collect all appropriate data and identify energy saving potentials (ESPs).
5. To assess those ESPs with regards to technical, economic, and environmental merits, and make decisions based on the economic evaluations.
6. To perform a techno-economic feasibility analysis of a microgrid application for the audited plant to integrate renewable energy use together with demand response measures.
7. To conclude the research with recommendations and future research.

1.4 LAYOUT OF THE THESIS

This chapter is comprised of seventeen chapters. The structure of the thesis is shown in Figure 1-2 and summarised below:

- CHAPTER 1 presents a brief introduction to the research study including the background and motivation and setting the aims and objectives the research as well as describing the layout of the thesis.

- In CHAPTER 2, a comprehensive critical review of the state-of-the-art for the global energy challenge and energy management studies in industry with a specific emphasis on marine manufacturing industry of a fast-developing country, Turkey is presented. The objective is to address the gaps in the state of the art so as to justify the study.

- In CHAPTER 3, a holistic energy management framework, which comprises of energy efficiency, renewable energy integration, and demand response participation, is introduced (Objective 1). In addition, the methodology to apply the proposed framework to a marine manufacturing plant as a case study is described. The application of the proposed energy management framework requires conducting a detailed energy audit and microgrid application. The remaining chapters from CHAPTER 4 to CHAPTER 8 presents the application of the proposed energy management framework to a marine manufacturing plant as described within the following paragraphs.

  The results of the energy audit conducted on the chosen manufacturing plant are presented in CHAPTER 4 to CHAPTER 7.

- A marine equipment/component manufacturing plant in the most industrious region of Turkey, Kocaeli, is chosen as a representative to be used for the main application case study (Objective 2). CHAPTER 4 introduces and describes the subject marine manufacturing plant. Some background information about the subject plant including the plant location, the industrial estate that the plant is based in, the business line in which the plant operates, product types and the customer profiles of the plant, and production volumes are provided. The production flows and processes in the plant are scrutinised in detailed. Following these, the energy balance and energy flows and overall energy consumption with respects to energy types are presented. This is followed by the description of the energy consuming systems in the chosen manufacturing plant including their energy input types and annual energy consumption figures as well as their contribution to the overall plant wide energy consumption. Besides, the target energy consuming systems that are to be included in the detailed energy auditing are determined in this chapter.

- The auditing results for the target energy consuming systems in production process systems are presented in CHAPTER 5 whereas energy consuming production support systems are presented in CHAPTER 6. More specifically; the energy auditing of Melting Process System, Grinding System, Abrasive Blasting System, Machine Shop, Sand Reclamation System, Sand Mixing System, and Heat Treatment System are presented in Chapter 5. Ventilation System, Compressed Air System, Cooling Tower Systems, Lighting Systems, and Plant Offices are presented in Chapter 6.

- The major outcomes of the energy auditing analysis presented in CHAPTER 5 and CHAPTER 6 are annual energy saving potentials together with associated equivalents for energy costs savings and CO_2 emissions reductions for each energy consuming systems. The identified energy saving potentials in each energy consuming systems are required to be evaluated and prioritised in terms of their cost-effectiveness as the final phase of the detailed energy audit. Economic evaluations are carried out in CHAPTER 7 through life cycle cost assessment, prioritisation, and decision making. Thus, the detailed energy auditing which aims to improve the energy efficiency of the chosen plant is completed (Objective 4-5).

- Conducting a microgrid feasibility analysis for the chosen plant is presented in CHAPTER 8 (Objective 6). The techno-economic feasibility analysis of a hybrid microgrid application with renewables and demand response for the chosen manufacturing plant is carried out based on a methodological approach involving modelling, simulation, optimisation, and sensitivity analysis. For this purpose, power consumption of the chosen manufacturing plant is modelled based on the power consumption profiles of each energy consuming systems obtained throughout the energy audit. Also, components of the hybrid microgrid are modelled based on the technical and economic parameters and simulations are conducted by using HOMER Pro Microgrid Modelling, Optimisation and Simulation Software creating various scenarios to find out the optimum microgrid configuration and demand response measure for the chosen manufacturing plant. Uncertainties of various parameters are also analysed through sensitivity analysis.

- Finally, the main findings of this research and thesis contributions and novelties are summarised, the limitations of this PhD study are discussed with potential recommendations for future research in CHAPTER 9 (Objective 7).

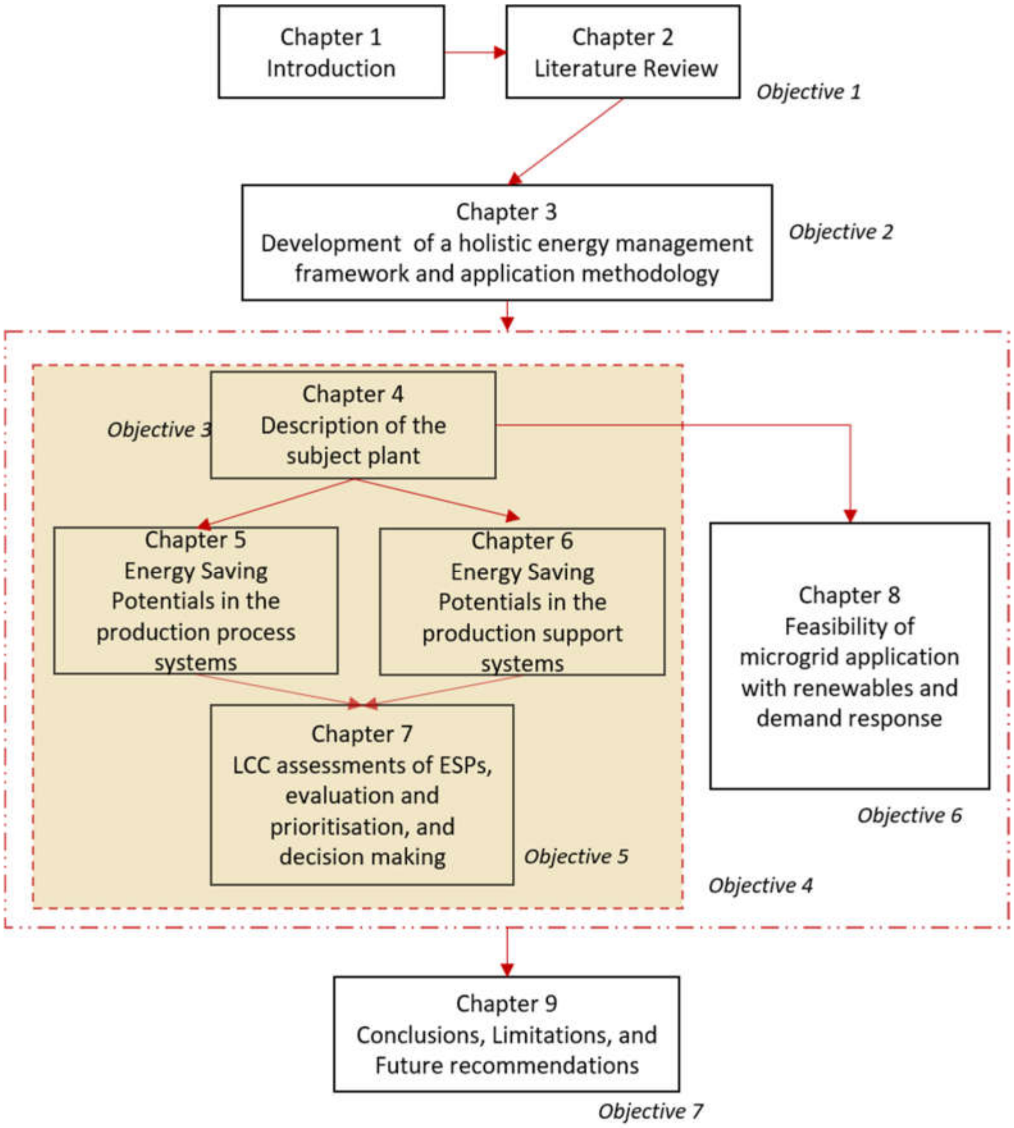


Figure 1-2: The workflow and structure of the thesis

1.5 CHAPTER SUMMARY

This chapter presented a brief introduction to the research study including the motivation, aim and objectives of the research as well as describing the layout of the thesis.

2

Literature Review

2.1 INTRODUCTION

As explained in Chapter 1, the motivation for committing to undertake this PhD research study was recognising the need to introduce the good energy management culture in the global marine manufacturing industry through the development of a holistic energy management approach, with a particular focus on a fast-growing developing country, Turkey. Within the framework of this motivation, the main objective of this chapter is to review the state-of-the-art for global energy challenge and energy management studies in industry with a specific emphasis on marine manufacturing industry of a fast-developing country, which is Turkey, in this case. The review is expected to identify major research gap(s) associated with the introduction and use of the appropriate energy management practices within the framework of the above emphasis (application) and hence justify the aims and main objectives of the thesis described in Chapter 1.

In order to meet the chapter objectives, this chapter is structured in two major sections: Backgrounds on the Energy Challenge (Section 2.2) and State-of-the-Art Review (Section 2.3). Section 2.2 provides a background on global energy issues of climate change (Section 2.2.1), energy security (Section 2.2.2), transition to low carbon economy (Section 2.2.3), power generation and the energy challenge (Section 2.2.4), industry and the energy challenge (Section 2.2.5), marine industry (Section 2.2.6), Turkey and the energy challenge (Section 2.2.7), Turkey and marine manufacturing industry (Section 2.2.8), and energy management (Section 2.2.9). This is followed by Section 2.3 which presents the critical review of previous researches.

Having conducted the literature survey, finally, the chapter presents concluding remarks in Section 2.4.

2.2 BACKGROUND ON THE ENERGY CHALLENGE

The industrialisation journey of human kind had a tremendous acceleration throughout the last century and now proceeding to the future with the same speed. The industrial revolution transformed the world into a new way of living and working. While the societies were preponderantly based on agriculture, an industrial era has started with the developments in mining, engineering, and manufacturing. This has resulted in very rapid innovations in science and technology which provided many benefits to the societies.

Fossil fuels are at the centre of this worldwide transformation because the availability and energy density of them offered tremendous opportunities. Starting from initially coal and latterly with oil and natural gas, ever-increasingly massive use of fossil fuels throughout the ongoing world industrialisation have impelled the human enterprise to a remarkable economic growth and then economic development since the Industrial Revolution. This has resulted in an entirely energy-dependent lifestyle. Today, energy use is embodied in almost every aspect of people`s life in developed countries and they demand to maintain their high level of life standards forever. On the other side, energy is a fundamental catalyser for developing nations` industrialisation and economic growth and development. Likewise in the past of yesterday`s developing but today`s developed countries, developing nations are in a growing hunger for energy to cater to their expanding industry, modernization of the agriculture and investments in their infrastructure, all of which underlying target is to reach the developed nations` life standards. Also, the overall world population is projected to increase mainly due to these countries. According to (UN, 2015), the world population has reached 7.3 billion as of mid-2015 and it is projected to be 8.5 billion in 2030 and 9.7 billion in 2050. By 2030, an additional 1.2 billion people compared to today will be demanding for energy. Growing human population means growing energy demand.

In the meantime, the world economy is expected to more than double until 2035 (BP, 2014). Given that population and economic growth are the key drivers for global energy demand (BP, 2014), the whole world is heading for an immense ever-increasing demand for energy which makes it a vital issue today. This can be clearly seen in Figure 2-1 which shows the past trends and future projections for global population, GDP, and primary energy consumption. It is expected that worldwide energy demand will increase by around 37% between 2013 and 2035 and non-OECD countries (emerging economies) will be responsible for 96% of this growth owing to their fast growing economy and population (BP, 2014).

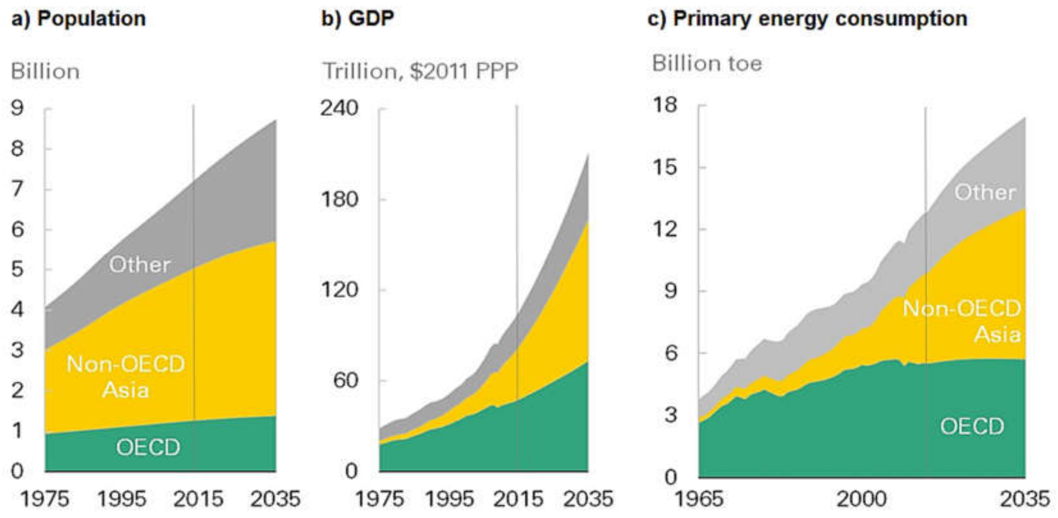


Figure 2-1: Historical and projected global population (a) and GDP (b) from 1975 to 2035, and primary energy consumption (c) in 1965-2035 (BP, 2014).

Economic growth, followed by **economic development** became the dominating paradigms in the last century (Jovane et al., 2008). However, little attention paid to the environmental issues throughout these tremendous economic growth and development which were catalysed by the excessive and unsustainable use of fossil-based energy resources. Most of the manufacturing policies and research and technological developments were addressing these paradigms (Jovane et al., 2008) with no consideration to the environment. But, the disregard of environmental considerations has resulted in various ongoing problems.

At this point, a variety of warnings has been pointed out from different science groups. Ecologists draw attention on environmental devastation and extinction of species due to the high production and consumption rates (Wilson, 2007) while geologists emphasize that the oil production may have already exceeded the peak level or will be passed soon (Kerr, 2009). A crucial alarm came from climatology science pointing out **climate change** with a strong and credible body of evidence (IPCC, 2007). Bearing the fact that fossil-based energy resources are unequally distributed over the Earth and not renewable and deplete someday in mind, this creates various problems in energy supply such as price volatilities and affordability for some countries. These problems results in a major challenge called as **energy security.**

In the following sections, two dimensions of the energy challenge, global climate change and energy security will be explained and discussed.

2.2.1 CLIMATE CHANGE

Climate change is the most outstanding epitome of energy related environmental challenges and one of the most significant current discussions in both academic and regulatory platforms. IPCC (2007) defines climate change as: "*A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or because of human activity.*"

The recent increase in the global temperature of the atmosphere represents the most significant change among the climate properties. This significant change is referred as Global Warming. It has been triggered by the dramatic increase of GHGs concentrations which partially absorb the solar energy radiating back from the Earth`s surface to the space and keep it in the atmosphere acting like a blanket (EPA, 2015). This makes the Earth`s surface warmer than it would be otherwise and causes an increase in the global temperature. GHGs emissions are, therefore, at the heart of the global warming and thus so of the climate change problem.

GHGs naturally exist in the atmosphere to some extent and there are also some natural factors such as volcanic eruptions and solar energy that increase the GHGs levels (IPCC, 2013). However, based on the exhaustive assessment of temperature records, climate forcing estimates, and sources of climate variability, the scientists have attributed a significant share of the increase in the GHGs concentrations over the last century to the human activities (NRC, 2012). There are large numbers of independent evidence confirming that the global warming is unequivocal and the primary cause of the global warming is human activities, predominantly the burning of fossil fuels releasing billions of tonnes GHGs to the atmosphere since the Industrial era started (EPA, 2015; IPCC, 2014; Melillo et al., 2014). For instance, the impact of human factor on global warming can be seen in Figure 2-2. It compares the human and natural influences based on the simulations of climate models and actual observations (Melillo et al., 2014). The green band in Figure 2-2 shows how the global temperature change would have evolved over the last century if the climate system was only influenced by the natural drivers. The blue band shows the combined effects of natural factors and human factors whereas the black line indicates the actual observed global average temperature change. These simulations show that when the human influences are superimposed on the impact of the natural drivers, the resulting temperature change closely matches the observed temperature changes (Melillo et al., 2014), confirming the human impact on the climate warming.

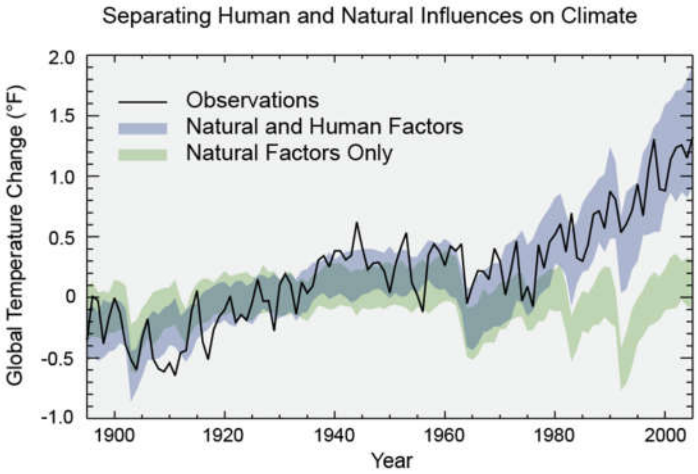


Figure 2-2: Effect of human influences on global temperature change (Melillo et al., 2014)

Major observed evidence for the global warming are the increases in the global air and ocean temperatures, melting of snow and ice, and rising global average sea level (IPCC, 2007). These increases can be graphically seen in Figure 2-3. These major changes due to the global warming possess various risks which can impose a variety of different negative impacts to ecosystem and society.

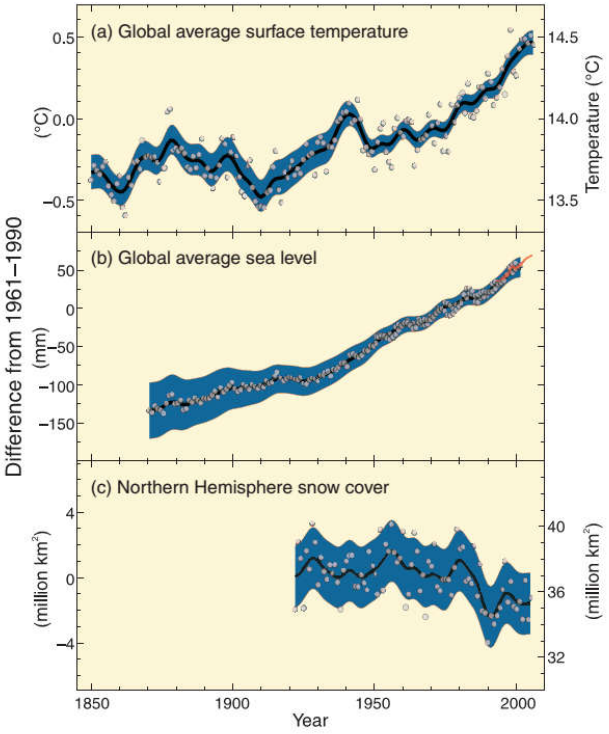


Figure 2-3: Observed changes in a) global average temperature; b) global sea level from tide gauge (blue) and satellite (red) data and c) Northern Hemisphere snow cover for March-April (IPCC, 2007).

2.2.1.1 INTERNATIONAL EFFORTS ON CLIMATE CHANGE

As a result of the overwhelming concerns among meteorologists regarding climate change, the World Meteorological Organisation (WMO) and the United Nations Environment Program (UNEP) set up the International Panel on Climate Change (IPCC) in November 1988. Upon the scientific evidence delivered by the first IPCC Assessment Report in 1990 laying emphasis on the requirement for a global synergy to fight against climate change, United Nations Framework Convention on Climate Change (UNFCCC) was created in 1992 with the aim of reducing global warming and coping with the adverse consequences of climate change (IPCC, 2010; UN, 1992).

In 1997 the Kyoto Protocol to the UNFCCC was signed by the Parties of the convention. It was the first global mechanism focusing on climate change at a global scale, having committed the Parties by setting internationally binding targets on the reduction of major GHG emissions (Table 2-1). The Kyoto Protocol came into force in 2005. 36 industrialized countries and the European Community committed to decrease the level of their collective GHG emissions by 5 % on average in comparison to the 1990 baseline levels between 2008 and 2012, which was the first commitment period.

During this five-year first commitment period, the focus was only on developed countries (excluding the USA and Australia) because they were recognised to be largely responsible for the current high levels of GHG emissions.

Table 2-1: GHGs (UNFCCC, 2015)

Carbon dioxide	CO_2
Methane	CH_4
Nitrous oxide	N_2O
Hydrofluorocarbons	HFCs
Perfluorocarbons	PFCs
Sulphur hexafluoride	SF_6

Many parties to the Kyoto protocol reduced their GHG emissions well below the target of 5.2% in the first commitment period. It is said that the collective GHGs emissions of the Parties at the end of the first commitment period was 22.6% lower than the 1990 base year (UNFCCC, 2015) which indicated a reduction well above the 5.2% target.

Despite this over-achievement of the developed countries with Kyoto targets, global GHGs emissions levels in the atmosphere continue to rise at a frightening rate, worsening the global warming and climate change. This sharp increase is ensuing from the collective GHG emissions of developing countries such as China, the largest CO_2 emitter in the world (Lin et al., 2014), in line with their economic growth where energy, particularly combustion of fossil fuels, is a fundamental input.

However, it is relevant to note that some of these developing countries manufacture goods mostly for the consumption of western developed countries such as USA and wealthy EU countries. The developed world by importing manufactured goods, particularly energy intensive industrial products, causes substantial emissions releases in less affluent developing countries with technologies of low efficiency. In a sense, the developed countries do “outsource” their GHG emissions to these countries with strategic advantages such as lower labour costs and access to supply chains at the expense of substantial GHG releases and thus they indirectly contribute to global warming.

A relatively recent study conducted by Davis and Caldeira (2010) found that approximately 23% of global CO_2 emissions from combustion of fossil fuels were generated during the manufacturing of goods which were finally consumed in a different country. This indicates that these goods are exported so that the emissions released during manufacturing of them are kind of exported in an embodied form. Figure 2-4 presents the top importers and exporters of CO_2 emissions embodied in goods imported or exported trough international trade together with some detail of the industry sectors accounting for traded emissions based on 2004-year data. The study (Davis and Caldeira, 2010) also compares each country`s individual CO_2 exports and imports. As can be observed from Figure 2-4, emerging economies such as China, Russia, India and Middle East countries exports CO_2 emissions more than they import. They are the major CO_2 exporters where, on the contrary, USA, Japan, West European countries which represent the developed world are the major CO_2 importers.

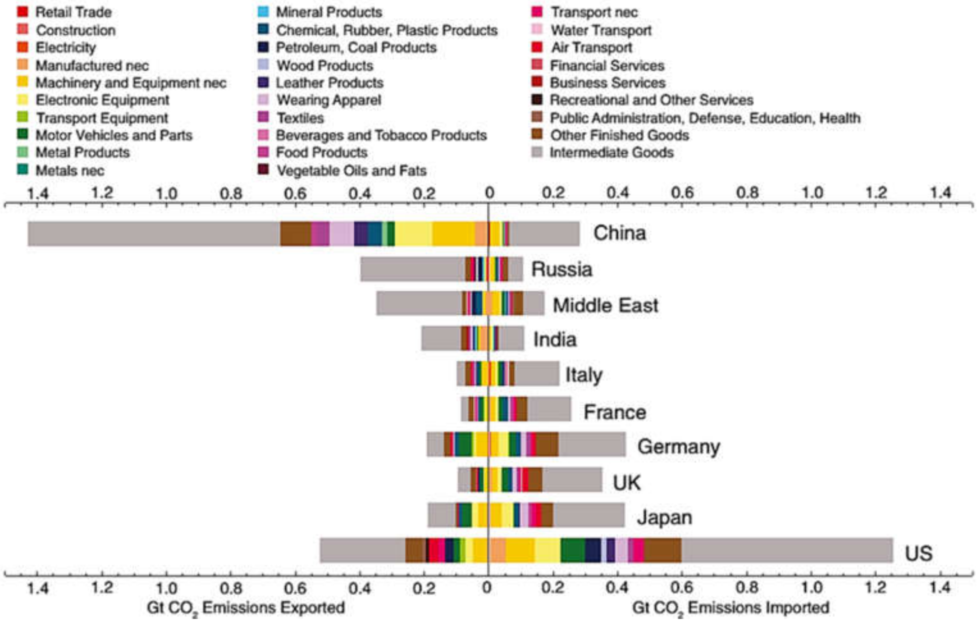


Figure 2-4: Top importers and exporters of CO_2 emissions embodied in goods imported or exported trough international trade (Davis and Caldeira, 2010)

In addition to the above, Davis and Caldeira (2010) showed that the CO_2 intensity of exports (i.e. the product of the CO_2 emissions per unit energy and energy consumption per US$ of export (kg-CO_2 per US$ of imports or exports)) from emerging countries such as China, Russia, Middle East, and India is very high compared to the CO_2 intensity of the imports to these countries, as it can be seen in Figure 2-5. The CO_2 intensity of exports from these countries is attributable to **the extensive use of carbon-intensive fuels like coal in these countries** and also to the low value of energy-intensive export goods. As for the developed countries such as USA, Western Europe, and Japan, they have a reverse situation since the CO_2 intensity of exports from these countries are very low compared to the developing countries and the CO_2 intensity of their imports. **This reflects that the exported goods from developed world are manufactured by consuming energy generated using low-carbon technologies and highly valued per unit of energy required to produce them.**

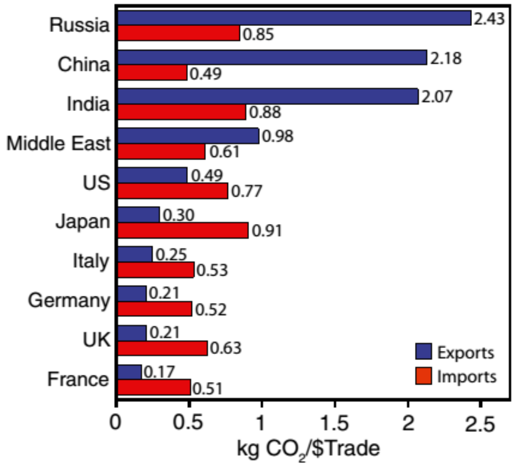


Figure 2-5: Mean CO_2 intensity of imports and exports to and from the largest net importing/exporting countries (Davis and Caldeira, 2010)

All the above observations clearly indicate that, while the focus of the Kyoto Protocol was merely developed countries, developing countries have also responsibility for climate change because of their rapidly growing economy. Coupled with intensive use of fossil fuels, as stated in the previous paragraphs, this aggravates the global climate change problem as it was encountered during the first commitment period of the Kyoto Protocol. This trend was such that the global GHG emissions in the atmosphere increased dramatically in comparison to the 1990 levels in spite of the dramatic GHG emissions reduction achieved by the developed countries. In other respects, the emerging economies cannot relinquish their industrialisation and manufacturing because these have a vital role in their economic growth and development, which have to be supported by substantial energy consumption, generally more economical in the form of fossil fuels.

Within the above framework, it is obvious that both developed and developing countries have common responsibilities in global climate change. Required actions to combat climate change should be taken by all the contributes and responsibility should be allocated to not just to the developed countries but also to the developing world.

Fortunately, the Paris Agreement, which is considered as a next key chapter in the history of global climate change effort (UNFCCC, 2015), has been adopted by the 196 Parties to the UNFCCC for a long-term global action plan in which they will commit themselves to reduce their GHGs on tackling global climate change. The Paris Agreement provides a new legally-binding framework for internationally coordinated efforts to combat climate change in the period after 2020 when the Kyoto Protocol ends (UNFCCC, 2016, 2015).

Different from the former actions, the Paris Agreement, the first-ever universal agreement on climate change combat, brings all countries (i.e. it should be noted that, while the Author has been writing this thesis, the US President Donald Trump announced on 1 June, 2017 that the US would withdraw the Paris Agreement) into a common cause to embark on vigorous efforts for mitigation and adaptation to climate change. While the Kyoto Protocol commits only developed countries to specific emissions reduction targets as explained above, all countries are encompassed in the Paris Agreement (Erbach, 2016; UNFCCC, 2016, 2015).

The central aim of the Paris Agreement is (Art. 2.1 a)

"To strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C the industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C".

To achieve this ambitious long-term target, the Paris Agreement obligates all countries to contribute to climate change mitigation and adaptation by developing their plans on how they will contribute and to express in a so-called **Nationally Determined Contributions (NDCs),** which have to be submitted to the Secretariat of the Convention. Countries must revise and update their NDCs every 5 years and the new NDC of each country must be more ambitious than the previous one. Besides, countries have to take measures to achieve their objectives and report on progress. Bearing the fact that the Paris Agreement is a legally binding treaty as a matter of international law in mind, **the ratifying countries will need to make significant changes to their economies to meet their initial NDC and progressively more ambitious NDCs later** on (Erbach, 2016; UNFCCC, 2016, 2015).

Despite the danger of human-induced climate change has been well accepted and there have been global efforts such as the Kyoto Protocol to mitigate it, the situation has worsened. Now, the Paris Agreement, the latest landmark step of the global climate change effort, is deemed to be the last chance for the humanity. With the Paris Agreement, the World has taken a historic step in the endeavour of global climate change and a new era on climate change fight has started.

However, the most important and challenging part will be the implementation. As mentioned earlier, while the World economy has been growing, this also implies that the demand for energy supplies have been growing too. Future projections for increasing energy demand is well-known. It is also well known that most global energy systems are dominated by fossil fuel supply chains (Hoggett et al., 2014). Economic growth and economic development catalysed by fossil fuels, which are the dominating paradigms of the last century as stated earlier, have to be redefined now. In this respect, the Paris Agreement sends a warning signal to all the sectors and markets that the time is ripe for a **"low carbon transition"** in all aspects of the economy.

2.2.2 ENERGY SECURITY

Energy security is the second dimension of the Energy Challenge the world is facing today. Similar to global climate change, it is an issue of paramount importance to many different stakeholders such as policymakers, energy using business sectors, developing nations and the larger communities who have life standards dependant on uninterrupted energy supply. As mentioned earlier, the aim of developing countries is to boost their economy and reach to the higher life standards as in developed nations at a faster rate. **Cheap and stable energy supply** has a critical role in the achievement of this aim. However, energy production of the world is heavily dependent on fossil-based resources such as coal, oil and gas; and the distribution of these sources across the globe is quite unequal as seen in Figure 2-6. As it is well known, only some countries have certain numbers of fossil source deposits. Outbreaks of wars, destabilized regimes, or regional tensions can lead to oil or gas supply disruptions (Ang et al., 2015b).

This poses a great challenge for **fast-growing developing countries with limited domestic energy resources**. While they need cheap and stable energy supply to cater their economy, their dependence on outsourcing for energy creates various risks and uncertainties which will affect their economic and social welfare.

In addition to the above, future of global energy security based on fossil-based energy sources are questionable because fossil resources are finite sources which are going to deplete. Their production will reach to a peak some day and start to decline. When the scarcity of these sources begins, their price will soar and political problems may take place. Even today there are various global political problems and highly volatile energy prices because of the unevenly distribution of limited fossil-based energy sources and growing demand on them. It is thus possible to hypothesize that fossil-based energy supply is limited and even likely to decline in the long term while the energy demand is growing substantially.

All these introduce the problem of energy security. As International Energy Agency (IEA, 2013) defines it, "***Energy security refers to the uninterrupted availability of energy sources at an affordable price***". Factors such as political problems, commercial disputes, infrastructure failure, depletion of resources, wars, terrorism, and developed countries` dominant dependence on imported energy as stated above can cause unbalances in energy security which results in highly volatile energy prices and disturbances in energy supply. For example, many EU countries left with severe shortages because of a gas dispute between Russia and transit-country Ukraine in 2009 (EU, 2015).

Energy security has a profound importance **for energy importing countries which have growing economies** because any instability in their access to energy directly affects their economic performance and growth. Energy prices are very volatile and this highly affects industry businesses; this is because energy is an important input to manufacturing and production which has a direct impact on the GDP (Gross Domestic Product) for a country and its overall economic health (Ghosh and Prelas, 2009).

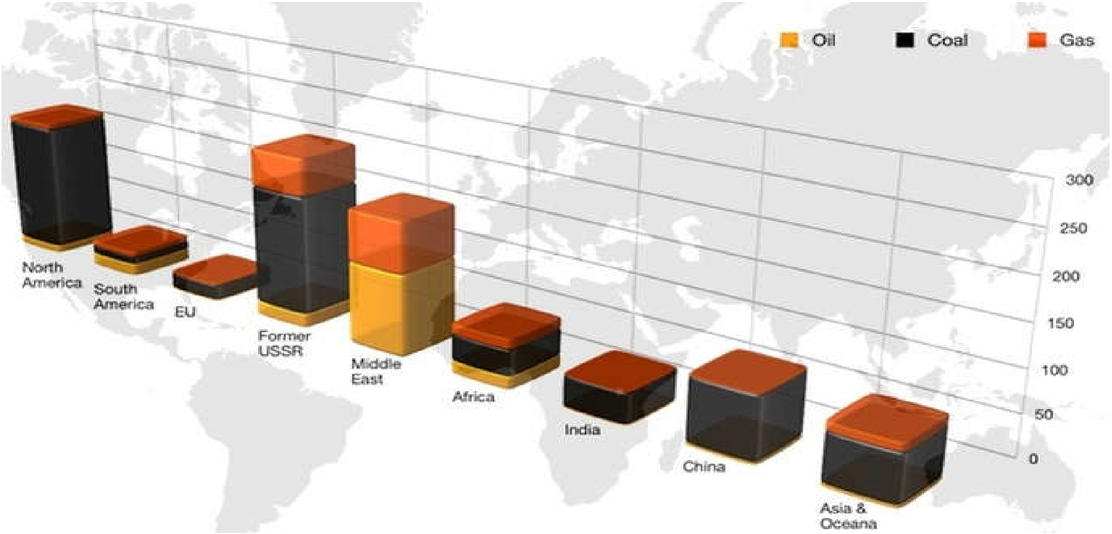


Figure 2-6: The amount and distribution of proven fossil fuel reserves (fuels are measured in billions of tonnes.) (Source: World Coal Association)

Also, the effect of energy security is an important concern for the competitiveness of enterprises of **energy importing countries operating in the global arena.** This is the case particularly for energy-intensive manufacturing industries that race with global rivals. For these industries energy cost has a significant share on their overall cost and their profitability will be adversely affected by high energy prices and energy disruptions. Thus, this makes **affordable and stable energy supply** an important competitiveness factor for them. **A typical example of these is plants which operate in marine industry such as shipbuilding, repairing, and offshore and marine equipment manufacturers which competes in a global arena.**

Reducing dependence on fossil-based energy sources and diversification of national energy inputs are essential for secure supply of energy to a country and its economy. By doing so, **energy importing countries** can reduce and mitigate the risks of energy import disruption and **price volatility** (Ang et al., 2015). Diversification of energy supply to a country can be achieved in various ways. For instance, a country can increase the number of its supplier countries **if it is strongly dependent on imported energy** (Ang et al., 2015). This is much better than being heavily dependent on a single supplier and can, to some extent, alleviate the risk of unsecure energy supply in short term. This is, however, still not enough from a long-term perspective. Domestic energy production should be increased and diversified. Furthermore, alternatives to finite fossil fuels such as renewables should be integrated to the energy portfolio to decrease the dependence on finite fossil fuels.

While these endeavours are towards ensuring stable supply of energy, **low energy prices** also must be ensured to be economically competitive for a country and its enterprises running in a globally open market. At this point, in order to increase **security of affordable energy supply**, a country with cheap coal resources might want to exploit this low-cost energy source. This effort can be effective for reducing energy costs and increasing energy diversity in short terms. However, reliance on depleting fossil-based energy sources will be retained putting the future security of stable energy supply at risk in long term. More importantly, securing low energy cost by generating power by using fossil fuels (e.g. coal fired power plants) will be in conflict with binding global climate change agreements and national GHG reduction plans as fossil fuels are the main culprit of the climate problem as explained earlier. Particularly coal is a very dirty form of energy in terms of environmental considerations.

2.2.3 TRANSITION TO LOW CARBON ECONOMY

As also defined earlier in Chapter 1, a low-carbon economy can be defined as an economy characterised by activities which emit low levels of carbon dioxide into the atmosphere ((Levy, 2010). Many academic fronts view a low carbon economy as an advancement approach which can be characterized by energy efficiency, minimized pollution, less carbon emission as well as high energy performance (Ganda and Ngwakwe, 2013). Similarly, Beinhocker and Oppenheim (2013) regards a low-carbon economy as a changing economic growth practice from excessive carbon energy to reduced carbon energy levels.

Both how energy is used (i.e. demand side) and how it is generated (i.e. supply side) have direct bearing and equal importance to achieve a low carbon transformation thereby coping with the energy challenge. Significant changes to the current energy supply and demand systems are essential to be decarbonized. There is some agreement that the desired approach to achieve this will include improving energy efficiency by saving and avoiding unnecessary use which can be achieved by behaviour change and technology improvement, almost full decarbonisation of electricity generation, and the extension of electricity into the transport and heat sectors (CCC, 2010; DECC, 2013; Hoggett et al., 2014; Speirs et al., 2010).

According the International Energy Agency (IEA, 2012), 57 % of the world`s CO_2 emissions reduction will come from end-use efficiency by 2030 showing a great potential for decarbonisation by using less energy per economic activity. Considering the fact that electricity system is easier to decarbonize than other fuels (IEA, 2011), **dependence on fossil-based power generation should be reduced and distributed generation of renewable energy should be promoted**. Also, power generated from low carbon sources such as renewables should be efficiently used by reduced demand. All in all, low-carbon transition is a matter of energy efficiency and clean energy structure (Liu and Feng, 2011) and all economic sectors of a country such as industry, power generation, agriculture, transportation, construction, and so on need to contribute this depending on their technical and economic potential.

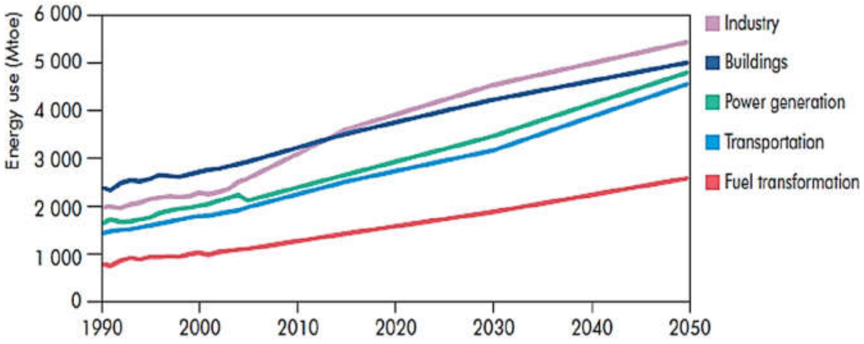
The EC low-carbon economy roadmap regards that a low-carbon transition is feasible and affordable, but requires innovation and investments (EC, 2011). It is expected that the low carbon transition will boost Europe`s economy owing to the development of clean technologies and low or zero-carbon energy thereby propelling employment and growth (EC, 2011). It will make the EU less dependent on expensive energy imports thereby improving its energy security and enabling achieve ambitious GHG emissions reduction targets.

In either developed or developing world, all energy using sectors have been forced by their governments to do their fair share to enable a low carbon transformation. Because low carbon economy will involve all aspects of an economy, all sectors will have responsibility and they will have their share. In this respect, as also stated in Chapter 1, the major paradigm changes have been witnessed in two major energy consumer sectors. The first one is in **power generation sector, from more centralised generation to distributed (i.e. decentralised) generation** which enables the integration of renewable energy sources, facilities deployment of microgrids and onsite generation for local users and reduces the transformation and distribution losses. The second paradigm shift is i**n manufacturing sector in the form of low carbon manufacturing** which creates a challenge for manufacturing plants to minimise their environmental burdens, particularly to decarbonize their production processes, while sustaining and improving their competitiveness.

The following section will be discussing the major global energy consumers; manufacturing and power generation sectors, their interrelated role in the energy challenge and how they will enable a low carbon transition. While doing these, special emphases will be given to Turkey and marine manufacturing plants, which are the focus of this PhD thesis.

2.2.4 POWER GENERATION AND THE ENERGY CHALLENGE

Power generation sector is globally one of the major energy consumers. While the global power generation was 19,131.7 TWh in 2006, it raised to 24,816.4 TWh in 2016, which indicates an increase of around 30% (BP, 2017). As Figure 2-7 shows the power generation sector, which is responsible for public electricity production that is consumed by various sectors as well, is globally the third biggest energy consumer. Furthermore, power plants in the world are mainly powered by non-renewable fossil fuels (Figure 2-8) and therefore one of the biggest sources of CO_2 emissions. According to the International Energy Agency (IEA, 2017a) fossil fuels were the source of 66.3% of global public electricity production in 2015. Therefore, power generation sector has a major role on the Energy Challenge.



Note: Final energy use for end-use sectors, net consumption of power and fuel for the transformation sectors. The power-generation sector includes heat plants.

Figure 2-7: Global Energy use by sectors from 1990 to 2050 (IEA, 2012)

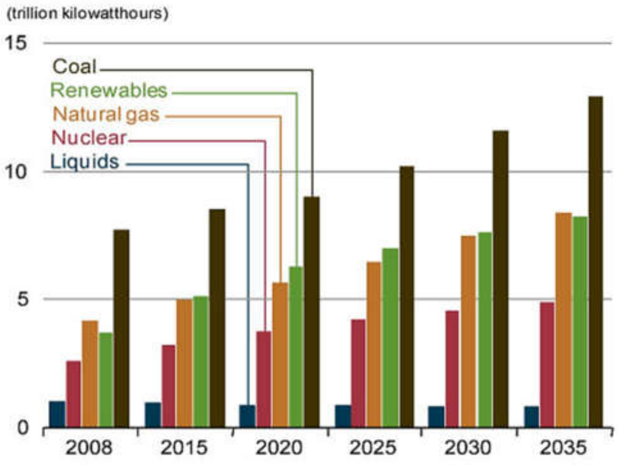


Figure 2-8: World net energy generation by fuel
(Source: http://www.eia.gov/forecasts/ieo/electricity.cfm)

2.2.4.1 PARADIGM CHANGE IN POWER GENERATION

Power generation today experiences a paradigm change which can be characterised by the rise of renewables and Distributed Generation (DG) and undergoing a rapid shift from central large-scale production to small-scale local production (P Sioshansi, 2014).

Traditional power supply chain that is ubiquitous today can be characterised by massive centralised electricity generation plants, which are placed far from the point of demand. In this system, primary energy is obtained from a variety of resources, which are dominantly fossil based, and transformed to bulk electricity at a number of large centralised power plants. It is then transported over long distances via the high voltage transmission network and medium distances via the distribution network, gradually stepping down to low voltages and delivered to a huge number of end users such as homes or businesses on a continuous and ready basis (Bouffard and Kirschen, 2008; Keane, 2007; Martin, 2009; Conner, 2003).

This means of the power supply has been globally the dominant power supply paradigm and called as Centralized Generation (CG). There are several reasons governed the expansion of CG such as the economic viability of power generation in bulk amounts and transporting it at high voltages as the higher the voltage, the greater the capacity and the greater the cost of otherwise similar equipment (Momoh et al., 2012; Willis, 2004). In these systems, the focus of power generation is to meet the load profile of power demand side whereas the network infrastructure is to ensure balance in the grid, ample capacity, and long-term planning to meet demand growth (P Sioshansi, 2014). Figure 2-9 illustrates the value chain in CG.

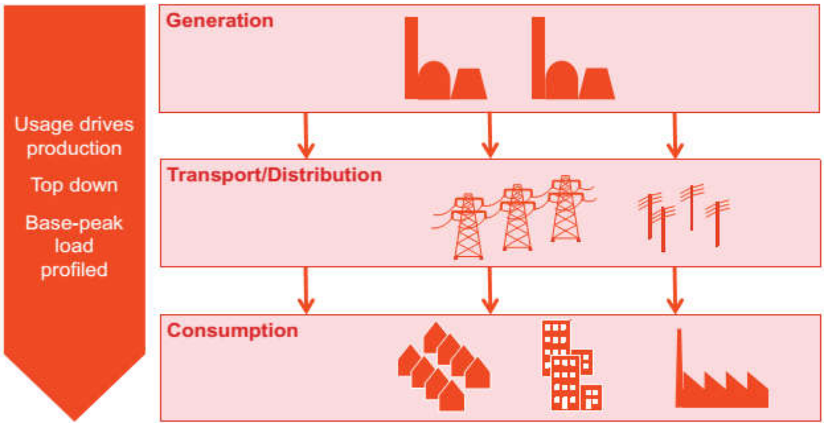


Figure 2-9: Value chain in centralized generation (P Sioshansi, 2014)

The alternative to CG is Distributed Generation (DG). DG is also commonly named as "decentralized", "embedded", "dispersed", and "onsite" generation (Allan et al., 2015). In general, small and modular power generation devices based on low carbon energy sources are used in DG. Power generation devices can be standalone or grid-connected and they are located close to an end user such as a major industrial facility, a military base, or a large college campus (EPA, 2018; Allan et al., 2015; Little, 1999) . DG systems mostly produce between 1 kW and 5 MW of power supply (Carley, 2009). Figure 2-10 illustrates the value chain in DG.

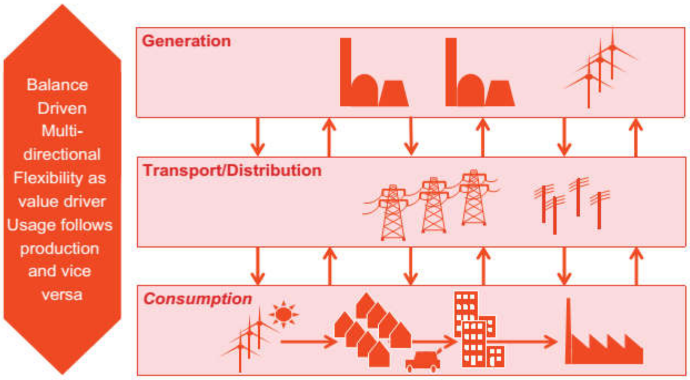
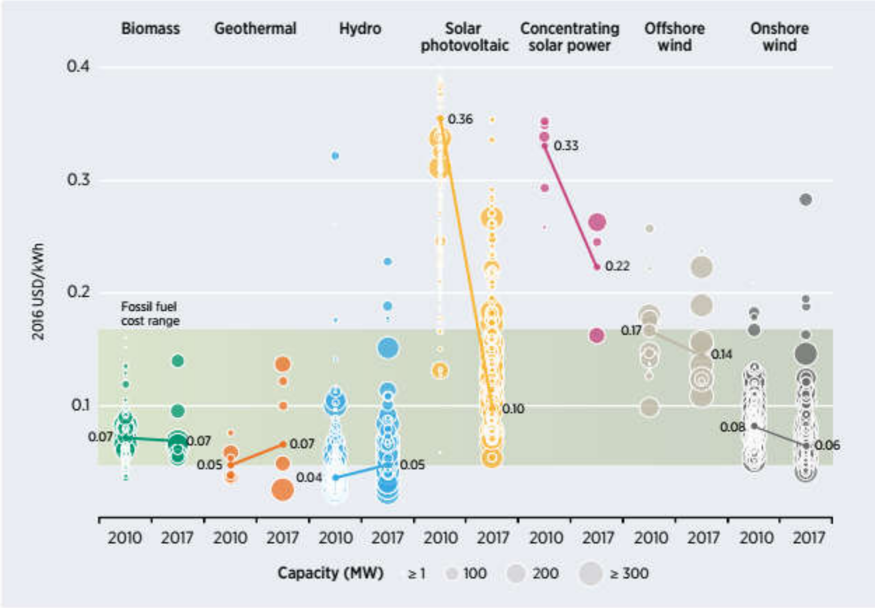


Figure 2-10: Value chain in Distributed Generation (P Sioshansi, 2014)

It was earlier suggested that fossil-based energy sources are limited and going to deplete someday. This will lead to significant increases in already high fossil fuel prices in line with the long-term decline in discovery rates of fossil fuels (Ayres et al., 2007). Ayres et al. (2007) argues that economies of scale associated with large centralised plants are coming to an end by virtue of capacity constraints and increasing fossil fuel prices whereas distributed generators such as environmentally friendly renewable generators are benefiting from rapid technological advancements such as improving the efficiency of technologies; investing in more efficient manufacturing technologies; and policy supports which have been reducing their unit costs (Allan et al., 2015; Ayres et al., 2007; IRENA, 2018). For example, as it is also shown in Figure 2-11, International Renewable Energy Agency (IRENA) reports that the global weighted-average levelized cost of electricity (LCOE) of solar PV fell 73% between 2010 and 2017 (IRENA, 2018). Similarly, the fall in the global weighted-average LCOE of onshore wind turbine was 23% in the same period (IRENA, 2018). What is more, IRENA reports that continuous cost reductions in solar and wind power technologies are expected considering the fact that the drivers behind lower equipment and installed costs have not yet run their course (IRENA, 2016a). Coupled these with various environmental benefits, DG with renewables has been becoming more competitive against fossil fuel-based CG (Allan et al., 2015) and there have been increasing interests in DG (Ogunjuyigbe et al., 2016).



Source: IRENA Renewable Cost Database.
Note: Each circle represents an individual project in the IRENA Renewable Cost Database, with the centre of the circle representing the LCOE value on the Y-axis and the diameter of the circle the size of the project. The lines represent the global weighted average LCOE value for a given years newly commissioned projects, where the weighting is based on capacity deployed by country/year.

Figure 2-11: Global levelised cost of electricity from utility-scale renewable power generation technologies, 2010-2017

DG systems can either be standalone or grid-connected (Allan et al., 2015). DG effectuates the integration of renewable energy systems such as wind turbines and PVs which are decentralized systems owing to their nature. Thus, they can be employed to produce power onsite and delivered efficiently to the end user without no or minimum transmission and distribution losses (Allan et al., 2015). This facilitates onsite power generation from indigenous energy sources such as renewables or waste heat at manufacturing plants or commercial buildings and enable them to generate their own power and be partially or completely self-sufficient thereby enhancing their energy security and environmentally friendliness. This can provide a competitive advantage to them by lowering the energy costs (IOREC, 2014) and enhancing their green image. These observations are particularly important for marine manufacturing plants, which do business in highly competitive market, and it is time for them to explore the feasibility of onsite power generation.

While the above paragraph is about advantageous benefits of DG through onsite DG generation for local users such as for marine manufacturing plants which is the focus of this thesis from a sectoral perspective, from a country point of view, changing concept of power generation from CG to DG has advantageous implications for a country`s power system. Increasing DG in a country`s power system will reduce the transmission and distribution losses (i.e. wasted energy) associated with CG and associated costs and environmental emissions. Furthermore, costly infrastructure and capacity upgrades in CG due to the increasing power demand will be avoided. These aspects are important considerations for countries which suffer from high transmission and distribution losses and need to expand power generation capacity due to increasing power demand as is the case with Turkey, as it will be discussed in detail in Section 2.2.7.

Because electricity is generated at or near the place of consumption in DG systems, end-users such as university campuses, household users or industrial plants are concerned with the deployment of DG. **Thus, one can say that increasing the deployment DG in a country`s power system can be achieved by the increased use of DG among the power end users in a country.** However, as it will have been also stated in the review of state-of-the art in Section 2.3, DG has globally been the subject of electrification of islanded rural or remote areas because grid extension to these places involve overwhelming investments (Farret and Simões, 2006). However, with the recent concerns on the paradigm change in power generation as discussed above, there is a growing interest for the deployment of DG for other end users owing to the benefits it provides. In this point, the potential of DG deployment with renewables for manufacturing plants, particularly the marine manufacturing plants, which is the focus of this thesis to be explored.

Bearing the all the above in mind, it is now a must for many countries to increase the penetration of DG with renewables to their power systems from the energy challenge perspective. This is particularly important for energy importing developing countries such as Turkey so as to reduce their dependence on outsourced energy, alleviate the problems with transmission and distribution losses and power quality problems peculiar to CG and enhance their climate change performance increasing the percent of renewable energy in their energy portfolio. Turkey`s situation, focus of this thesis from a country perspective, will be discussed in the forthcoming sections.

All in all, DG strongly enables and contributes towards a low carbon transition of a country through enabling low carbon transition of its major power consumer sectors such as the globally top energy consumer, industry which will be discussed in the following section with a particular focus on manufacturing sector and marine manufacturing plants amongst other modes of industry sectors.

2.2.5 INDUSTRY AND THE ENERGY CHALLENGE

Industry can be regarded as a locomotive for a country`s economy; and energy is a vital fuel to power it. In line with this, the industry is the one of major energy end user sectors. The industry sector accounts for almost 36% of global final energy consumption and 24% of worldwide GHG emissions in 2014 (IEA, 2017b). According to International Energy Agency, the global energy use of the industrial sector is projected to grow by 2000 Mtoe between 2010 and 2050, which makes it the major energy consuming sector among all. 49% of final energy use by industry was because of developing countries whereas 40 % was due to developed countries and 11% economies in transition (Worrell et al., 2009). **Although some facilities in developing nations are new and they sometimes use the latest technology, many older and inefficient facilities are still in use in both industrialised and developing countries (Worrell et al., 2009).**

It should also be noted that the industrial sector is also globally a major consumer of electricity produced by the power generation sector being responsible for 42.3 % of global electricity consumption (IEA, 2017a) .This means that any reductions in industrial power demand will reduce the load on power generation sector which is another major fossil-fuel consumer as explained previously. Industrial sector comprises of a diverse group of branches including manufacturing, agriculture, mining, and construction and energy is consumed to power wide range of activities, such as processing and assembly, space conditioning, and lighting (Abdelaziz et al., 2011). According to IEA (2005), "*The energy intensity of most industrial processes is at least 50% higher than the theoretical minimum*". This fact represents a significant potential for energy efficiency improvement and associated reduction of GHG emissions in industrial sector. According to a scenario by the International Energy Agency (SFS, 2015), it is projected that the cumulative additional investments in industry reach $1.1 trillion by 2035, giving rise to $3.3 trillion of energy cost saving over the same period. **However, developing countries need technology transfer (hardware, software, and know-how) to be able to improve energy efficiency of their industrial sectors and achieve emission reductions (Worrell et al., 2009).**

The above facts about the industry and the before-explained critical and important role as well as the problems developing countries have in terms of the global Energy challenge present a research gap and one of the reasons that motivates the Author to focus on an industrial sector in Turkey, which is a fast-growing developing economy that faces the energy challenge severely as it will be explained in Section 2.2.7.

2.2.5.1 MANUFACTURING INDUSTRY

Amongst the industrial sectors, manufacturing sector has a vital importance for both developed and developing countries. For developing world, it is leverage for industrialisation and increasing incomes. As for developed nations, manufacturing is a source of innovation and competitiveness. It is responsible for the creation of products and services that improve life standard and create wealth (Despeisse, 2013). In parallel to this, manufacturing industry is required to be fuelled with high portions of energy compared to other industrial sectors. Therefore, it can be said that manufacturing sector is globally a crucial energy consumer and thus a critical producer of global

CO_2 emissions. According to International Energy Agency (IEA, 2008), the manufacturing industry was the major global energy consuming sector in 2005 with a share of 33% among all energy consuming sectors. Consequently, the biggest fraction of global CO_2 emissions in 2005 were majorly released by manufacturing industry as can be seen Figure 2-12.

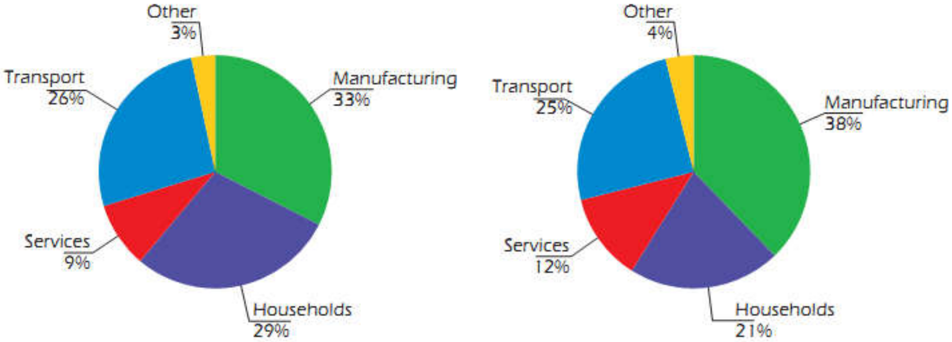


Figure 2-12: Total Global Energy Consumptions (left) and CO_2 emissions in 2005 (right) (IEA, 2008)

As seen, manufacturing sector is globally a vital contributor to the defined energy challenge being a carbon intensive sector. A considerable contribution to tackle with the energy challenge can come from manufacturing sector because of its relevance on overall energy use and emission release rates. As a consequence of this, it has recently gain greater attention and has become a target in most international and national climate change and energy security policies. International and national policies aside, there are also strong market pressures for manufacturing companies to consider the Energy Challenge in their business and operations.

On the one hand, consumer awareness towards more low-carbon or greener products which are manufactured within more energy efficient and environmentally friendly manufacturing plants has been increasing. Being certified by an energy management system certification like ISO 50001 or carbon emissions requirements is now demanded and dictated by most consumers from their suppliers in their purchasing contracts. In return, companies have to response to consumer awareness by reducing their environmental impact and having a green corporate image. By doing so they will have a competitive edge against their rivals in the market.

On the other hand, rising and volatile energy prices can affect the competitiveness of manufacturing companies because higher energy prices will increase their manufacturing costs. This is particularly a case for energy intensive plants doing business in an open market such as marine industry where there is a fierce competition. For energy intensive companies, energy cost constitutes a major fraction of the overall cost and thus directly impacts a company`s competitiveness. Owing to this, using less energy per value generated will not only lead to less carbon emissions but also provide a major competitiveness edge for such plants and more profit. While business benefit of less energy use is directly related to a company`s own energy performance, rising energy prices also affect the cost of other manufacturing inputs from a downstream affect perspective. Other manufacturing resources can increase continuously in coming years (Berger, 2009) because the rising energy prices can result in an increase in production costs of these materials such as steel, etc. (Bunse et al., 2011). Therefore, a collective effort from all stakeholders to reduce energy consumption and dependence on fossil fuels can also yield other economic benefits.

Bearing these in mind, there are three basic drivers for manufacturing companies to improve energy performance to reduce GHG emissions and energy costs: regulative drivers, market pressure from customer, increasing and highly volatile energy prices (Figure 2-13).

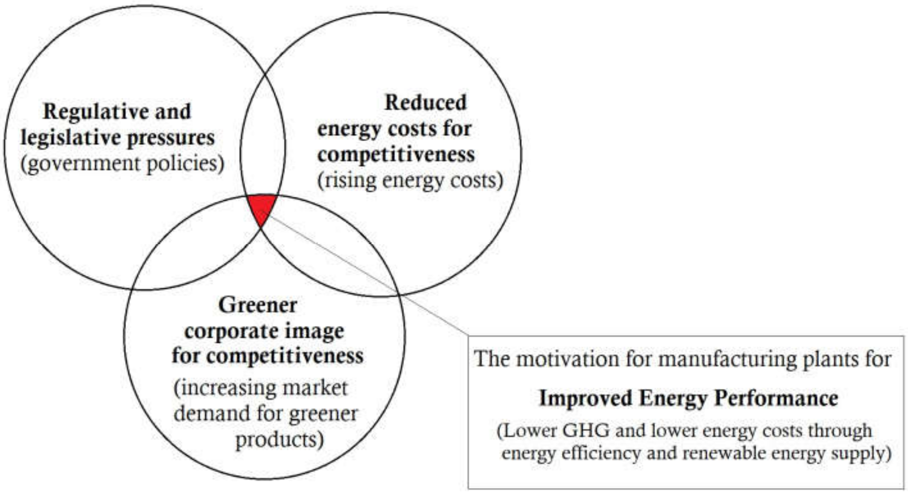


Figure 2-13: Drivers for improved energy performance in manufacturing plants

Improved energy performance, which can be defined as *"low GHG emissions and low energy costs through reduced energy consumption and low carbon energy use"* in this thesis, is a novel driver for manufacturing plants as a response mechanism to the Energy Challenge. If they cannot achieve this, they will face both regulative and market pressures. The consumption and cost of energy is now an ever important consideration for manufacturing plants (EW, 2015). Although they cannot control rising energy prices, national and international policies or the global economy, they can improve the way they manage energy in their operations (ISO, 2015).

2.2.5.1.1 Small and Medium Size Manufacturing Enterprises

Small and medium-size enterprises (SMEs) have a major role in worldwide economy due to the fact that they account for 99% of enterprises and provide approximately 60% of employment (IEA, 2015). About 50 % of global gross value added and from 16 to 80% of gross domestic product (GDP) depending on the country comes from SMEs (IEA, 2015). For instance, almost 90 million people are employed in SMEs and around 1.1 million new jobs per year are created in the EU. Similarly, SMEs account for almost 60 % of GDP in China and account for 60 % for manufacturing output (IEA, 2015).

One may regard their individual energy consumption as modest compared to large companies; however, their aggregated energy use is significant (IEA, 2015). There are also very energy intensive SME manufacturing plants such as foundries (Trianni et al., 2013) which consumes excessive amounts of energy for melting processes. According to IEA estimates, SMEs account for more than 13% of total global energy consumption and 30% of their energy use can be reduced by cost-effective energy efficiency measures This fact represents a significant energy efficiency gap for SME manufacturing plants.

Bearing the above in mind, increasing energy efficiency and reducing GHGs in SME manufacturing plants offers considerable benefits from the Energy Challenge. Being a major part of manufacturing industry, all energy related challenges defined in the previous section apply to SME manufacturing plants, as well. Therefore, drivers for improved energy performance, which are national and international policies (i.e. regulative and legislative pressures), consumer demand for low carbon products (i.e. market demand), and rising energy prices (i.e. competitiveness), have vital importance for SME manufacturing companies nowadays.

Despite all these, as the International Energy Agency (IEA, 2015) mentions, industrial and commercial SMEs are globally receiving little support from government subsidies because their energy consumption and the efficiency potential is unnoticed whereas large companies are increasingly benefiting from government programs and subsidies. Besides, there are various barriers that SMEs encounter to implement energy saving practises (IEA, 2015). These include that SMEs seldom have enough time and resource to explore energy efficiency options in their enterprises (IEA, 2015). Furthermore, they lack of information regarding where and how energy is used in their enterprises and usually have not enough internal capacity to improve their energy efficiency and set up energy management programs or an EnMS in comparison to larger industrial enterprises (IEA, 2015; Shipley, A.M., 2001). According to a study by (EC, 2007), 63% of SMEs in the EU do not have simple rules or devices for energy saving whereas about 29 % of them have instituted some measures for energy and resource saving at their enterprises. The percent of SMEs which employs a comprehensive system in place is only 4 % (EC, 2007).

Bearing the above facts regarding SMEs and importance of manufacturing plants in terms of energy challenge in mind, SME manufacturing plants are the focus of this PhD thesis from a sectoral and enterprise type perspective. **Amongst manufacturing plants, marine manufacturing plants such**

as marine equipment manufacturers, and shipbuilding and repairing yards requires special attention. The following section will discuss and explain the grounds.

2.2.6 MARINE INDUSTRY

Marine Industry plays a remarkable role in functioning the world economy and it is an indispensable part of it. It can be defined as "all businesses that own, operate, design, build, supply equipment or specialist services to all type of ships and other floating entities" (Mellbye et al., 2015). Today, ships carry around 90% of the world trade and seaborne trade is forecast to double over the next 15 years. Indeed, the recent Global Marine Technology Trends 2030 Report (Shenoi et al., 2015) expects that the marine industry will see growth in the future and will play expanding and positive roles in international seaborne trade and the global economy.

An important segment of the marine industry is marine manufacturing sector including shipbuilding and repair yards and marine equipment manufacturers, which have tremendous importance to the functioning of the world economy and world trade (OECD, 2010) by manufacturing large and complex marine vessels such as cruises, ships, offshore platforms, etc., which consists of diverse machinery and equipment. Today there are around 3400 shipyards in the world with varying size and capacity (Clarkson, 2013) and majority of them produce the commercial ships, which are global industry`s main assets. In 2007, the world fleet of seagoing merchant ships was around 74,398 vessels over 100gt (Stopford, 2013). All these ships and other marine structures are built in shipyards and various equipment such propellers, rudders, and various on-board machinery and equipment are manufactured by marine equipment manufacturers. The world fleet is cyclically renewed. When the global economy is upward, the shipyards` order-books will always be full for new buildings and repairs; thus, a number of diverse manufacturing activities which will consume substantial amounts of energy will take place. With this respect, shipyards and marine equipment manufacturers are important representatives of manufacturing branch of marine industry and they will be called as marine manufacturing industry in this thesis.

In addition to the above issues, in parallel to the increasing demand for food, raw material, and energy in line with the increasing world population and globalisation, emerging marine activities such as offshore renewable energy, aquaculture, deep ocean mining, marine biotechnology, and so on, are expected to show a fast development and grow. Indeed, oceans are vast reservoirs of food, energy, and other resources, representing a unique opportunity for innovations in pharmaceuticals, development of industries, and sustainable solutions (Shenoi et al., 2015). For example, the marine biotechnology industry, which involves applications focusing on aquaculture, biodegradation, or the use of biological sensors, is expected to grow by around 10% per annum in the coming years.

Similarly, deep ocean mining, which involves the extraction of resources such as copper, nickel, silver, cobalt, golds, etc. from the ocean floor through offshore operations using specialised subsea equipment for commercial applications, is expected to grow in parallel to the advances in technologies deployable in deep oceans and growing concerns regarding the supply of minerals from existing onshore mines (Shenoi et al., 2015). It is expected that the 10% of the world`s mineral will be supplied from the ocean floors in 2030 and the global turnover of deep ocean mining will grow from almost nothing to €10 billion in 2030 (Shenoi et al., 2015). Hence, these new emerging sectors will lead to a progressive growth in associated marine industries. In addition to biotechnology and deep ocean mining, an important emerging marine industry is marine renewable energy industry, which harnesses energy from sea and oceans, namely, from wind, tides, waves and thermal differences between deep and shallow sea water (Esteban and Leary, 2012). The marine renewables industry has important potential in terms of the climate change concerns, and hence interest in marine renewables energy resources has picked up over the last few years (Callaghan, 2006). According to the European Commission, there is a potential to create over 20,000 direct jobs in the EU by 2035 through the marine energy industry (EC, 2013). Similarly, according to (Esteban and Leary, 2012), the employment in offshore and ocean energy could globally reach around 1 million people by 2030, which shows the future potential of this sector.

Coupled with the grow of shipping and ocean industries such as maritime transportation, maritime tourism, offshore oil and gas production, it is certain that there will be more demand for marine manufacturing industry. Hence, the global marine manufacturing industry will experience a big growth by providing ships and boats such as submarines, yachts and superyachts, fishing vessels, unmanned, rib, etc. and equipment and machinery systems such as onboard equipment and accessories, engine, propulsion, rudder etc. as well as other marine floating structures, various machinery and equipment systems to the emerging industries, and marine energy devices such as offshore wind and tidal turbines, etc.

All in all, marine manufacturing plants are indispensable segment of the entire marine industry and will experience huge growth in short and long terms in line with the growth and expansion of other marine sectors. Bearing this potential in mind, one can say that marine manufacturing industry has important implications in terms of the Energy Challenge.

Indeed, as representatives of manufacturing sector in marine industry, marine manufacturing plants are subject to the Energy Challenge defined in Section 2.2 and in a sense, they share the same fate with other manufacturing branches as discussed in Section 2.2.5.1. Although this industry provides for one of the most energy-efficient modes of transportation (i.e. shipping) (OECD, 2010), activities in manufacturing plants in marine industry are highly energy intensive and environmentally polluting. For instance, a ship is a giant structure consisting of various systems of which construction require very diverse shipyard manufacturing processes such as cutting, bending, blasting, and welding, and so on. Similarly, manufacturing of various machinery and equipment such as marine engines and marine propellers and other on-board equipment involve energy intensive processes such as melting and machining and take place in marine equipment manufacturing plants. Besides these manufacturing processes, there are various support systems such as ventilation systems, compressed air systems, cooling towers, etc. which use substantial amounts of energy. Based on a study carried out by Kameyama et al. (2004), averaged electricity consumption at a shipbuilding yard to build a bulk carrier with a cargo capacity of 76,000 dwt (dead weight ton) was 1.7 million kWh during the entire manufacturing process which led to generations of 15,000 t-CO_2. According to Bhaskar (2009), the energy consumption to manufacture another transportation vehicle, a car, is about 700 kWh/vehicle. This means that a 76,000-dwt bulk carrier equals to about 2428 cars in terms of energy consumption during the manufacturing stages in their life cycles.

All the systems and processes which take place in manufacturing activities in marine industry consume energy causing direct (i.e. combustion of fossil fuels onsite are direct release of GHGs in situ as a result of the combustion) or indirect (i.e. an electricity consumer causes indirect release of GHGs consuming electricity which is generated by mainly fossil-fuel-powered central power stations) release of GHG emissions and contribute to climate change and affect the energy security of the country they are located in.

Therefore, being subjected to the Energy Challenge, the drives for improved energy performance (Figure 2-13) applies to manufacturing plants in marine industry, as well. In fact, these drivers affect manufacturing plants of marine industry more than any other sectors because this industry represents one of the world`s most open and competitive markets (Stopford, 2009) which makes this industry different than others. To give an example from shipbuilding sector, a ship-owner takes several quotations before ordering a ship and prices change violently upwards or downwards depending on the number of shipyards from various countries (Stopford, 2009). While marine industry market is already volatile, volatility also in energy costs in manufacture of a ship and its equipment will increase the uncertainties for its manufacturers. In such a fiercely competitive market, business factors such as cost cutting, and good corporate image are imperative. As is well known, shipbuilding industry has moved to developing countries such as China which has the advantage of low labour cost, one of the main factors which have made Chinese shipyards a leader in shipbuilding industry. In this regard, global rivals from different countries which have relatively higher cost inputs could consider improved energy performance as a strategic measure to improve their competitiveness. This is of tremendous importance for the enterprises located in energy importing countries such as Turkey because security of affordable and secure energy supply is problematic in these countries.

Besides all these, green corporate image is another important issue for the competitiveness of marine manufacturing companies. Many ship owners, particularly from developed world, now opt for plants with good corporate image, technologically advanced, environmentally friendly, and energy-considerate manufacturing plants to construct their vessels or order for related equipment such as propellers and on-board machinery and equipment.

The author of this thesis made an interview with a business development engineer of a Turkish shipyard (Vural, 2014) which revealed that their consideration to energy and environmental issues in their business activities was increasing day by day because Turkish shipbuilding companies are now doing business with European companies (e.g. Norwegian companies) which are very sensitive to these issues. At this point, a manufacturing plant in marine industry with energy efficient manufacturing system certified and equipped with an EnMS can have a competitive advantage over its global rivals. Similarly, a manufacturing plant which has an on-site clean power generation system based on renewable generators such as a wind turbine and photovoltaic modules can attract its customers more than others which lack such a facility.

Bearing the above in mind, reducing energy consumption and associated GHG emissions through energy efficiency and clean onsite power generation offers great opportunities for manufacturing plants operating in marine industry, particularly for energy intensive ones, in such a competitive global marketplace of the marine world. Therefore, improved energy performance has a remarkable importance and it is becoming a top priority business factor for manufacturing plants in marine industry. Bearing the important concerns regarding the SMEs in the previous section in mind, improved energy performance for SME manufacturing plants in marine industry is a top challenge.

Despite these important aspects of manufacturing activities in marine industry, the priority of research and discussion in marine industry regarding climate change and other environmental issues has been mainly given to the use phase of ships at sea (i.e. off-shore facilities). Research efforts regarding energy efficiency and climate change issues in this sector can be traced mainly in subjects such as ship design aspects covering new innovative design and optimisation approaches, increasing fuel consumption efficiency of ships or the abatement of CO_2 from ships through operational measures such as speed reduction and weather routing or technical measures such as energy efficiency retrofitting, waste heat recovery, etc. which can be applied to new build ships or for retrofit of existing ships. The most important study and evident implication of these is the IMO's studies on "GHG Emissions from Ships" and EEDI/EEOI applications (IMO, 2011). In addition, relatively recently completed EU-funded research project TARGETS (TARGETS, 2014) and two UK based EPSRC funded "Low Carbon Shipping" and "Shipping in Climate Change" (LCS, 2013; SCC, 2017) are the most recent examples of major research efforts in this field.

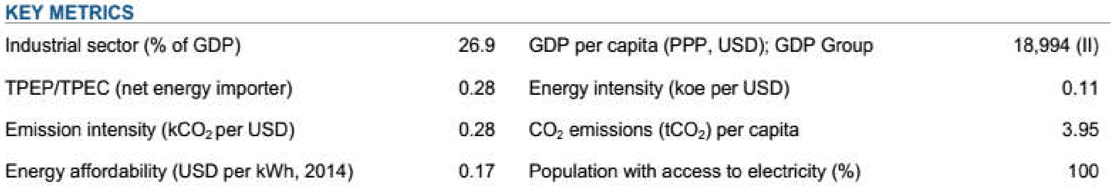
To see the real contribution of entire marine industry to the Energy Challenge, all segments, i.e. from marine transport to manufacturing activities, have to be taken cognizance of. Therefore, marine manufacturing plants, the important - but neglected - part of marine industry, need to be addressed in terms of the Energy Challenge concerns. Without taking the manufacturing activities in marine industry into consideration, the whole picture cannot be completed.

Bearing the all above in mind, a research attempt therefore to fill this gap should contribute to the understandings of energy use characteristics and associated environmental impacts from manufacturing activities in marine industry as well as gathering attentions of marine manufacturing plants, policy makers, and other stakeholders in marine industry for the before-defined energy challenge concerns. By doing so, it will also contribute to the climate change mitigation of manufacturing activities in marine industry.

2.2.7 TURKEY AND THE ENERGY CHALLENGE

The Turkish economy is defined as an emerging and largely developing one which makes Turkey one of the world`s newly industrialised countries (WB, 2015). Turkey has become one of the biggest emerging economies in the world over the last 30 years owing to the rapid increase in its population and industrialisation. According to OECD, Turkey was the 11th largest economy in the world with a GDP of 960.1 billion USD in 2007. Table 2-2 summaries some key data about Turkey. The increases in GDP per capita and population can be seen in Figure 2-14 and Figure 2-15, respectively. The World Energy Council (WEC) classifies Turkey as one of the highly-industrialized countries which are defined as emerging economies with large manufacturing sectors. Economies of these countries are based on energy- and emission-intensive activities (WEC, 2015).

Table 2-2: Some key data about Turkey (WEC, 2015)



KEY METRICS

Industrial sector (% of GDP)	26.9	GDP per capita (PPP, USD); GDP Group	18,994 (II)
TPEP/TPEC (net energy importer)	0.28	Energy intensity (koe per USD)	0.11
Emission intensity (kCO_2 per USD)	0.28	CO_2 emissions (tCO_2) per capita	3.95
Energy affordability (USD per kWh, 2014)	0.17	Population with access to electricity (%)	100

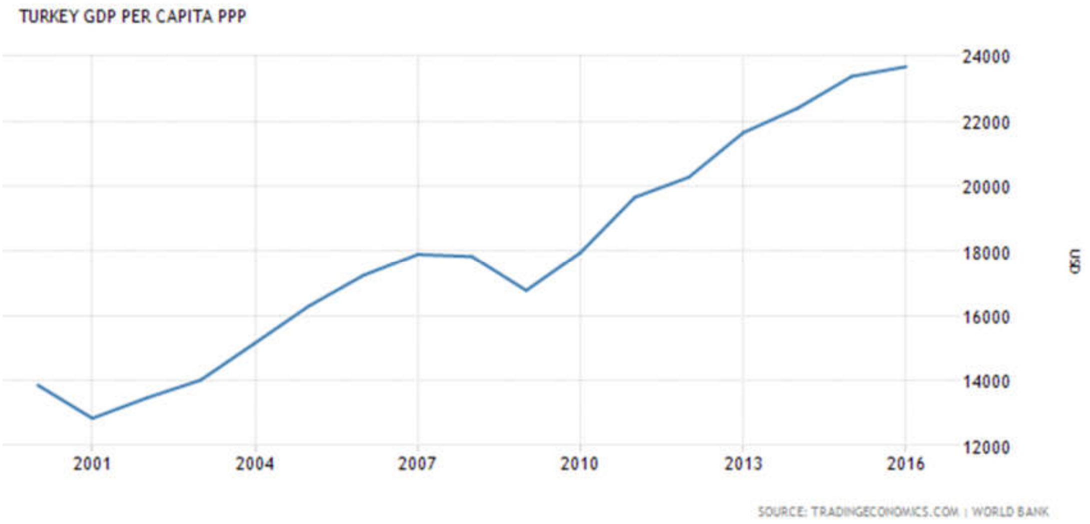


Figure 2-14: GDP per capita for Turkey from 2000 to 2016

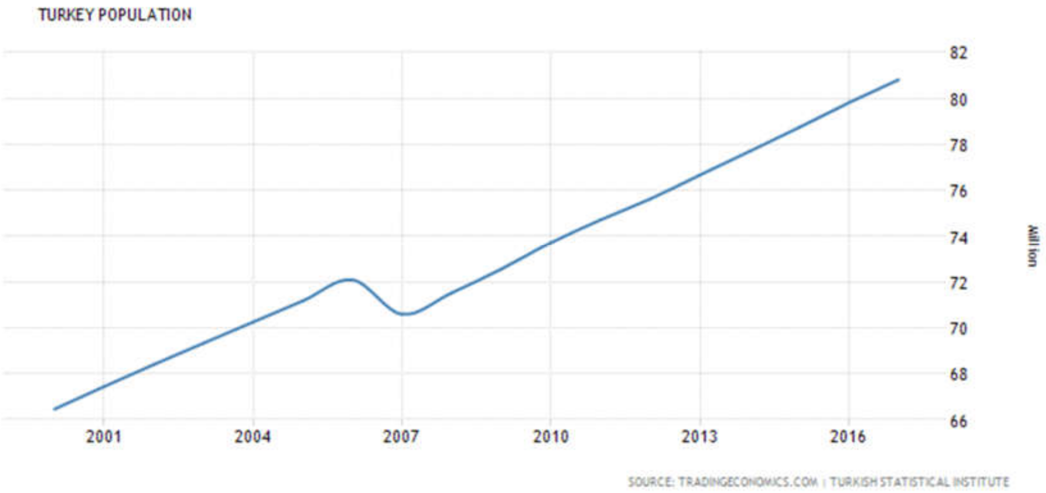


Figure 2-15: Population of Turkey from 2000 to 2018

Coupled with the fast growing economy and increasing young population, according to International Energy Agency (IEA, 2013), Turkey`s Total Primary Energy Supply (TPES) has risen substantially from 24.4 million tonnes of oil equivalent (Mtoe) in 1973 to 114.1 Mtoe in 2011 at a compound annual growth rate of 4%. The increasing trend of Turkey`s TPES from 1973 to 2011 can be seen in Figure 2-16. In addition to this, it is considered that TPES is most likely to continue to grow at a compound annual growth rate of about 4.5% from 2015 to 2030, rising to over 237 Mtoe in 2030 (IEA, 2013). In this respect, Turkey has become one of the fastest growing energy demanding countries in the world. For instance, Turkey has been the second country in terms of natural gas and electricity demand growth over the last decades, after China (MFA, 2016). Turkey`s increasing electricity demand and demand growth rate can be seen in Figure 2-17.

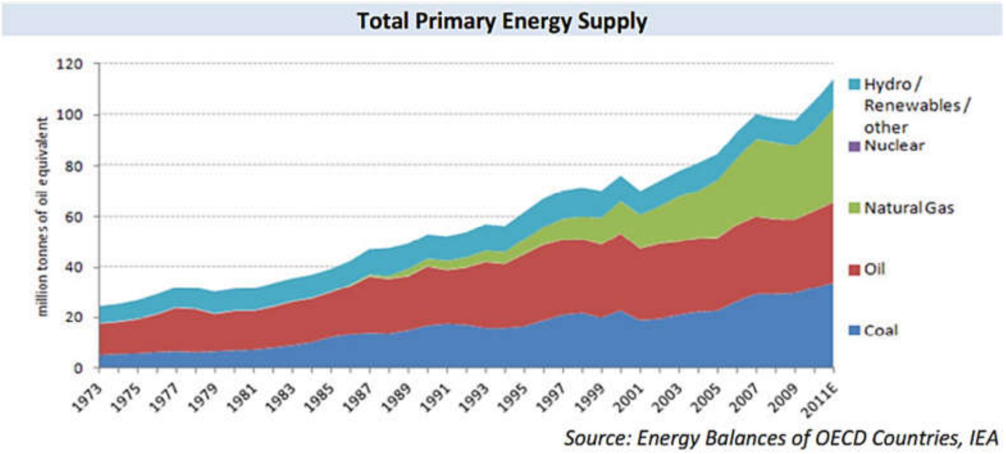


Figure 2-16: TPES in Turkey between 1973 and 2011

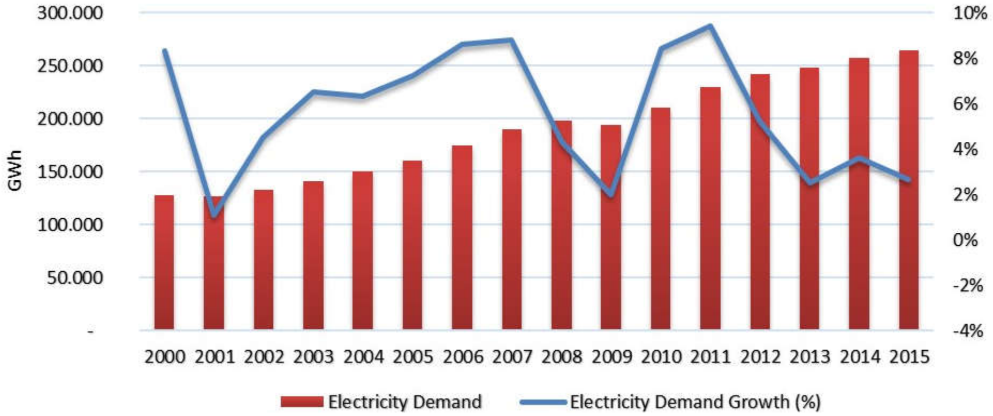


Figure 2-17: Electricity demand and demand growth rate by year (EMRA, 2015)

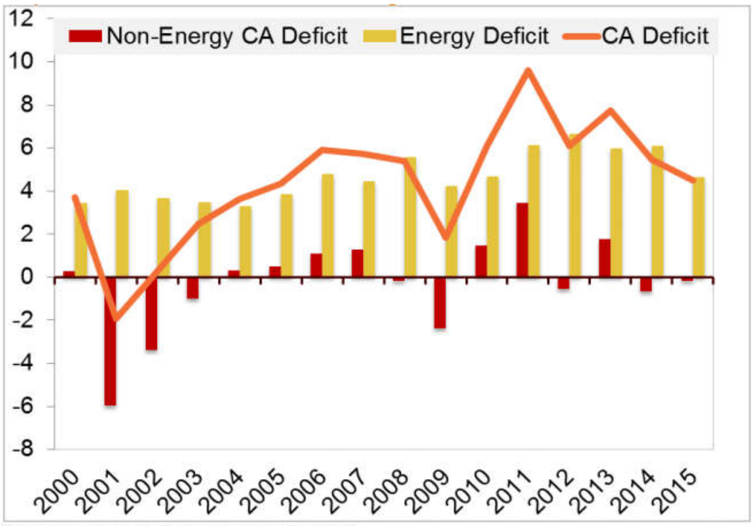
While the energy demand of Turkey has been growing fast, unfortunately she is not a lucky country in terms of having indigenous fossil-based energy resources; she is an energy dependent country in a politically volatile region and net energy importer of mainly fossil fuels. Increasing energy demand and limited domestic energy resources has forced Turkey to increase its dependence on imported energy supply, primarily on oil and natural gas supplies (Benli, 2013). Only about 25% of total energy demand is being supplied by domestic energy sources at present. The energy import ratio is about 75 % (MFA, 2016). Turkey imports around 89% of its oil supplies and almost 99% of natural gas use (MFA, 2016).

2.2.7.1 TURKEY AND ENERGY SECURITY

Meeting the increasing energy demand of a fast-growing economy with very limited domestic energy sources and depending on foreign energy supply is a very challenging and risky task. Energy dependence is a great concern and there are various important implications of such a situation with regards to the energy security for Turkey.

First, the imported energy costs too much for the Turkish economy. According to Turkish Statistical Institute, Turkey`s imported energy cost was $52.5 billion in 2011 whereas it approached $52.5 billion in 2012 and around $54 billion each in 2013 and 2014 (AA, 2014). The contribution of Turkey`s energy imports to its current account deficit is quite striking. The relation between the current account deficiency and energy deficiency of Turkey between 2000 and 2015 can be seen in Figure 2-18. Taking the year 2011 as an example, the overall export of Turkey was about $135 billion whereas the overall import was around $241 billion. Thus, the current account deficit for Turkey was $77.1 billion in 2011. These figures mean that the imported energy cost accounts for 68% of the current account deficit of the Turkish economy showing its impact on the Turkish economy. Growing economy will bring in growing energy deficit within the current consumption trends and this is not sustainable for the Turkish economy.

In addition to these, as mentioned earlier, global energy (i.e. oil and gas) prices are very volatile and directly affected from any regional and global political conflicts in today`s world (i.e. where Turkey is exactly in the middle of) which will consequently increase the vulnerability of the Turkish economy and cause uncertainties.



Source: Central Bank of Turkey and Turkstat

Figure 2-18: The relation between the current account deficiency and energy deficiency of Turkey between 2000 and 2015

Second, Turkey`s overwhelming reliance on foreign energy supply poses an enormous risk to national energy security. As seen in Figure 2-19 and Figure 2-20, natural gas has a critical role for Turkey`s power generation accounting for a major share in fuel input mix. Despite this importance, Turkey imports 99% of her natural gas use because of being deprived of domestic natural gas deposits. On top of that, Turkey is dependent on few countries in natural gas supply which worsens security of stable energy supply.

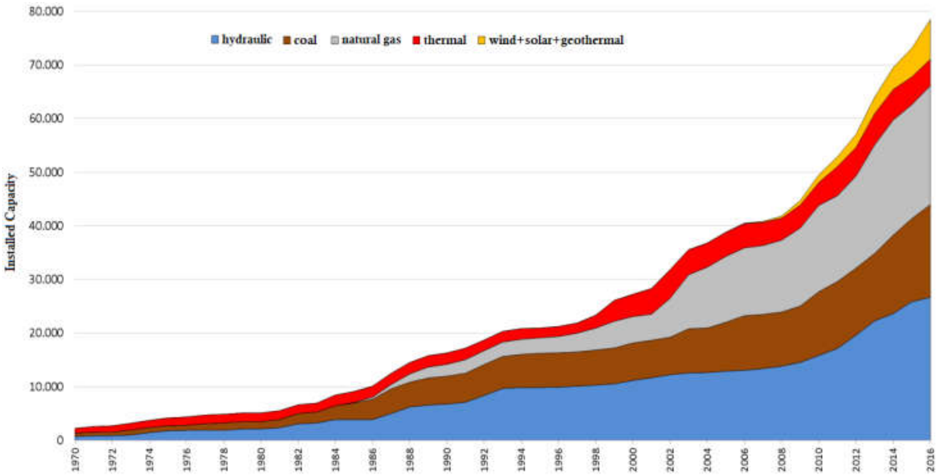


Figure 2-19: Electricity generation by fuel source in Turkey between 1970 and 2016

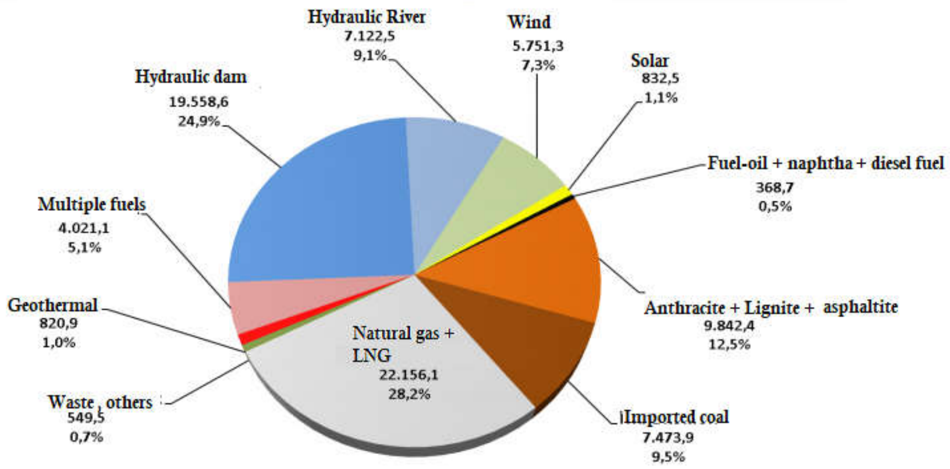


Figure 2-20: Electricity generation by fuel type in Turkey in 2016 (TEITAS, 2018)

As seen in Figure 2-21 and Figure 2-22 imports natural gas from various countries in which Russia is the major supplier. For instance, in 2015, Russia had the significant share in Turkey`s natural gas import accounting for 52.8% of overall natural gas supply whereas Iran and Azerbaijan accounted for 15.3% and 12%, respectively. In this respect, Turkey is overwhelmingly dependent on Russia for natural gas. Indeed, the recent military jet crisis between Turkey and Russia in November 2015 brought into question the dependence of Turkey on Russian natural gas supply and highlighted the importance of diversification of energy supplies as well as reducing the dependence on foreign energy supply for Turkey to ensure the security of a stable energy supply.

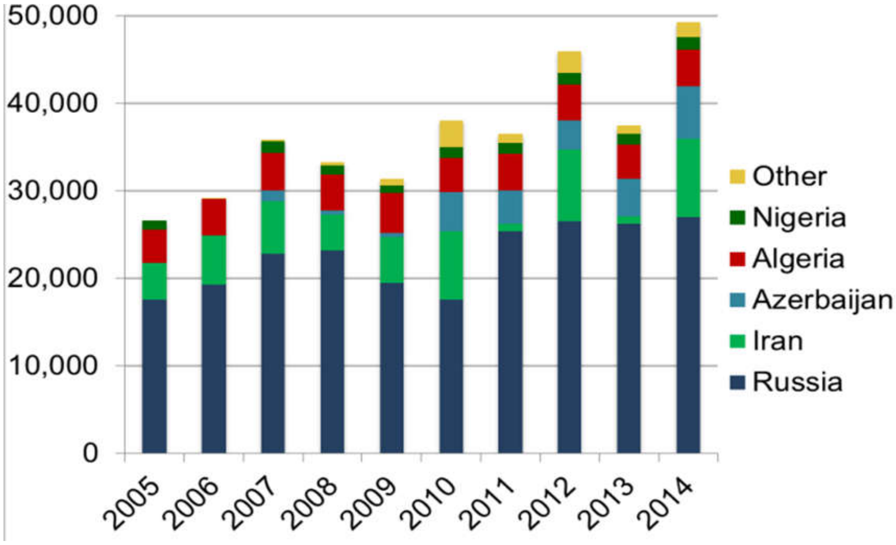


Figure 2-21: Turkey`s Annual Natural Gas Imports (EMRA, 2015)

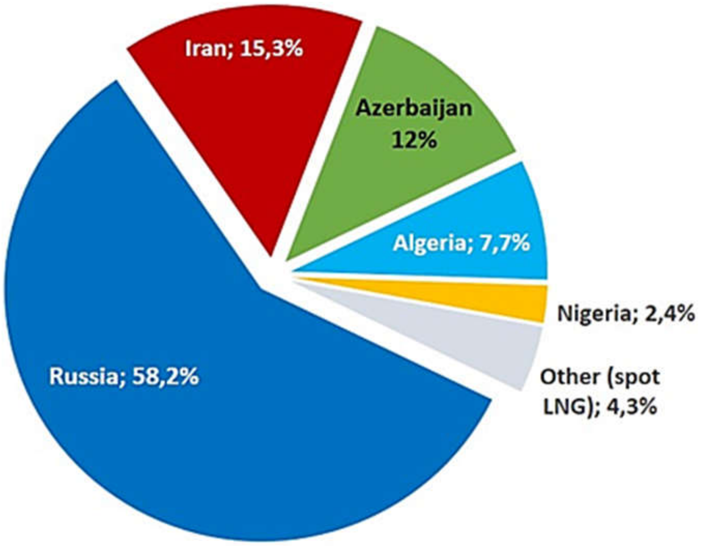


Figure 2-22: Turkey`s Natural Gas Imports by Country in 2015 (EMRA, 2015)

While Turkey is strongly dependent on imported fuels for electricity generation, another problem for the country is the distribution and transmission losses (TDL), which can be classified as technical and non-technical losses (Tasdoven et al., 2012). Technical losses are generally due to the physical characteristics of the transmission and distribution system such as the power lost in transmission lines and transformers because of their internal electrical resistance (Suriyamongkol, 2002). On the other side, non-technical losses are related to the external actions to the power system (Suriyamongkol, 2002). Two major elements in non-technical losses are power pilferage (power theft) and unpaid bills (Tasdoven et al., 2012).

The rate of the lost electricity in Turkey is significant. For example, the sum of the electricity losses in Istanbul (3.1 billion kWh) and Sanliurfa (3 billion kWh) is more than the annual power produced by Keban Dam (6 billion kWh) (Tasdoven et al., 2012; TEDAS, 2009) clearly showing the significance of electricity losses in the country. The rate of the overall technical and non-technical electricity losses was 14.82% in 2014. In this regard, Turkey was leader in terms of TDLs among the OECD countries. As shown in Figure 2-23, while the OECD average was 6.3%, it was 14.82% for Turkey.

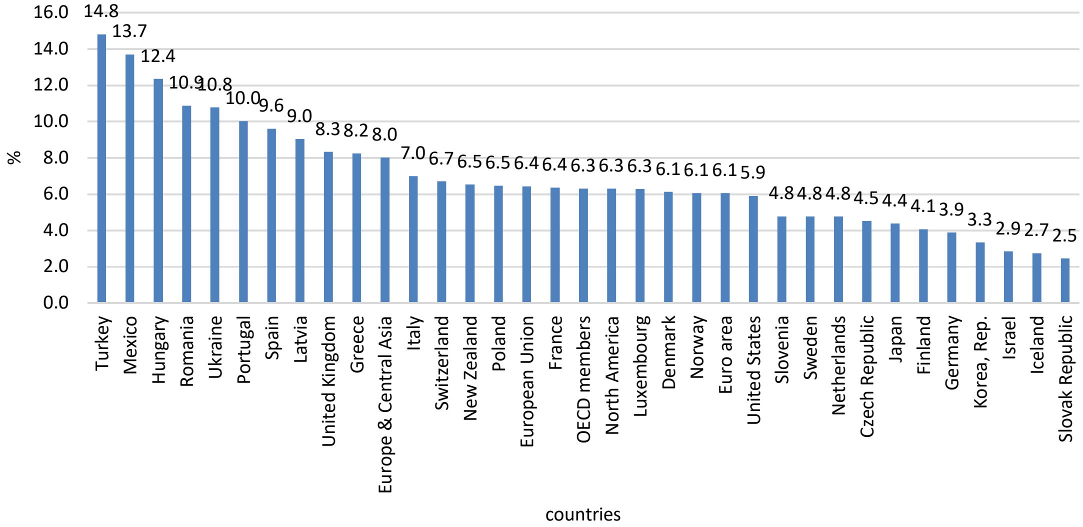


Figure 2-23: TDLs in OECD countries, World, OECD and EU average in 2014 (data taken from World Bank (2014)

Non-technical losses (i.e. power pilferage) can be obviated through governance approaches and the Turkish Government has already stepped into action through various approaches such as privatization and economic regulation of the electricity market. Besides these, some additional tools such as grants and public information can be applied as proposed and discussed for their effectiveness by (Tasdoven et al., 2012).

As for the technical losses, they are related to the technical characteristics of the power transmission and distribution system. For instance, systems with long transmission lines induce more losses than the systems with short line (Onat, 2010). Also, the quality and condition of the system components such as transformers and lines can influence the TDLs (Onat, 2010). The losses associated with the quality and condition of the system components can be avoided through high quality components and good maintenance practises (Onat, 2010). While these measures can be effective for short term, the Turkish power generation sector should benefit from the paradigm change in power generation in the form of from more CG to DG as discussed in Section 2.2.4. This is because the major reason behind the high TDLs is the intensity of CG in Turkey. Although the major power generation facilities are mainly centred at the East and South East regions of Turkey, the major power consumer regions are the West and North West regions because of the population and development differences between the regions (Onat, 2010). The power is transferred from the producer regions to the consumers using very long transmission lines. Therefore, the share of DG in the Turkish power generation system should be increased. In this respect, DG can be popularised among the Turkish industrial sectors, of which major part is located in the North West of Turkey.

2.2.7.2 TURKEY AND CLIMATE CHANGE

In addition to the above explained challenge of energy security and its implications for the Turkish economy, Turkey faces the other dimension of the Energy Challenge, Climate Change. Turkey is a major GHG polluter and a contributor to climate Change. As it was shown in Figure 2-16, coal, oil, and natural gas (i.e. fossil fuels) are the major elements of Turkey`s TPES. In 2016, the share of oil, natural gas, and coal in Turkey`s TPES were 31%, 28%, and 27%, respectively. The renewables including hydro accounted for only 12% (IEA, 2013). These figures show the preponderance of fossil fuels in Turkey`s energy portfolio. In parallel with dependence on fossil fuels and increasing domestic energy demand owing to growing economy, Turkey` s GHG emissions has steadily risen from 210.7 million tonnes in 1990 to 496.1 million tonnes in 2016 (TSI, 2017), as can be seen in Figure 2-24. These figures mean an increase of 135.1% in GHG emissions showing the contribution of Turkey to global climate change.

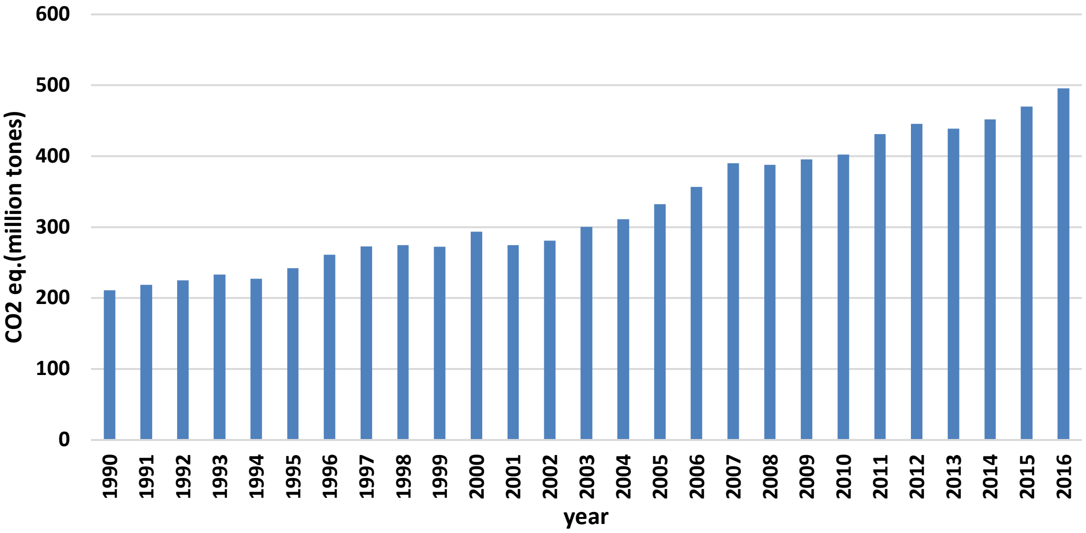


Figure 2-24: GHG emissions trend of Turkey: overall CO_2 equivalent emissions during the period 1990-2016 (TSI, 2017)

Although the energy challenge will affect every country during the next decades, it will be more challenging for Turkey. On the one hand, her growing economy must be powered with high amounts of energy demand; particularly fossil fuels are significantly needed because power generation in Turkey is mainly based on thermal plants, which are fired by coal and natural gas. Despite this, as discussed above, Turkey is a poor country in terms of natural gas reserves and almost completely dependent on foreign natural gas supply, which imposes adverse implications for her economy and national energy security. On the other hand, Turkey is a major GHG polluter because of excessive use of fossil fuels, particularly the coal in power generation, and, thus, climate change concerns need to be addressed because Turkey is a party to the legally binding Paris Agreement. In this regard, Turkey faces extreme difficulties to cope with the energy challenge and balance the conflicting dimensions of the Energy Trilemma.

All the above highlights the paramount importance of low carbon transformation for Turkey to be able to achieve these impressive targets and overcome the energy challenge. Hence, in harmony with this, the primary aims of Turkey are (MFA, 2016):

- to diversify its energy supply routes and source countries
- to increase the share of renewables and include the nuclear in its energy mix
- to take significant steps to increase energy efficiency
- to contribute to Europe`s energy security

The development of renewable energy sources and the promotion of energy efficiency measures are two of the priorities of Turkish energy policy (EBRD, 2014). The Turkish government aims to increase the share of renewables and add nuclear power into Turkey`s energy portfolio with the aim of reducing the dependence on foreign energy supply and increasing the use of domestic energy production in a climate friendly way to reduce GHGs (MFA, 2016). Turkey is a very rich country in terms of indigenous renewable energy resources such as wind, solar, and geothermal. For instance, Turkey`s annual wind energy potential is estimated to be 160 TWh of which about 124 billion kWh is technically feasible (Ediger and Kenter, 1999; Ogulata, 2003). Similarly, annual solar energy technical potential is estimated to be 6105 TWh (Balat, 2005).

Despite these facts showing the great potential of sun and wind, 92 % of renewable-based electricity generation comes from hydropower whereas other renewable energy sources account for less than 5% (Melikoglu, 2013) which is very marginal taking the renewable energy potential of the country into account. Turkey is a rich country and has the second largest economic potential in terms of hydropower in Europe (Erdogdu, 2011). However, share of hydropower (i.e. 92% of renewable-based power generation) indicates the lack of diversity in Turkey`s renewable energy mix which is not welcomed in terms of energy security (Melikoglu, 2013). In addition to this concern, electricity generation from hydropower is a kind of CG which possess various drawbacks as explained in Section 2.2.4. Despite Turkey`s enormous potential for wind and solar energy, Turkey`s installed generation capacities from these renewables are 4503 MW for wind power and 248.8 MW for PV power as of 2015-end. These mean that wind power contributes to 6.1% of overall power generation whereas PV`s contribution is just 0.3% (TEIAS, 2016). For instance, the total installed PV power capacity in Germany was about 40GW at the end of 2015 and it covered approximately 7.5 % of Germany`s final electricity consumption in 2015 PV power can meet 35% of the momentary power demand on sunny days whereas it can cover 50% on weekends and holidays and weekends (Wirth and Schneider, 2016) although solar energy potential in Germany is lower than that of Turkey. As seen in Figure 2-25, the yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules in Turkey varies between 1400 kWh/m^2 and 2100 kWh/m^2 whereas it is between 1000 kWh/m^2 and 1400 kWh/m^2 for Germany.

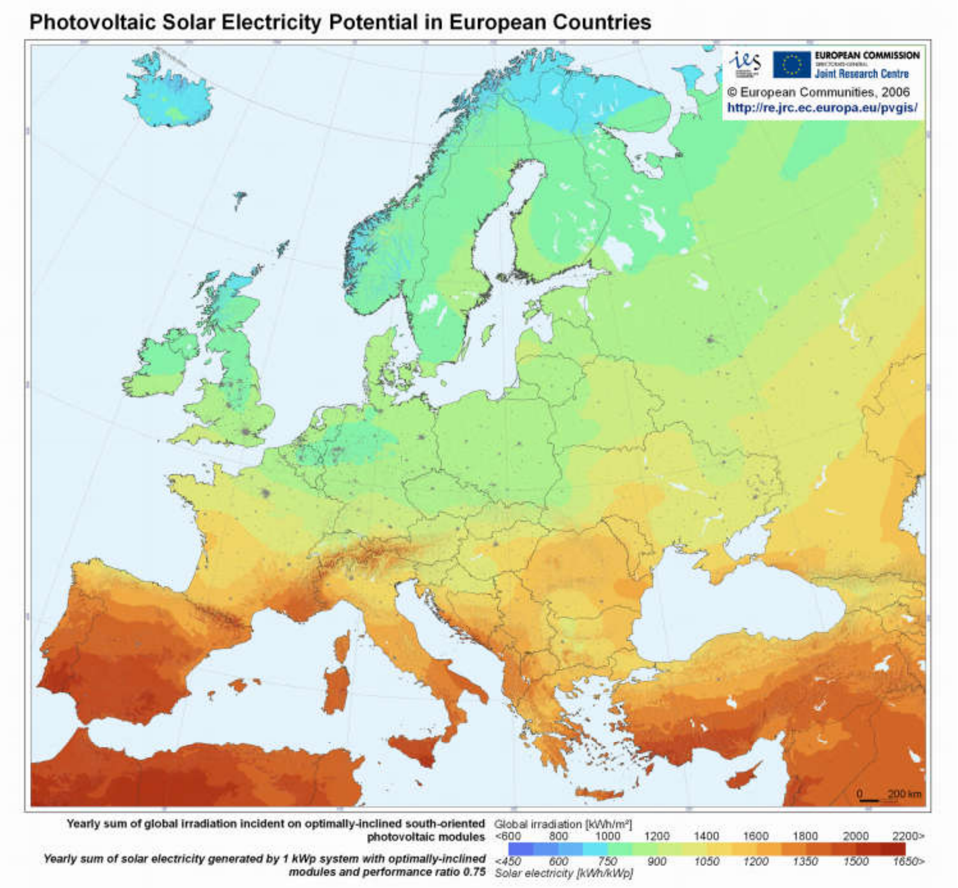


Figure 2-25: Photovoltaic Solar Electricity Potential in European Countries

Fortunately, according to the National Renewable Energy Action Plan of Turkey (EBRD, 2014), Turkey takes action and plans to have 34 GW of hydro generation capacity, 20 GW of wind, 5 GW of solar, and 1 GW in both geothermal and biomass generation capacity by 2030 which would require a sevenfold increase in non-hydro renewables in less than a decade. Alongside renewable energy, of particular note is Turkey`s commitment to reduce her energy intensity (energy consumption per unit GDP) by 2023 at least 20% with reference to 2011 figures (EBRD, 2014). According to the International Energy Agency (IEA, 2009), Turkey`s energy intensity is around twice that of the OECD countries average (Figure 2-26) while energy consumption per capita is about one fifth of that in OECD countries which indicates a great potential of energy intensity reduction.

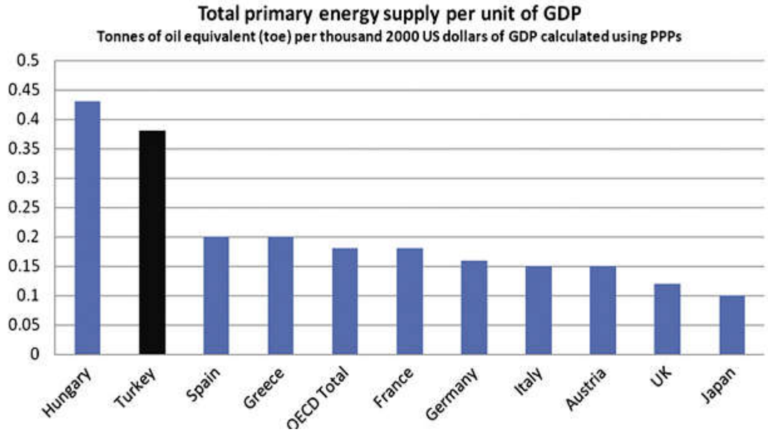


Figure 2-26: Energy intensity of Turkey and OECD countries (Ates and Durakbasa, 2012)

It is out of question to think that Turkey`s ambitious energy plans have no implications for her major energy using sectors. The major paradigm changes which have been explained in previous section is unavoidable for these sectors. In 2014, power generation and manufacturing sectors accounted for 42.4% and 38.4%, respectively in total energy consumption of Turkey (TSI, 2017). In parallel to their intensive energy use, these two sectors are major CO_2 emitters as can be seen in Figure 2-27. Furthermore, the manufacturing sector is the leading consumer Turkey`s overall electricity consumption using 78,033,897 MWh of electricity (TSI, 2017). This implies that the manufacturing sector also triggers the energy use of power generation sector by demanding electricity. As such, any reductions in energy intensity of the manufacturing sector and promotion of increased power self-sufficiency by deploying renewable energy with DG will reduce the load on power generation sector.

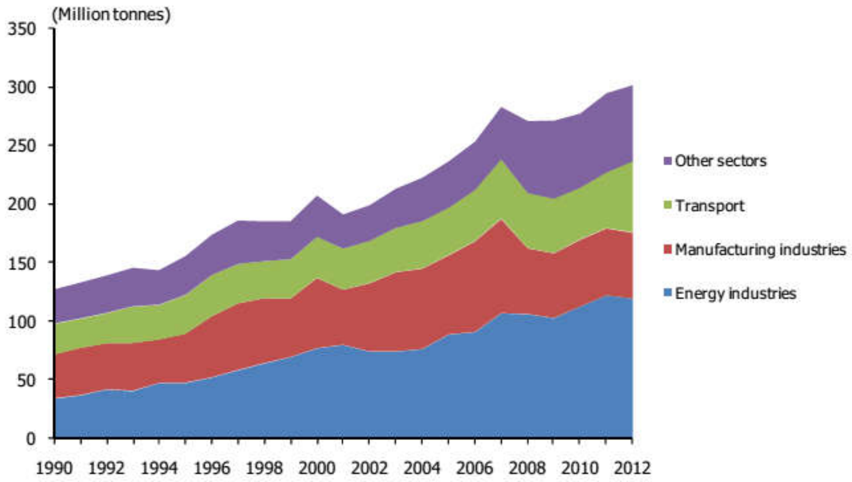


Figure 2-27: CO_2 emissions from different sectors in Turkey between 1990 and 2012 (TSI, 2012)

In accordance with the above facts, the Turkish government pays special attention to the manufacturing sector. The Turkish government defines seven strategic goals in order to achieve the 2023 energy targets in the Energy Efficiency Strategy 2012-2023 document, approved by Turkey`s High Planning Council on February 27, 2012 (MENR, 2012). These are as follows:

1. to reduce energy intensity and energy losses in industry and services sectors.
2. to decrease energy demand and carbon emissions of the buildings; to promote sustainable environment friendly buildings using renewable energy sources.
3. to provide market transformation of energy efficient products.
4. to increase efficiency in production, transmission and distribution of electricity, to decrease energy losses and harmful environment emissions.
5. to reduce unit fossil fuel consumption of motorized vehicles, to increase share of public transportation in highway, sea road and railroad and to prevent unnecessary fuel consumption in urban transportation.
6. to use energy effectively and efficiently in public sector.
7. to strengthen institutional capacities and collaborations, to increase use of state of the art technology and awareness activities, to develop financial mechanisms except public financial institutions.

1st and 4th strategies purposes directly relate to manufacturing plants and power generation plants, respectively. According to the Energy Efficiency Strategy 2012-2023 Document, the Energy-Efficiency Strategy defines four sub-activities within the industrial sectors as follows (MENR, 2012).

1. to define applicable measures in energy efficiency with the savings potential in industry subsectors.

2. to require the business enterprises, obliged to establish an energy. management unit or nominate energy manager in the industry and services sectors, and the industrial zones to have ISO 50001 Energy Management Systems Standard in the relation of them with the public enterprises.
3. preparing action plans identifying needed efficiency measures, their energy-savings potential, and their cost, based on periodic energy audits.
4. encouraging investment in energy-efficiency measures by establishing additional financial incentive programs.

2.2.8 TURKEY AND MARINE MANUFACTURING INDUSTRY

Turkey is a natural bridge between two great continents, Asia and Europe (RTME, 2017), being located at the crossroad of them. With a coastline of about 8,483 km (Bloem et al., 2013), the country is surrounded by the Black Sea, the Marmara Sea, the Aegean Sea, and the Mediterranean Sea. Turkey has borders with Georgia, Armenia, Azerbaijan (Nakhichevan) and Iran to the East, Bulgaria and Greece to the West, Syria and Iraq to the South, and Russia, Ukraine and Romania to the North. Therefore, Turkey is a very strategically located country from an international trade perspective (Bloem et al., 2013). These facts necessitate Turkey to have close relation to marine industry, thus, it not surprised that this industry is of great importance in Turkey.

In fact, Turkey has long tradition of maritime activities. For example, the Turkish shipbuilding industry has a history of 600-year old tradition in Anatolia (RTME, 2017). The first shipyard was established in 1390 in Gelibolu in Ottoman reign (Bloem et al., 2013) and the largest shipyards in the world in the 16th century was already Turkish. Combining these traditional skills with the modern techniques and education, particularly since the early 1990s, the modern shipbuilding industry of Turkey has evolved into an internationally known trademark with its modern, technologically developed and quality certified shipyards employing a well-experienced work force that can build ships, mega-yachts and sailing boats as well as carryout extensive repair and conversion works, which made Turkey the fifth largest shipbuilding country in the world in the last 5 years (RTME, 2017). Currently, there are 80 shipyards in operation in Turkey, mostly in direct vicinity of Istanbul, Yalova, and Kocaeli, with the following technical characteristics (RTME, 2017):

- 4.4 million DWT (Deadweight ton) new shipbuilding capacity.
- 19 million DWT repair and maintenance capacity.
- 239,000-ton steel processing capacity.

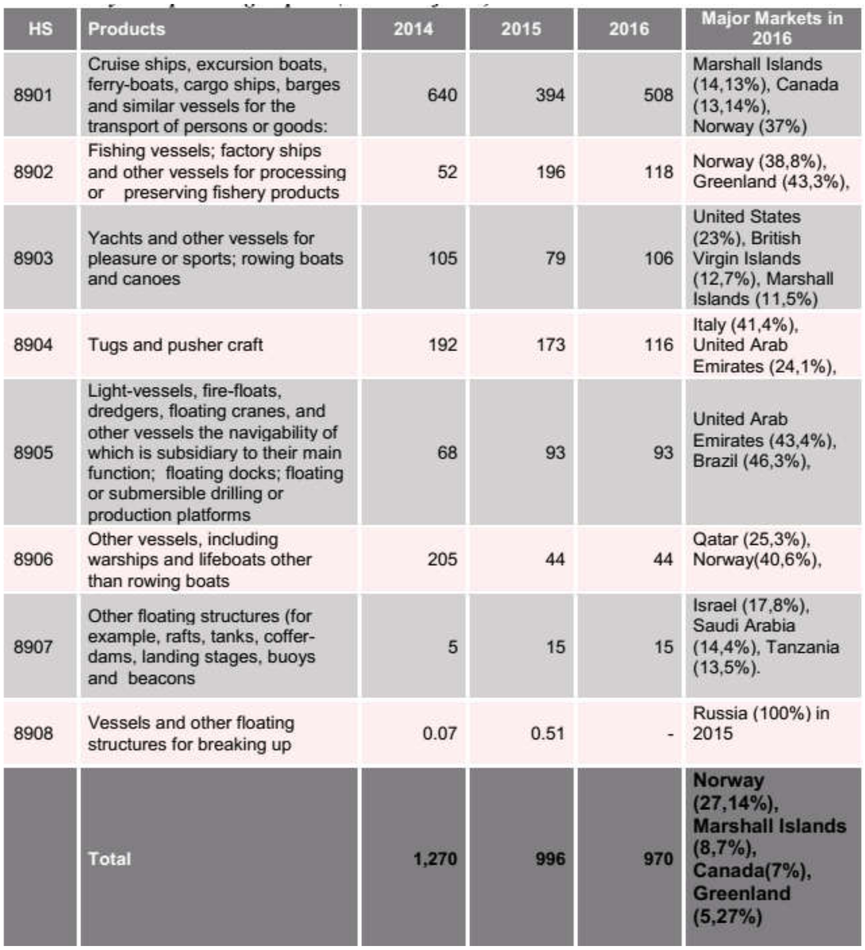
- an 80,000 DWT new shipbuilding capacity as one piece.
- 15 floating docks of different sizes and one dry dock.

As of 2014, 249 ships with a total DWT of 550,000 had been built by the Turkish shipyards (RTME, 2017). Today, Turkey is the top manufacturer for low-tonnage chemical tankers in Europe (RTME, 2017). Despite being badly affected by the global economic crisis in 2009, the Turkish shipbuilding industry has taken suitable measures to recover its affects. For instance, the Turkish shipyards has increasingly tapped into niche markets and there has been a growing participation by the Turkish shipyards in the international trade in new ships. The Turkish shipbuilding sector can manufacture various niche market vessels such as research vessels, tugs, fishing boats, supply vessels, offshore boats, and mega-yachts (OECD, 2011). Today, the Turkish shipbuilding industry builds highly efficient tugboats and fishing vessels for many European countries such as Norway, Germany, and Denmark. For instance, the world`s first LNG-fuelled tugboat was built by a Turkish shipyard in 2014 (Sanmar, 2014). In addition to these, an important marine manufacturing sector in the Turkish shipbuilding industry is mega-yacht manufacturing (RTME, 2017). In recent years, this sector has experienced a notable progress in manufacturing of boats, yachts and mega yachts and hence made Turkey the number third on the world list of mega-yacht manufacturers as of January 2017 (RTME, 2017). In line with all these, there has been a strong growth in the marine equipment manufacturing sector in Turkey (OECD, 2011).

As well as being recognised for their expertise of manufacturing specialised commercial vessels, the Turkish shipbuilding has also improved its expertise in naval and coast guard projects (Kiran, 2013). While Turkey used to import naval ships in the past, now the Turkish shipbuilding industry is capable of manufacturing naval ships to the Turkish Navy, which has made Turkey one of the few countries capable of building their own naval ships (Kiran, 2013).

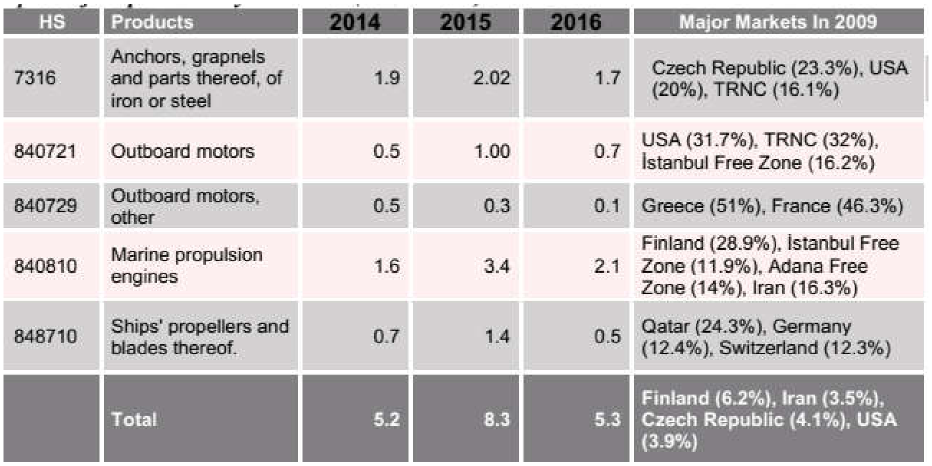
Because of the above facts, the contribution of the shipbuilding industry of Turkey to the national economy is precious. Most of the ships built by the Turkish shipbuilding industry are exported; particularly, almost all the ships constructed between 2002-2009 were exported to the EU member countries (TCS, 2015). Therefore, the shipbuilding industry of Turkey has considerable export potential contributing to the national economy of Turkey. For instance, as also shown Table 2-3, the value of exports of this sector in 2016 was US$0.9 billion with a 2.6% decline compared to the export value of US$0.996 billion realised in 2015 (RTME, 2017). As seen in Table 2-4, the major markets for the Turkish shipyards are Norway, Marshall Islands, Canada, and Greenland (RTME, 2017).

Table 2-3: Turkey`s Shipbuilding Exports (Millions of US$) (RTME, 2017).



HS	Products	2014	2015	2016	Major Markets in 2016
8901	Cruise ships, excursion boats, ferry-boats, cargo ships, barges and similar vessels for the transport of persons or goods:	640	394	508	Marshall Islands (14,13%), Canada (13,14%), Norway (37%)
8902	Fishing vessels; factory ships and other vessels for processing or preserving fishery products	52	196	118	Norway (38,8%), Greenland (43,3%),
8903	Yachts and other vessels for pleasure or sports; rowing boats and canoes	105	79	106	United States (23%), British Virgin Islands (12,7%), Marshall Islands (11,5%)
8904	Tugs and pusher craft	192	173	116	Italy (41,4%), United Arab Emirates (24,1%),
8905	Light-vessels, fire-floats, dredgers, floating cranes, and other vessels the navigability of which is subsidiary to their main function; floating docks; floating or submersible drilling or production platforms	68	93	93	United Arab Emirates (43,4%), Brazil (46,3%),
8906	Other vessels, including warships and lifeboats other than rowing boats	205	44	44	Qatar (25,3%), Norway(40,6%),
8907	Other floating structures (for example, rafts, tanks, coffer-dams, landing stages, buoys and beacons	5	15	15	Israel (17,8%), Saudi Arabia (14,4%), Tanzania (13,5%).
8908	Vessels and other floating structures for breaking up	0.07	0.51	-	Russia (100%) in 2015
	Total	**1,270**	**996**	**970**	**Norway (27,14%), Marshall Islands (8,7%), Canada(7%), Greenland (5,27%)**

Table 2-4: Export of other marine manufacturing sectors (US$ million) (RTME, 2017).



HS	Products	2014	2015	2016	Major Markets In 2009
7316	Anchors, grapnels and parts thereof, of iron or steel	1.9	2.02	1.7	Czech Republic (23.3%), USA (20%), TRNC (16.1%)
840721	Outboard motors	0.5	1.00	0.7	USA (31.7%), TRNC (32%), İstanbul Free Zone (16.2%)
840729	Outboard motors, other	0.5	0.3	0.1	Greece (51%), France (46.3%)
840810	Marine propulsion engines	1.6	3.4	2.1	Finland (28.9%), İstanbul Free Zone (11.9%), Adana Free Zone (14%), Iran (16.3%)
848710	Ships' propellers and blades thereof.	0.7	1.4	0.5	Qatar (24.3%), Germany (12.4%), Switzerland (12.3%)
	Total	**5.2**	**8.3**	**5.3**	**Finland (6.2%), Iran (3.5%), Czech Republic (4.1%), USA (3.9%)**

While these values of both shipbuilding and other marine manufacturing sectors account for a relatively small portion of the overall GDP of Turkey, their importance should not be underestimated considering the fact that this represents the output of an industry sector which not only creates employment opportunity to a large number of people, but also increases the country`s industrial capacity as well as its technological know-how (OECD, 2011) and creates raw material demands on other sectors such as steel industries. In this respect, as it is well known, the marine manufacturing industry, which covers the sectors such as shipbuilding yards and marine equipment manufacturers, is a very strategic industry for a country`s economy.

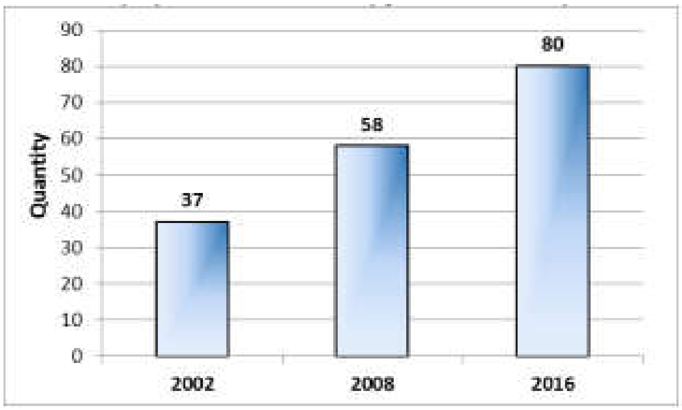
As reported by OECD Council Working Party on Shipbuilding in 2011 (OECD, 2011), there are two main advantageous aspects of a viable competitive marine equipment manufacturing sector to the Turkish economy (OECD, 2011). First, this sector directly contributes to the national economy through providing employment and attracting investment (OECD, 2011). For instance, the number of workers employed by the marine equipment sector was over 100,000 during the peak of business in 2007, which is by far more than that of the shipbuilding industry itself which was around 40,000 workers (OECD, 2011). What is more, it also increases the diversity of the economy since shipbuilding yards require diverse machine and equipment and other materials to use to construct the ships. Second, a robust and competitive marine equipment manufacturing industry in Turkey can reduce the dependence of Turkish shipyards on foreign supply on various major material and equipment.

Thus, this advantage provides them with better ability to compete with global rivals in the open market (OECD, 2011). In parallel to these facts, a group of Turkish marine equipment manufacturers initiated a joint work to build a ship specialised organised industrial zone, which is the first project of its kind in Turkey focusing on marine equipment, in Yalova-Altinova Region of Turkey, which is the second largest shipbuilding location after Tuzla region. What is more, five Turkish shipyards have decided to build a consortium to develop the country`s first indigenous ship engine (Begedil, 2018).

Considering the fact that there is an increasing demand for environmentally friendly equipment and materials for building environmentally friendly green ships as well as green retrofits, this sector offers great commercial and export opportunities (OECD, 2011). Besides, the global demand for shipbuilding will continue in the short and long terms owing to the growing world economy as well as the replacement needs of old vessels. For instance, the average age of the Turkish Merchant Fleet (1000 GT and over), which consists of 567 vessels of different ship types (mostly dry cargo, bulk carriers, containers, chemical tankers), is 23.85 as of 2016 (TCS, 2017) whereas the average operating life span of an average standard vessel is considered to be 25 years. This means that, depending on the global economy and market conditions, there may be more demand for the replacement of these vessels, which can create opportunities for the Turkish marine manufacturing sector. In addition to these, from a long-term perspective, the emerging marine industries which have been described in Section 2.2.6 can provide great opportunities to the Turkish marine manufacturers.

The Turkish Government recognizes this fact regarding the importance of marine manufacturing industries, the shipbuilding sector itself and marine equipment manufacturers, as well. Based on a survey conducted by (OECD, 2011) in 2007, these industries were perceived by the Turkish government as being a very important provider of employment, a contributor to industrial capacity, and a tool to attract investment (OECD, 2011). The massive support from the Turkish government through placing orders for various vessel needs of the Turkish Navy has been a "lifebuoy" for the Turkish marine manufacturing sector to survive in the global economic crisis in 2009 (OECD, 2011). For example, more than 50 domestic marine manufacturing companies have been provided with business opportunities in the MILGEM (National Ship) Project (SSM, 2017). As well as creating business opportunities to domestic companies, the technical capabilities and expertise of them are aimed to be improved as they are provided with the necessary know-how, experience and infrastructure by means of having a number of naval projects built at Turkish Shipyards, such as MILGEM, Multi-Purpose Amphibious Assault Ship, Amphibious Ship, Submarine Rescue Mother Ship, Coast Guard Search & Rescue Boat, and New Type Patrol Boat, which are the most evidential examples (SSM, 2017).

In parallel to all these, in spite of the negative effects of the 2009 global crisis, there has been a notable growth in the production and export capacity of the Turkish shipbuilding and marine equipment manufacturing sector, including a significant product diversification (Fonseca, 2015). The negative impacts of the economic downturn have been recovered through focusing on niche markets and product diversification, increasing ship repairing activities, and with the help of above mentioned naval projects of the Turkish Government. In the last 15 years, the number of shipyards increased from 37 to 80 (TCS, 2017), as shown in Figure 2-28. While the shipyards founded capacity was 550,000 DWT in 2002, it has reached up to 4,52 million DWT in 2016, which means a growth more over 6 times than 2002 (TCS, 2017). While the Turkish shipyards was 20% self-sufficient a decade ago, now they are 70% self-sufficient in production (Begedil, 2018). In this regard, the Turkish Shipbuilding industry expects to have a share of 20 billion USD from the overall national aim of increasing its export to 500 billion USD by the year 2023 (Kiran, 2013).



Source: Ministry of Transport, Maritime Affairs and Communications 04/2017

Figure 2-28: Number of the Turkish shipyards in 2002, 2008, and 2016

The Turkish marine manufacturing sectors have made significant investment over the last few years to modern their facilities and improve their technological capacities (OECD, 2011). They are certified with quality and environmental management standards. However, good energy management practises in their production systems is still lacking. Giving required importance over the effective energy management practises in their manufacturing systems will certainly strengthen the ability of the Turkish marine manufacturing sector to compete effectively in the open marine market through increased greener corporate image and reduced energy costs. Therefore, it is essential for marine manufacturing enterprises of Turkey to improve the energy performance of their manufacturing systems and expand their know-how in this issue

Based on the above facts regarding the importance and potential of the Turkish marine manufacturing industry in terms of both the national economy and energy challenge considerations, the major aim of this PhD research study is to establish the good energy management culture in the Turkish marine manufacturing industry through effective energy management practises such as energy auditing, increased use of renewables, and demand response measures. This will reduce the energy costs and strengthen the greener corporate image of Turkish marine manufacturing plants and open opportunities across the global market. This will in turn produce export opportunities for Turkish economy. What is more, reducing the energy intensity in Turkish marine manufacturing plants as an important part of the Turkish Manufacturing Sector, which is a top energy consumer in the country, will contribute to Turkey`s CO_2 reduction goals to cope with the climate change challenge as well as to secure energy supply.

2.2.9 ENERGY MANAGEMENT

Energy management is a central theme to low-carbon manufacturing. It can be defined as a combination of energy practices, efficiency techniques, and management of related processes aimed at reducing energy use and GHGs emissions of a company (Amundsen, 1999; Kannan and Boie, 2003). Alternatively, it can be referred to as "*the proactive, organised and systematic coordination of a company`s use of energy to meet the requirements, taking into account environmental and economic objectives (IMO, 2011)*"

Energy management assists a plant to reduce energy costs by means of improved energy performance and optimised use of energy-related assets and energy sources (DOE, 2016a). Therefore, implementing some form of energy management is a primary step towards saving energy and energy costs, reducing GHG emissions, and staying competitive in the market (DOE, 2016a). Implementation of any technical and management practices which will save energy and its cost and reduce GHGs emissions in an organisation can be regarded as energy management. According to a research carried out by (Caffal, 1995), industries can save up to 40% of total energy use by adopting energy management practises.

There can be many different plans or methods to develop an energy management program in an organisation. Also, there can be many different means to improve the energy performance of a facility or site. This can be by means of using more energy efficient equipment, switching to low carbon energy sources, avoiding the excess energy consumption which is determined to be unnecessary in a process or system, or changing power consumption patterns within the manufacturing site which is called as demand response techniques. The appropriate means and associated energy saving potentials, which will increase the energy performance of the organization, can be identified through conducting an energy audit within the plant. Once they are identified, quantified, and ensured that they are technically feasible (e.g. do not cause any disruption on the production), they can be prioritised for implementation with regards to various criteria such as economic and environmental merits. Thereafter, an action plan can be prepared to implement the selected energy saving measures.

At the heart of Energy Management is continuous improvement which means that energy management benefits should be continuous, rather than one-time results (DOE, 2016a). After implementing the actions which will improve the energy performance of the organisation, it is of importance to ensure that the implemented actions are sustainable. A plant should proactively and strategically manage energy use across the plant to ensure obtained benefits are continuous and long term (DOE, 2016a). Otherwise, the first initiative for energy management and effort spent in the energy audit can fail. Therefore, energy management should be a part of the culture of an organisation such as quality and safety. In this regard, an EnMS is essential to maintain the success of the implemented energy saving actions as well as to ensure the continuous improvement.

An EnMS can be defined as (DOE, 2016b):

> *an interacting series of processes that enables an organization to systematically achieve and sustain energy management actions and energy performance improvements. It provides the processes and systems needed to incorporate energy considerations and energy management into daily operations as part of an organizational strategy for continually improving energy performance.*

Therefore, an EnMS establishes the structure and discipline to implement technical and management strategies which lead to substantial energy, cost, and GHGs emission reductions and to sustain those savings over time (ISO, 2015). By employing an EnMS, energy management becomes a part of the organisational culture of a company and ongoing management of the energy uses and compliance with energy related legal and other requirements are sustained (DOE, 2016a).

It establishes clear responsibilities, documented procedures, ongoing training, internal audits for conformance, corrective and preventive action, management reviews, and continual improvement (Kannan and Boie, 2003). The major benefits of implementing an EnMS are summarised as follows (DOE, 2016a; SEAI, 2015):

- It integrates energy management culture in day-to-day operations,
- It ensures that senior managers commit to energy efficiency and that all staff play a role in the process; thus, energy management becomes an integrated business approach rather than single initiatives,
- It enables the plant to become proactive rather than reactive in dealing with energy issues,
- It provides a systematic framework for energy improvement and it standardises processes so that improvements are sustained over time,
- It ensures that a process of continual improvement is sustained,
- It helps a plant comply with energy efficiency and emission reduction obligations,
- It reduces energy costs and reduces the risk to energy price fluctuations.

In addition to the above, a company can optimise its industrial systems and improve overall monitoring of system inefficiencies by implementing an EnMS (Nulty, 2015). By virtue of the after-effects of this such as enhanced production and capacity utilization, reduced pollution and resource use, and lower operation and maintenance costs, implementing an EnMS increases the competitiveness of the organisation (Nulty, 2015). Taking these and the above-stated benefits into account, it is essential to implement an EnMS for a successful energy management program within an organisation.

An EnMS can be implemented according to either available ISO 50001 energy management standard or a custom EnMS (Nulty, 2015). ISO 50001 has been adopted by many countries as their national EnMS standards; therefore, organisations who wishes to implement an energy management program within their facilities can follow the structured framework of ISO 50001. This will also help them fulfilling the requirements to be certified by the ISO 50001. A recent study by (McKane et al., 2017) estimates that in 2030 ISO 50001 will result in about 16 EJ of annual primary energy savings, and 1000 Mt of avoided annual CO_2 energy savings given that a 50% uptake level of ISO 50001 in the industrial and commercial sectors by 2030 is realized.

2.2.9.1 ISO 50001-2018

ISO 50001-2018 is a voluntary international standard developed by the International Organisation for Standardization (ISO) that specifies requirements to establish and implement an EnMS. The ISO 50001 follows the Plan-Do-Check-Act (PDCA) management cycle, which is the common element found in all of ISO`s management systems and standards, and structures energy management processes around this PDCA framework, which actions are planned, implemented, checked, and the results are used to continually improve both energy performance and the EnMS (DOE, 2016b; ISO, 2015). The standard addresses the following (IMO, 2016):

- Energy use and consumption evaluations through performing energy reviews and development of energy policies.
- Measurement, documentation and reporting of energy use.
- Design and procurement practices for energy-using equipment, systems, and processes.
- Development of an energy management plan and other factors effecting energy performance that can be monitored and influenced by the organisation.

To do these, the ISO 50001 provides a framework of requirements enabling organisations to (ISO, 2015):

- Develop a policy for more efficient use of energy
- Fix targets and objectives to meet the policy
- Use data to better understand and make decisions concerning energy consumption
- Measure the results
- Review the effectiveness of the policy
- Continually improve energy management

Although there can be minor differences between the ISO 50001 and custom EnMS models, the main elements are like EnMS model of the ISO 50001 as can be seen in Figure 2-29.

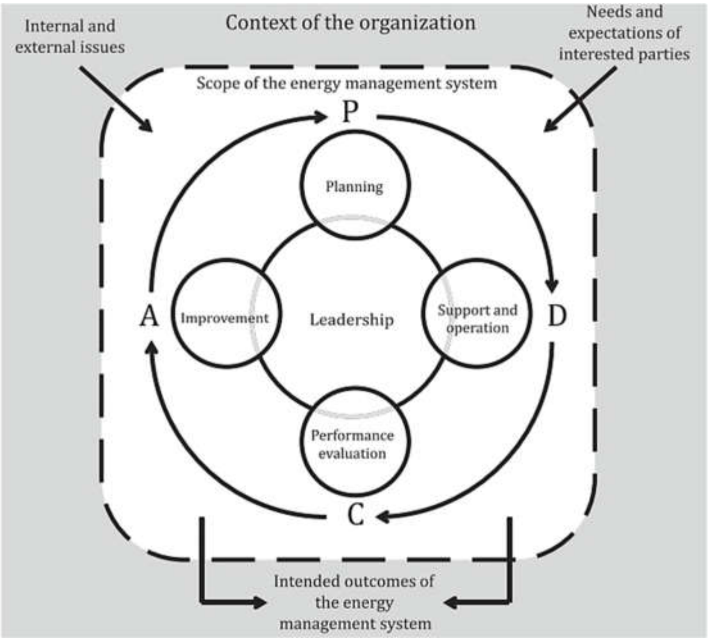


Figure 2-29: Energy Management System Model (ISO, 2018)

The successful implementation of an EnMS, whether the ISO 50001 or a customised approach, can be realised through following a sequence of key steps (Nulty, 2015):

1. Management decision
2. Planning
3. Implementation
4. Checking
5. Review

2.2.9.1.1 Plan

Context of the organisation

Understanding the organisation and its context

A company should analyze its organisational context to determine external and internal issues that are associated with the purpose of the EnMS to be implemented and that can affect the energy performance of the plant as well as the EnMS (ISO, 2018). Internal issues can include (ISO, 2018):

- core business objectives and strategy;
- asset management plans;
- financial resources affecting the organisation;
- sustainability consideration;
- contingency plans for interruptions in energy supply;
- maturity of existing technology;
- operational risks and liability considerations;

External issues can include:

- issues related to interested parties such as existing national or sector objectives, requirements or standards;
- restrictions or limitations on energy supply, security and reliability;
- energy costs or the availability of types of energy;
- effects of weather;
- effects of climate change;
- effects of GHGs emissions.

Understanding the needs and expectations of interested parties

The organisation should determine the interested parties and their requirements in terms of its energy performance and the EnMS so that these can be addressed through the EnMS. The organisation should ensure its access to the applicable legal and other requirements associataed with its energy performance and understand how those requirements applies to them. Also, these legal and other requirements should be reviewed at defined intervals (ISO, 2018).

Determining the scope of the EnMS

The organisation should determine the boundries and applicability of the EnMs to establish its scope. While doing this, the needs and expectations of interested parties mentioned above should be considered. Also, it should be ensured that the scope and boundries of the EnMS include the authority of the organisation to control its energy efficiency, energy use and energy consumption. The EnMS scope and boundries are mainted as documented information (ISO, 2018).

Leadership

The top management of the organization should show leadership and commitment for continual improvement of its energy performance and the effectiveness of the EnMS (ISO, 2018).

Leadership and commitment

A greater involvement of the top management in the EnMS is of importance for the success and effectiveness of the EnMS. Therefore, the top management should demonstrate leadership and commitment in terms of continual improvement of the energy peformance of the company and the effectiveness of the EnMS. The EnMS should be a part of the overall business strategy of the company (Howell, 2014; ISO, 2018).

Also, the top management must involve in the communication and continued review and approval of the management system and provide leadership and support when and where needed (Howell, 2014). This is essential for the success and sustainability of the energy management because without the enthusiasm, commitment, and support of the top management neither the EnMS can be implemented successfully nor the any improvement in energy performance can be realized (Howell, 2014).

Energy Policy

The commitment of the top management and the overall intention of the organization for managing energy must be formally expressed, documented, communicated, and understood by everyone in the organization, including on-site contractors (Eccleston et al., 2011). For this reason, it is the responsibility of the top management to establish, implement, and maintain an energy policy which will state the organisation`s vision for energy management (Howell, 2014). While the energy policy may vary from company to company, it should involve basic common commitments (Howell, 2014). ISO 5000:20018 requires the top management to establish an energy policy that (ISO, 2018):

- “is appropriate to the purpose of the organization;
- provides a framework for setting and revieweing objectives and energy targets

- includes a commitment to ensure the availability of information and necessary resources to achive objectives and energy targets;
- includes a commitment to satisfy applicable legal requirements and other requirements related to energy efficiency, energy use and energy consumption;
- includes a commitment to continual improvement of energy performance and the EnMS;
- supports the procurement of energy efficient products and services that impacy energy performance.
- supports design activities that consider energy performance improvement (ISO, 2018)."

According to ISO 50001:2018, the energy policy should (ISO, 2018):

- "be available as documented information;
- be communicated within the organisation;
- be available to interested parties, as appropriate;
- be periodically reviewed and updated as necessary (ISO, 2018)".

Energy Manager and Energy Team

Once the top management commitment is obtained, an energy manager (also called as energy director or energy champion) is needed to be attained (Smith and Parmenter, 2016). The energy manager can be a member of the engineering staff in a large team, or an electrician, a maintenance supervisor (Smith and Parmenter, 2016). It is the responsibility of the energy manager to ensure that the EnMS is planned, developed, implemented, and sustained with continuous improvement (Howell, 2014).

One would expect that the energy manager alone cannot do all his energy management responsibilities. For this reason, an energy team, which is led by the energy manager, can be created. This will also increase the involvement of the people from various departments in the organisation.

Developing Energy Plan

The energy manager and energy team need to develop a plan to achieve the goals expressed in the energy policy. This energy plan should include the specific processes essential to improving energy performance (Eccleston et al., 2011). These include:

- energy review process.
- energy baselining.
- energy performance indicators.
- objectives.
- targets.
- actions.

Energy Review and Baselining

This step can be considered as the status quo of the energy performance of the organisation. The outcomes of energy review and baselining processes will provide the basis and a starting point to perform actions for energy performance improvements. In the energy review process, the following activities are done (Parrish and Ledewitz, 2012) :

- setting a scope and boundary for EnMS.
- understanding past and present energy consumption, energy types.
- identifying significant energy uses.
- developing a set of energy efficiency measures to reduce the energy consumption of significant energy users.
- developing an energy baseline.
- developing energy performance indicators to assess the effectiveness of the energy efficiency measures.
- developing objectives and targets for the organisation that support energy policy.
- developing action plans to achieve the objectives and targets.

As stated above, ISO 50001-2018 requires the identification of significant energy users and appropriate energy efficiency measures to apply on them. Focusing on significant energy uses within the facility can be regarded as a wise approach because they can offer considerable energy saving potentials. **However, the collective effect of less energy users should not be underestimated. The sum of the energy saving potentials identified in less energy using systems**

might be considerable. Therefore, especially at the planning phase of establishing an energy management system, it will be rational to conduct a detailed energy audit which covers all the energy using systems and all energy aspects in an organisation so that a thorough picture of the baseline energy performance can be taken.

From a technical point of view, the review part of the planning phase can be considered as an energy audit. The energy review and baselining steps can be achieved by conducting an energy auditing in the organisation**. In fact, energy auditing can be regarded as a precondition for establishing an EnMS.** Figure 2-30 illustrates the role of the auditing procedure in the overall ISO 50001 EnMS structure. Therefore, it is clear that energy auditing is a part of the planning stage (Kluczek and Olszewski, 2017).

Conducting an energy audit is crucial for understanding energy consumption characteristics of an organisation and identifying energy performance improvement potentials. A qualified energy auditor can conduct a detailed energy audit and assess all relevant aspects related to the energy performance of the organisation and establish energy performance indicators. The key output of the energy audit is a detailed energy performance analysis of the organisation together with a comprehensive list of the identified energy performance improving measures prioritized with respect to their technical, economic, and environmental merits. **These measures can include technical measures such as operations and maintenance, retrofit and modifications in processes and systems, shifting low carbon energy uses, etc. Besides the technical measures, there can be various factors such as organisational barriers which discourages efficient use of energy such as lack of awareness of the employees. Identification and assessment these aspects should also be included in the energy audit**. More detail for energy auditing is provided in Section 2.2.10.

Thereafter, based on the energy auditing results, realistic and meaningful objectives and targets that supports the energy policy can be created (Smith and Parmenter, 2016). Besides, an energy management action plan to achieve these objectives and targets is developed.

Finally, the outcome of the energy planning phase is “an action plan for energy performance improvement”, which have been authorised, funded, and staffed by top management, shall be used in the implementation phase (Eccleston et al., 2011).

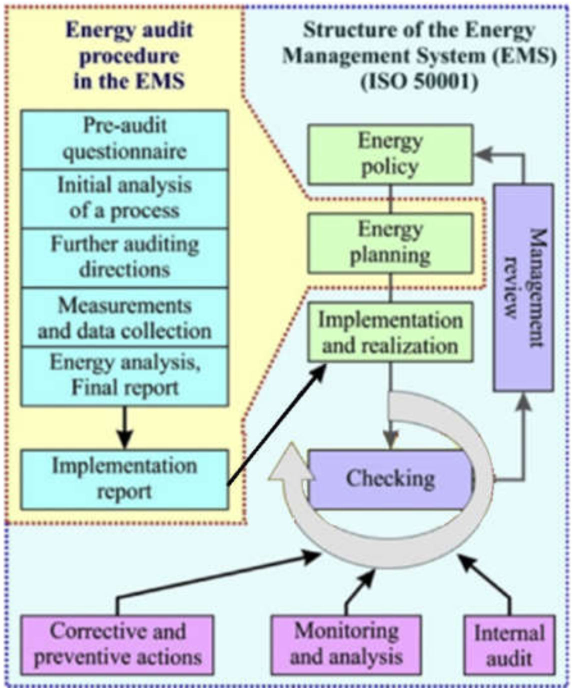


Figure 2-30: Structure of energy audit inscribed in the ISO 50001 energy management system (EnMS) (adapted from Kluczek and Olszewski, 2017)

2.2.9.1.2 Implementation

In the planning phase, a major energy action plan to improve their energy performance is developed. The execution of these actions are the responsibility of the energy manager and energy team. It should be ensured that the roles and responsibilities are clearly defined and agreed upon for each person that will be involved in implementing the energy action plan. (DOE, 2014). Besides, it should be ensured that the people such as employees associated with the energy management action plan are aware of the changes to their operations. They should be motivated for successful implementation of the actions, which can be accomplished by means of training and awareness activities (DOE, 2014).

When all the above have been done and the action plans have been implemented, the next phase of energy management system, i.e. checking, takes place to check the results of these actions to see the improvement (DOE, 2014).

2.2.9.1.3 Checking

In this phase of the EnMS, the progress of the implemented actions in the previous phase are checked to ensure that they are progressing as planned (DOE, 2014). This is done in accordance with the predefined milestones developed in the energy management action plan (DOE, 2014). To be able to check the progress of the implemented energy management actions, a sufficient and regular data gathering must be in place for an effective evaluation of the progress (DOE, 2014). The scope of data and frequency of collection are prescribed in the action plan (DOE, 2014). Ongoing checking can be accomplished through monitoring, analyses, etc.

When the projects of the implemented actions are completed, the results must be evaluated comparing it against the estimated savings or expectations from the implemented. If the actions are not producing the expected results, then, appropriate corrections are done (DOE, 2014).

In achieving the above, an internal energy audit can be conducted. The objectives and scope of the audit can be established in a way to check the progress and results of the undertaken actions based on previous energy audit. This can be considered as a follow-up audit. Before starting it, it is essential to do a review of the energy management action plan prepared and implemented in the previous phases so that the performance of the already implemented actions and EnMS can be examined (Eccleston et al., 2011). The focus of the internal audit is primarily on to evaluate how well the planned and established EnMS is being implemented in the organisation and to assess its overall effectiveness with respective to the organisation`s energy policy and energy objectives and targets established in the planning phase.

The outcomes of the internal audit is verification of that the energy action plans have been undertaken within the agreed upon timeframe as well as validating their effectiveness (Eccleston et al., 2011). Based on the results, corrective and preventive actions can be taken if there are any nonconformities or ineffectiveness.

2.2.9.1.4 Review

ISO 50001 requires that the top management reviews the energy management system at planned intervals for its suitability, adequacy, and effectiveness (Howell, 2014). To do this, a management review meeting is organised and the top management is briefed on the progress and results of the energy management actions, energy management and a review of the EnMS program itself (DOE, 2014). The management review meeting agenda can include the following items (Howell, 2014):

1. Energy management action plan reviews, energy audit results

2. Evaluation of legal and other compliance and any changes to legal or other requirements
3. The energy performance of the organisation
4. The status of corrective and preventative actions
5. The performance of the EnMS
6. The extent to which goals and objectives have been met
7. Recommendations for improvement

Management reviews are essential parts of the check and act phases of continually improvement of an organisation of EnMS. The output of the review phase indicates the necessary changes and actions for improvement. (Howell, 2014).

2.2.10 ENERGY AUDIT

As one also can understand from the above, the ISO 50001 provide only general requirements for the operational level for companies on how to realize energy efficiency in their plants (Doerr et al., 2013; ISO 50001, 2018). It defines neither specific performance criteria regarding energy efficiency (Introna et al., 2014) nor energy efficiency means. The standard just proposes a management model that contributes to develop and implement the energy policy and to establish targets, goals and action plan outcomes of the analysis and control of energy consumption data (Introna et al., 2014). Despite this, carrying out an energy review is a requirement and measuring and analysing energy efficiency and its influencing factors and identifying and implementing appropriate measures to achieve energy efficiency is the responsibility of the organisation (Doerr et al., 2013; ISO 50001, 2011). This is foundation to build an efficient EnMS with low energy consumption, low-pollution and low-emissions in an industrial organisation (Alhourani and Saxena, 2009).

Bearing the above in mind, it is important to note that energy audit is crucial for understanding energy consumption characteristics of a plant and identifying energy and energy cost saving potentials to see the energy performance improvement potential within its production systems. In fact, as also stated in Section 2.2.9.1.1, an energy audit is the initial step and a precondition to correctly establish and implement an EnMS. However, it is relevant to note that an energy audit defined in the above form is different from an internal audit of an EnMS which can be seen in Figure 2-29. As also explained in Section 2.2.9.1.3, the purpose of an internal audit of an EnMS is to evaluate the processes, procedures and implementation of the EnMS to check whether they are appropriate to the organisation, implementation status and conforming to requirements of the EnMS standard (DOE, 2016b).

Energy audit is highly implemented key tool in the area of energy management (Saidur, 2010a). In an energy audit, energy consumption characteristics of a plant or an energy using system are examined so as to ensure that energy is being used in an efficient manner. If it is not used efficiently, areas with inefficiencies where energy is wasted are identified for improvement. Together with this, related cost savings and emissions reduction potentials are realised. In a sense, it is similar to financial accounting (EMSD, 2007).

The objective of an energy audit can vary from one organisation to another and it can also have various degrees of complexity (CIPEC, 2011; Hasanbeigi and Lynn, 2010). Nonetheless, the underlying reasons to conduct an energy audit are usually to understand how energy is consumed within a plant and to identify potentials for energy savings (Hasanbeigi and Lynn, 2010). In this respect, a typical energy audit process involves (CIPEC, 2011):

- data collection and review.
- plant surveys and system measurements.
- observation and review of operating practices.
- data analysis.

The information obtained through the audit by means of data collection, surveys and measurements is further analysed in order to identify energy saving potentials (ESPs), energy cost saving potentials (ECSP), and GHG emissions reduction potentials (ERP). A plant can conduct energy audit by the energy auditor and energy team established in the planning phase or can outsource an energy auditor. Because recommendations suggested by the auditors depends on auditor's experience and knowledge (Kluczek and Olszewski, 2017), it is very important for an energy auditor to have a full understanding of energy using systems.

2.2.10.1 Energy Audit Types

In general, energy audits can be classified in two major groups (AG, 2011; APO, 2008; CIPEC, 2011; EMSD, 2007; Hasanbeigi and Lynn, 2010; Thumann and Younger, 2008):

1. preliminary audit (or walk-through audit).
2. detailed audit.

In a preliminary audit, the readily available or easily obtained data is used to simple analysis of energy use in a plant. There is no need for a lot of measurements in this audit type. It can be regarded as relatively quick exercise (APO, 2008):

1. to determine the energy use in the plant.
2. to estimate the scope for saving.
3. to identify the most like for attention.
4. to identify immediate savings.
5. to set a reference point.
6. to identify areas where more detailed analysis is needed.

As for detailed energy audit, more detailed data and information are needed in this audit type because all major energy consuming systems are evaluated. A detailed audit provides the most accurate estimation of energy and costs savings and economic analyses are conducted for identified potentials (APO, 2008).

In the literature, there are various generic methodologies to perform a detailed energy audit (AG, 2011; APO, 2008; CIPEC, 2011; EMSD, 2007; Hasanbeigi and Lynn, 2010; Thumann and Younger, 2008). Various handbooks and guidelines are readily available which energy managers, plant owners, researchers can use. It is not rationale to expect an energy auditor to follow the exactly same steps and procedures for energy auditing different plants. The methodology for energy audit can show difference from one plant to another. Besides, intellectual profundity of methods for energy analysis and measurements is dependent on the experience and knowledge of the energy auditor (Kluczek and Olszewski, 2017).

In addition to the energy saving benefits of implementing an energy auditing, other potential benefits should not be overlooked (Kluczek and Olszewski, 2017). The non-energy benefits of making energy efficiency investments as a result of energy audits can include (Kluczek and Olszewski, 2017):

- better working conditions.
- improved product quality and increased productivity (Worrell et al., 2001).

- reduced cost of environmental compliance, raw material savings (Mikulčić et al., 2016).
- reduced emissions, extended equipment life and reduced maintenance requirements (Pye and McKane, 2000).

Conducting a preliminary or walk-through audit cannot provide a compherensive assessment of energy efficiency potentials within a plant. It may provide a basic understanding of energy management practises and awareness in a plant together with the determination of possible areas with inefficiencies. However, a preliminary / walk-through energy audit can be useful if it is conducted as an initial step to detailed energy audit to lay the groundwork for further detailed assessments and analyses.

In spite of their importance and essentialness in terms of energy efficiency, as far as "**improved energy performance**" is concerned, energy audit tools fail to address all the aspects of energy performance in a manufacturing plant. This is because the main motivation of energy auditing tools is to increase the energy efficiency through the identification of energy saving potentials focusing on the demand side of energy use in a plant excluding the supply side thereby paying no attention to energy performance.

As it will have been described in Chapter 3, both the demand and supply sides of energy use have a bearing on the energy performance of plant. For example, energy demand side represents the energy consumption whereas energy supply side is responsible for energy unit costs and environmental emission factor of the supplied energy. Thus, both sides of energy use and their interactions determine the parameters of "energy cost" and "GHG emissions" that have to be lowered for energy performance improvement. In other words, "improved energy performance" entails a more compherensive consideration of the enabling measures for low energy costs and low GHG emissions.

In this regard, rather than solely focusing on one aspect of energy performance, as is the case with for energy auditing, all aspects of energy performance including demand side, supply side, and their interaction should be taken into account.

As will have been described in Chapter 3, from the point of the demand side view, increasing energy efficiency reduces energy cost and GHG emissions. From the supply side perspective, increased use of low carbon renewable energies such wind or solar PV power through a microgrid application or onsite generation should be considered to reduce GHG emissions and energy costs. Similarly, alternative utility suppliers can be taken into account for lower unit cost rates and lower GHG emissions, or time-of-use tariffs offered by the electricity supplier(s) can be evaluated for demand response participation potential which can provide further cost savings. These measures can be applied either standalone or together. Therefore, the enabling measures for improved energy performance should be holistically approached for a compherensive assessment. In addition to technical assessments, econonomic evaluations should be considered to assess the cost-effectiveness of the enabling measures.

All in all, the existing energy audit tools fails in terms of compherensive consideration of energy performance and improvement potential. Bearing this in mind, a compherensive methodology framework is needed for the assessment and improvement of energy performance in manufacturing plants. Energy auditing can be factored into such a methodology framework. Bearing this and the state-of-the-art gaps identified in the following section, the research presented in this thesis develops a holistic energy management methodology framework for a compherensive assessment and improvement of energy performance in manufacturing plants in Chapter 3.

2.3 STATE-OF-THE ART REVIEW

With the recent overwhelming concerns in the energy challenge, there has been a surge of research interest around the world in the industrial energy management field. As discussed in Section 2.2.9 industrial energy management is a very broad concept covering various themes. As such, the research pertinent to the industrial energy management field varies dramatically.

Because the motivation and focus of this PhD study is into improved energy performance in marine manufacturing plants of Turkey through good energy management practices as also already been outlined in Chapter 1, the systematic review of the relevant research studies within scientific literature sources represented by academic studies will be centred around the major subject areas of:

1. Manufacturing machine/equipment/process level energy efficiency/management studies (Micro level).
2. Plant/facility/site/company/organisation level (Macro level) studies into the field of energy management themes covering the methodologies of case studies, qualitative methods such as interviews or surveys, or mixed approaches, conceptual or theoretical designs, and literature reviews;
    - with sector focus (i.e. chemical, textile, manufacturing, etc.) .
    - with a with geographical focus (i.e. a single-country, or multiple-country/cross-country/global focus.

3. Industrial applications of microgrid/onsite energy generation/renewable energy use/demand response measures.

The above is carried out with the objective of obtaining a clear understanding of the most recent research efforts within the related themes and identifying and justifying the existing gaps which this PhD thesis will fulfil. For this purpose, all articles published on the territory of industrial energy management, energy auditing, renewable energy use, and demand response through microgrid applications were searched on online databases. Thus, it is aimed to identify the research gaps from sectoral perspective as well as from a country point of view so as to justify the Author`s focus on marine manufacturing industry and Turkey.

2.3.1 MANUFACTURING MACHINE/EQUIPMENT/PROCESS LEVEL (MICRO LEVEL)

The research in energy consumption at machine level has concentrated on individual equipment, machinery and workstations within a production system. Until recently, minimising energy use was hardly addressed by many machine designers. With increasing consideration on machine energy efficiency, studies into machine energy consumption have increased. Some studies address at the machine energy efficiency from design point of view (e.g. Devoldere et al., 2007; Gutowski et al., 2006; Herrmann et al., 2011; Thiede et al., 2012) while some focuses on operational aspects to minimise energy consumption (Rajemi et al., 2010; Weyand et al., 2011; Zein et al., 2011). Studies at machine level are of important to increase their energy efficiency since they provide a basic understanding of efficiency improvement measures of the machines so that necessary actions can be taken.

Various studies for different types of production machines show that electricity consumption of these machines is normally not constant over time. It is rather dynamic depending on the production process, the actual state of the machine, and the machine configuration (Thiede et al., 2012; Zein et al., 2011)

Devoldere et al. (2007) conducted an analysis on energy consumption of a 5-axis milling machine and they found that 65% of operation time was non-productive which accounted for up to 47% of the total energy consumption Figure 2-31. The results of this study shows that a considerable portion of machine energy use is independent of the material being processed. This is because production machines comprise of various energy using components such as auxiliary equipment, tool changers, machine lubrication systems, cutting fluid pump, etc. The presence of these components results in additional energy requirements to power them as also mentioned by Thiede et al. (2012).

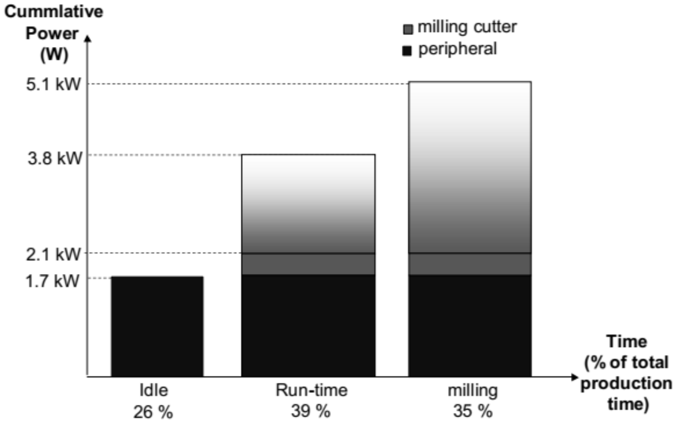


Figure 2-31: Relative Energy consumption per production mode (Devoldere et al., 2007)

While constant energy component of production machines depends on the specifications of machine itself, variable energy consumption is dependent on the processing parameters. Diaz et al. (2010) conducted a study into the variable energy consumption characteristics of a milling machine in various manufacturing environments. For this purpose, they observed the impact of different feed rates for a cutting process and found that the energy used per unit increased at lower feed rates. Rajemi et al. (2010) machined three work pieces on a lathe at different speeds to observe the relation between energy cutting speed and the energy consumption and found a positive correlation (Figure 2-32).

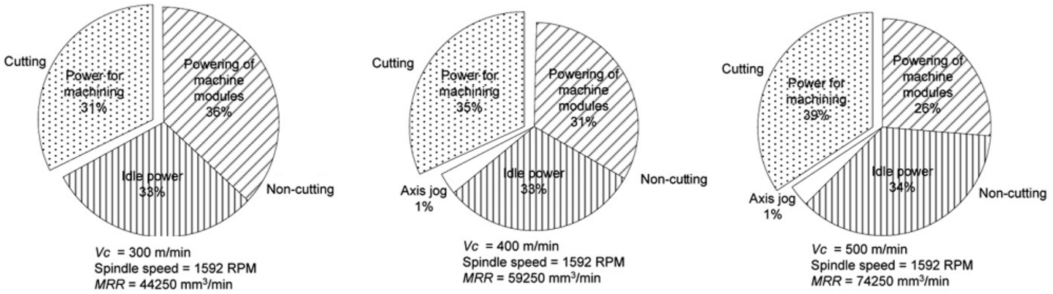
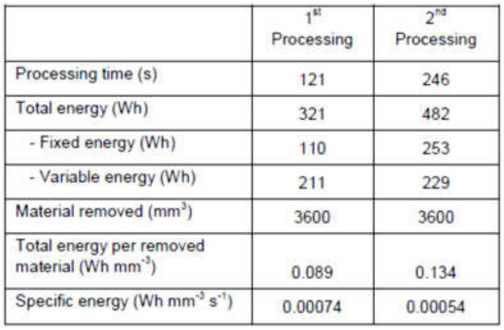


Figure 2-32: Power distribution for different cutting speeds (Rajemi et al. 2010)

Another processing factor affecting variable energy consumption of production machines is material removal rates. Herrmann et al. (2011) investigated the relation between machine tool energy consumption and varying material removal rates (MRR), performing two grinding processes with different values of MRRs (50% difference) on the same grinding machine. According to the result shown in Table 2-5, the machining process with higher MRR preponderates in terms of energy consumed per removed material. For the same of volume of material removal, the process with higher MRR required less processing time as shown in Table 2-5. As fixed energy consumption of machine tool is constant, the cumulative impact of the fixed energy consumption over time decreased by virtue of the decreased processing time as a result of higher MRR. Variable energy demand changed very slightly as this depends on the material specification rather than time. From this study, it can be concluded that, particularly where work surface quality is neglected, the higher MRR as much as possible can be used as an optimisation measure for energy efficiency as this alleviate the impact of the fixed power.

Table 2-5: Comparison of two machining processes with different MRRs with respect to the energy demands (Herrmann et al. 2011)



	1st Processing	2nd Processing
Processing time (s)	121	246
Total energy (Wh)	321	482
- Fixed energy (Wh)	110	253
- Variable energy (Wh)	211	229
Material removed (mm^3)	3600	3600
Total energy per removed material ($Wh\ mm^{-3}$)	0.089	0.134
Specific energy ($Wh\ mm^{-3}\ s^{-1}$)	0.00074	0.00054

Gutowski et al. (2006) shows the positive correlation between lower processing rates and higher specific electricity requirements for 36 examples from 10 different manufacturing processes based on the data from various studies. As Figure 2-33 depicts, electricity requirement of each individual manufacturing process is decreasing with the increasing material process rates.

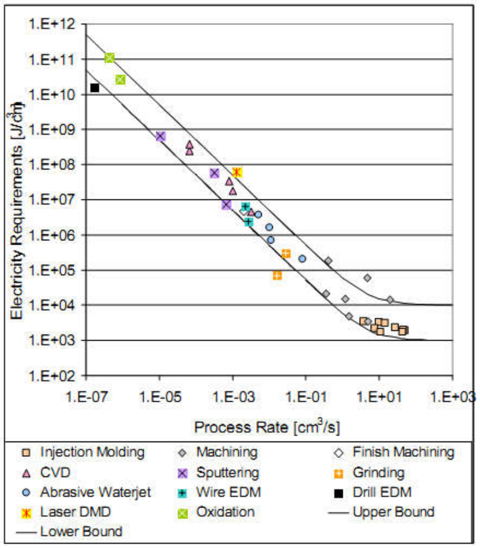


Figure 2-33: Specific electricity requirements for various manufacturing processes as a function of the rate of material processed (Gutowski et al., 2006)

The results of Herrmann et al. (2011) and Gutowski et al. (2006) suggest two important strategies to minimize the energy demand of a process. First one is increasing the process rate as this significantly reduces the fixed power demand through reducing the processing time. Second is using more effective machines with higher throughputs. These two strategies are coupled. If the processing rate of a machine is limited, then another machine can be considered. Especially new generation machines provide higher throughput rates with less specific energy consumption. Based on a cost-benefit analysis, old machines can be replaced with new ones.

Efficiency of new machines was investigated by Kordonowy, David N., (2002). Automated milling machines analysed in this study are of similar size and capacity and feature much of the same auxiliary equipment, as Figure 2-34 and Figure 2-35 reflect, the older machine requires much larger energy for its auxiliary equipment. The energy requirement for constant start-up operations (such as computer and fans, coolant pump, servos, etc.) is 27% of total energy requirement in the 1988 Cincinnati Milacron milling machine while it is only 13.2% in the 1998 Bridgeport milling machine. Similarly, constant run-time energy use accounts for 20.2% of total energy requirement in the newer machine, whereas it amounts to 24.9% in older machine (Kordonowy, David N., 2002).

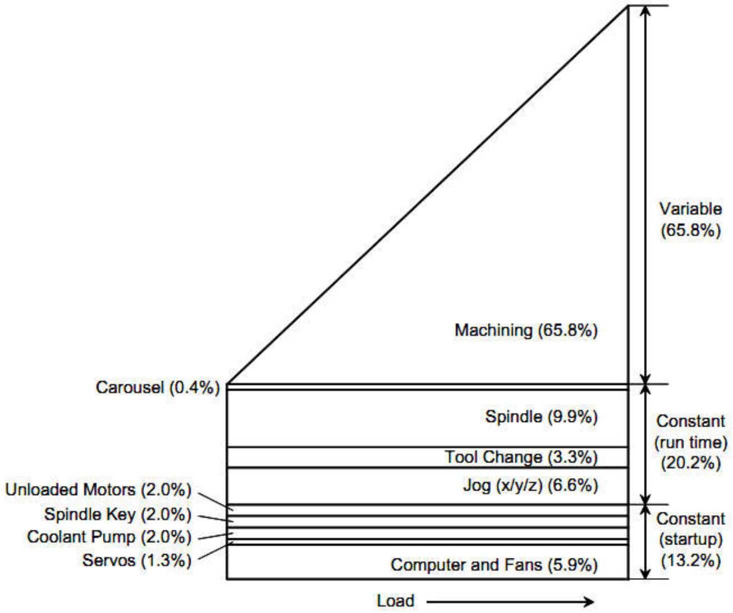


Figure 2-34: Machining energy use breakdown for a 1998 Bridgeport automated milling machine with a 5.8 kW spindle motor ((Kordonowy, David N., 2002).

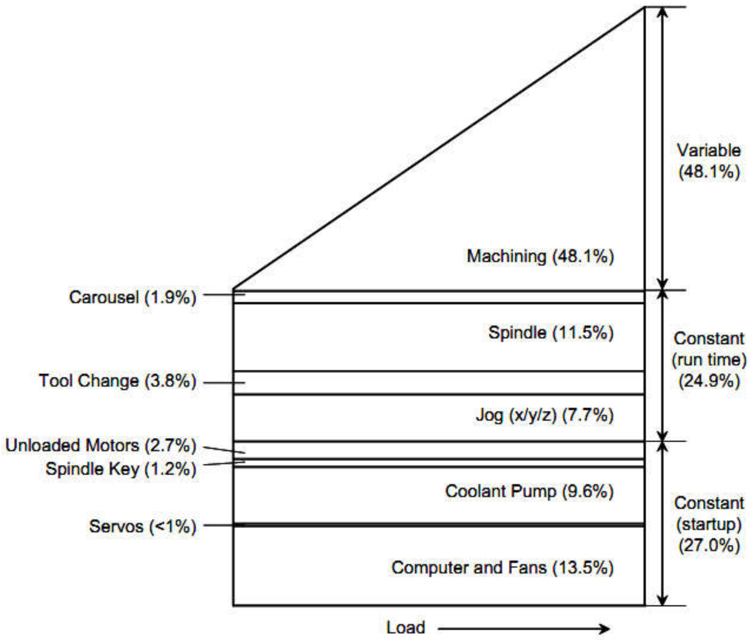


Figure 2-35: Machining energy use breakdown for a 1988 Cincinnati Milacron automated milling machine with a 6 kW spindle motor ((Kordonowy, David N., 2002).

Another analysis regarding the energy consumption and machine-age relation was conducted by Deshpande et al (2011). A rod component was produced on two different aged three-axis vertical spindle milling machine. As Figure 2-36 shows, Machine 2, the relatively older one, consumed more energy than Machine 1 while the first one required less time to finish the work less than the second one. When two machines are available in the same plant, the decision can be made for the one with less energy consumption. But, if the optimisation variable is time, then the old one can be selected in this example.

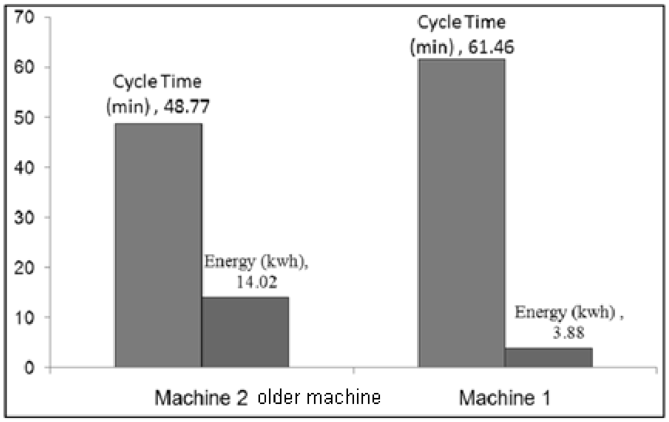
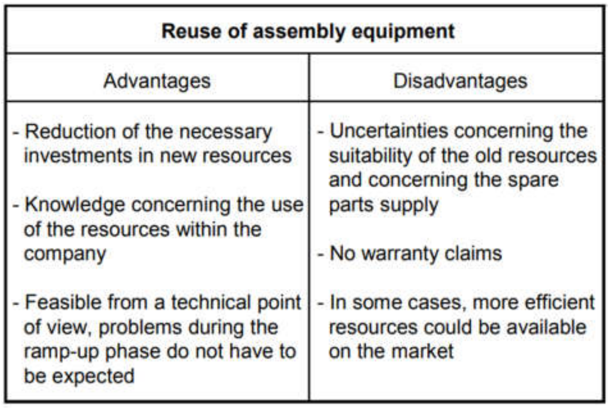


Figure 2-36: Comparison of two different-age machines` energy consumption (Deshpande et al., 2011).

A complementary study into the impact of new machine on energy efficiency of the overall system was carried out by Weyand et al. (2011). According to this study, although the reuse of an old machine might reduce the initial investment costs, it can eventually be more expensive than purchasing a new machine as an old one would be more energy consuming which would result in higher operating costs. The study suggests that not only technical factors and investment costs should be considered when new investment is planned, but also life cycle aspects such as energy consumption should be considered. Table 2-6 shows some advantages and disadvantages of using old production machine (Weyand et al., 2011).

Table 2-6**:** Advantages and disadvantages of reusing resources (Weyand et al., 2011)



Reuse of assembly equipment	
Advantages	Disadvantages
- Reduction of the necessary investments in new resources - Knowledge concerning the use of the resources within the company - Feasible from a technical point of view, problems during the ramp-up phase do not have to be expected	- Uncertainties concerning the suitability of the old resources and concerning the spare parts supply - No warranty claims - In some cases, more efficient resources could be available on the market

An analysis into press-brake with hydraulic pump was done by Devoldere et al. (2007). According to the analysis, only 35% of the overall energy use was for productive purpose (Figure 2-37). This was because the hydraulic pump of the press worked during all production modes regardless of productive or non-productive. This emphasizes the importance of reducing non-productive time as a means to achieve energy efficiency on machine level.

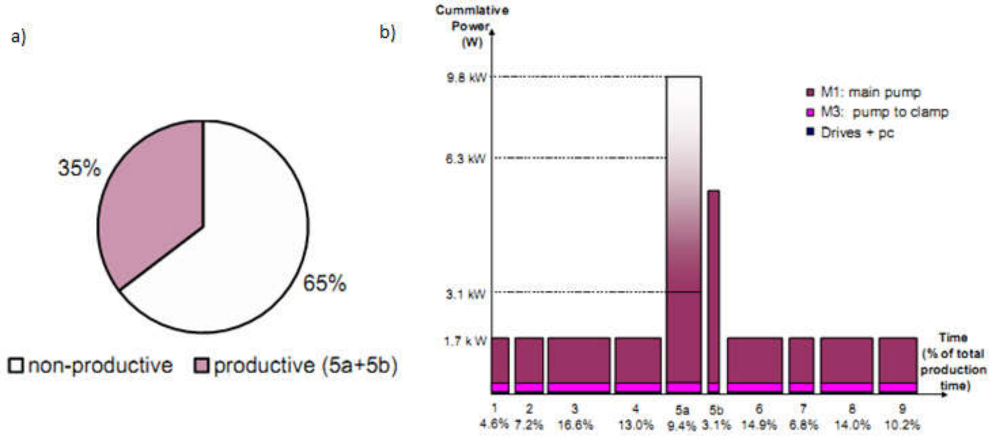


Figure 2-37 a) Total energy consumption of the press brake b) relative energy consumption per production mode (Devoldere et al., 2007).

Thus far, machine level energy efficiency studies have been reviewed. Single machine considerations provide good insights regarding the technical and organisational measures and factors that affects energy performance of production machines. These factors can be taken into account both by machine designers/producers and plant owners who employ them in their plants. However, **as far as "improved energy performance of a manufacturing plant" is concerned, the approach to achieve it in a manufacturing facility should be more comprehensive incorporating all energy performance aspects such as overall plant analysis and use of alternative low carbon energies.** In the simplest terms, these micro-level studies of machine and equipment considerations do not even give an idea regarding the cost-effectiveness of the energy efficiency improvements they provide.

2.3.2 PLANT/FACILITY/ORGANISATION LEVEL (MACRO LEVEL)

Having reviewed the machine/equipment level studies, it is appropriate to review major studies in the field of energy management approaches and energy auditing/assessment case studies at plant/facility level in various industrial sectors such as chemical plants, textile factories, and manufacturing plants, etc. in different countries of the World. In addition to these, there are a number of researchers who investigated the status quo of energy management as well as the barriers and drivers for energy management in various industrial sectors of different countries.

For instance, Thollander and Ottosson (2010) described and analysed the energy management practises in two different energy intensive industries of a developed country, Sweden: the pulp and paper industry and the foundry industry. According to the results of this study, about one-third of the studied pulp and paper mills and about two fifth of the studied foundries did not consider energy costs in their cost allocation, which means that energy cost is not given priority in these studied mills and foundries although they are categorised as energy intensive. Also, the results showed that only about 40% the studied mills and 25% of the foundries could be considered in terms of practising energy management practises. The results of this study clearly showed that energy was not highly prioritised in these Swedish industries in that period of time, which can be regarded as surprising given the energy intensive nature of them. Based on the results, the Authors point out that there is a large energy efficiency potential in the industries and countries either intensive or less energy intensive (Thollander and Ottosson, 2010).

Another major energy intensive Swedish industry, process industry, was studied by Rudberg et al. (2013). By conducting a literature review in the process industries and an explorative single-case study in a Swedish chemical company, Rudberg et al. (2013) found that energy was seldom treated strategically and its strategic importance was neglected in energy intensive companies, similar to the results of Thollander and Ottosson (2010). Hence, they investigated the necessary prerequisites to put energy management on the strategic agenda in the process industries. Based on the results, the authors recommended the following prerequisites for making energy management more strategic in a company (Rudberg et al., 2013):

- Political continuity in governmental regulations concerning energy issues which will lower the risk in energy savings investments for the companies.
- Treating energy as “core” to the business. Even if energy is not “core business”, it can be “core” to the business because, for example, energy cost can account for a major part of overall cost.
- Attending an energy manager within the organisation who will have the main responsibility for the corporate energy management to integrate energy planning and energy saving initiatives corporate-wide.

Considering the above recommendations, it is clear that the authors refers to the planning phase of energy management implementation and emphasizes the importance of top management commitment and attaining an energy manager to make energy management more strategic in Swedish process industries. While these are the internal factors, the Authors points out the political continuity in governmental regulations as the external drivers.

Suk et al. (2013) conducted a questionnaire survey to the energy-intensive companies in a developed world country, the Republic of Korea, with the aim of measuring their industrial energy saving activities and identifying their determinant factors. The authors found that more than 90% of the surveyed Korean companies practiced various energy saving activities which requires relatively lower costs and efforts. The authors found out that external factors which are coercive, normative, and mimetic indicated no major influence on energy saving activities of the Korean companies whereas internal factors such as the willingness for energy saving, support from top management, and internal training specific for energy saving determine a company`s practise level of energy saving activities. The authors also suggested that more technical support to the companies, particularly to the SMEs, should be provided to improve their practises in energy saving activities.

Another developed country of the Far-east, Japan, was studied by Liu et al. (2014). Similar to Suk et al. (2013), Liu et al. (2014) measured energy saving activities and their determinant factors of companies in Hyogo, Japan by carrying out an empirical study. The study discovered that the surveyed companies showed high participation to managerial energy saving activities. Also, the results of the study indicated that internal factors showed a significant and positive affect on the level of energy saving activities for the surveyed companies whereas external pressures seemed to have no significant affect.

Pons et al. (2013) investigated the adoption status of energy reduction and resource consumption technologies in Spanish and Slovenian manufacturing companies based on a European Manufacturing Survey. The authors further identified the impact of implementation of these technologies on the environmental performance of manufacturing firms. The results indicated implementation rates varying between 8% and 56%, which can be considered as relatively low. Further, the results showed that there is a positive relationship between energy efficiency technologies and environmental performance.

Hrovatin et al. (2016) investigated what factors impact Slovenian manufacturing firms` decisions to invest in energy efficiency and clean technologies. The authors found that the following factors significantly increases the possibility of investing in energy efficiency and clean technologies by Slovenian manufacturing firms: share of energy costs; market share; and export orientation. Also, the Authors found that the energy efficiency gap is less likely to exist in large and well-performing firms, pointing out the SME firms as a primary target for policy measures.

While the reviewed studies above were generally into the developed countries, a developing African country was studied by Apeaning and Thollander (2013). The authors empirically investigated the adoption rate of energy efficiency measures and technologies in the largest industrial park of Ghana. Also, they investigated the barriers to and the driving forces for the implementation of energy efficiency measures in the industrial park. The results showed that energy was poorly managed within the surveyed companies of the industrial park with low implementation rates of energy efficiency measures. The authors found that the economic factors such as lack of budget funding and access to capital were the most important barriers regarding the low implementation of energy efficiency measures and technologies. As for the driving forces, cost reductions resulting from lowered energy use and rising energy prices were found to be the most important drivers.

A similar analysis to Thollander and Ottosson (2010) was conducted by Ates and Durakbasa (2012). The authors performed a survey study to investigate the major bottlenecks and shortcomings of the energy intensive industries (i.e. iron, steel, cement, paper, ceramics, and textile industries) of a developing country, Turkey, in terms of energy management implications. The study found out that only 22% of the surveyed companies practise corporate energy management in Turkey. Lack of synergy between the stakeholders, the extent and scope of energy manager courses, and inadequate awareness of financial support for energy management activities were found to be the main barrier to proper implementation of energy management among the Turkish energy intensive industries of iron, steel, cement, paper, ceramics, and textile industrial sectors. The authors offered the following policy options to overcome these barriers: strengthening and restructuring of legal and institutional frameworks, promotion of energy efficiency, education, training, and capacity building and facilitating implementation of the international energy management standard ISO 50001.

As the studies reviewed above shows, the diffusion of energy efficiency technologies and measures in industrial can be regarded as low due to a variety of barriers as studied by the Authors. This indicates an unexplored large energy efficiency potential within the industrial sectors. As the studies demonstrates, external factors such as political regulations etc are to some extent important drivers for companies to implement energy management. However, **without a real commitment from a company itself, successful integration, and implementation of energy management in a company is impossible. In this respect, internal drivers gain importance. In this regard, what would motivate the top management for a fully commitment to energy management should be explored. The answer is quite clear. As mentioned by many Authors (Apeaning and Thollander, 2013), gaining competitive edge through improved greener corporate image in the business market and cost reductions owing improved energy performance are the most effective internal drivers for top managements to take action for energy management. As such, the companies can be convinced by means of concentre analyses and examples that will unfold the potential and benefits of the improved energy performance within their facilities.**

In line with the above, there are a number of research efforts exploring energy efficiency potentials and effective energy efficiency measures for industrial applications. For instance, Abdelaziz et al. (2011) gave a comprehensive literature review encompassing industrial energy saving achieved through management, technology and policy measures. The authors reviewed various energy saving technologies such as high efficiency electric motors, variable speed driving, and waste heat recovery and they found that payback periods of most energy saving measures were economically viable in most cases based on the results of real-time applications of these technologies in various plants around the world reported in the literature. Environmental benefits of such technologies such as CO_2 reductions were also given by the Authors.

A similar study to Abdelaziz et al. (2011) was carried out by Saidur (2010a). They gave a comprehensive literature review on energy efficiency issues in industrial electric motors and described their energy use characteristics, energy losses and energy saving tactics to overcome these losses. Moreover, a number of different policy measures for efficiency in electric motors from different countries such as USA, Canada, Mexico, Brazil, EU, Australia, and New Zealand were presented.

While the above reviewed studies were related to the cross-sectoral energy efficiency measures such as using energy efficient electric motors, there are also sector-specific studies. A good example is Hasanbeigi et al. (2014),which provided a technical review in emerging iron making techniques as alternatives to the conventional ones for the purpose of energy efficiency and CO_2 reductions. This paper provides a well-structured database of information on 12 alternative emerging ironmaking technologies. The database covers information on energy savings and environmental benefits of these emerging technologies together with costs and commercialisation statues. The authors reported that COREXs Process, FINEXs Process, and Coal-Based HYL Process were very promising alternative ironmaking technologies among all because these eliminate energy intensive coke production and because they were already commercialized. The authors points to the very low adoption of these less energy-intense technologies by the steel industry worldwide in spite of their advantages, which refers to a large potential of energy efficiency in these industries.

Another sector-specific study into the iron and steel manufacturing was performed by Quader et al. (2015). Similar to Hasanbeigi et al. (2014),the authors provided a comprehensive review of the worldwide carbon reduction programs as well as new CO_2 breakthrough technologies for energy saving and carbon capture and storage in iron and steel manufacturing. This review presented a discussion regarding the selection of appropriate technologies, their barriers and development and deployment stages. The authors found that energy efficiency and CO_2 reductions in iron and steel making could be realized through various technology options such as recovery of high temperature waste heat resources from gas streams in manufacturing processes in iron and steel making such as gas streams from blast furnaces. Similarly, using higher quality raw materials in blast furnace for steel making and fuel replacement with lower carbon emission factors such as shifting from coal to natural gas would mitigate CO_2 emissions from blast furnaces. However, the authors mentioned that these measures would reduce CO_2 emissions to some extent and they addressed applying breakthrough technologies such as the use of bioenergy, CO_2 capture and storage technologies, hydrogen-based steelmaking, iron-ore electrolysis, and biomass-based steel.

Iron and steel industry was also addressed by Zhang and Wang (2008) with an emphasis to Chinese enterprises. Based on their empirical study on 90 Chinese iron and steel plants, the authors provided a statistical evidence that some productive efficiency growth can be attributed to the adoption and amelioration of two specific energy saving measures, which are pulverized coal injection technology and continuous casting technology.

Madlool et al. (2011) made a comprehensive review of energy use and savings in the cement industries. The authors reviewed and presented energy use at different sections of cement industries, specific energy consumptions, types of energy use, and details of cement manufacturing processes.

Besides, various energy saving measures applicable the cement industries were analysed together with their implementation cost, payback periods, and CO_2 reduction benefits.

A study into Malaysian rubber producing industries was conducted by Saidur and Mekhilef (2010). They conducted walk-through energy audits in 22 tyre producing plants in Malaysia and the results showed that the electric motors in these plants accounted for a substantial share of overall plant energy consumption. Accordingly, the authors recommended energy saving measures such as using variable speed drives and high energy efficient motors to increase the energy efficiency in rubber industries.

In addition to the studies involving energy efficiency analysis and measures, some studies proposed energy management frameworks, either generic or tailored for specific industries. For example, Drumm et al. (2013) developed a Structured Efficiency System for Energy (STRUCTese ®) for chemical plants (Figure 2-38), which allows the detailed measurement and tracking of energy efficiency. This study proposes a structured approach to determine energy inefficiencies in a plant, finding energy saving opportunities, technical evaluation and implementation of them.

Figure 2-38: STRUCTese ® workflow (Drumm et al., 2013)

A similar energy management framework was introduced in Thiede et al. (2012a). In this study, a guided method for the systematic identification of most promising improvement potentials was suggested in a textile plant. Like in Drumm et al. (2013), the study developed a so-called energy portfolio which allows the classification and prioritization of energy consumers in a plant. Based on this portfolio, the study aims to derive target-oriented action plans towards energy efficiency improvement. The study provides a pragmatic and practical framework for finding the energy wastes by focusing on major energy consumers and then further analysing them for improvement. This is somewhat similar to the identification of significant energy users in the planning stage of the ISO 50001.

The authors of the above reviewed studies (Drumm et al., 2013; Thiede et al., 2012b) aim to assist the chemical plants and textile plants by introducing their energy management frameworks. The companies can build their energy management program or EnMS based on the framework offered by these studies. However, as in the case of the ISO 50001, the most important thing prior to the implementing an EnMS is conducting an energy audit of which results can be a building basis to implement the EnMS. The results of the energy audit which untaps energy performance improvement potential within a facility will enhance the motivation of the top management for energy management whereby the likelihood of success of the EnMS to be established in later stages is increased. Also, the studies fail to consider the use of renewable energy at plant level, which is essential for a truly sustainable plant in terms of environmental point of view as mentioned before.

A similar study to the studies above was conducted for a chemical plant. Gharaie et al. (2012) presented a new approach to identifying the effect and cost-effective solutions to reduce CO_2 emissions in a chemical plant. The approach presented by the authors applies a hierarchical conceptual design produce to reduce CO_2 emissions so as to minimise the cost of achieving a specific emission targets within a given investment limit. The proposed approach produce combines three main strategies: the first step is exploiting heat recovery potentials by retrofitting the heat exchanger networks; the second one is operational optimisation of the utility system; while fuel switching is followed as the third step. Therefore, this study addresses the specific characteristics aspects of the chemical plant rather than being a generic framework. What is more, differently from the likes, this study also conducted a case study. The Authors applied the proposed approach in a case study and found to be an effective approach for generating and evaluating cost-effective solutions for CO_2 emissions reduction from industrial sites. According to the results of the case study, a reduction of 199.9 kt of CO_2 from 264 kt of CO_2 could be realized through following the proposed procedure.

An energy management method for food industry was introduced by Muller et al. (2007a). The proposed method consists of top-down modelling and bottom-up approaches. The former correlates the measured energy consumptions with the final products and allocates the energy use among major energy using systems. Doing this, priorities are set for energy saving. The latter is based on a thermodynamic analysis which determines the theoretical energy requirements of the processes so that a comparison with actual measured consumption values can be done to identify energy saving potentials. The authors applied their energy management method in a factory and found out that a major part of the energy saving potentials identified could be realized with good housekeeping and require limited investment.

Food industry was also studied by Jekayinfa and Olajide (2007). The energy utilisation patterns in the production of three different cassava products were studied in 18 cassava processing mills.

Gordić et al. (2010) developed an EnMS for a Serbian car manufacturing company. The study first conducted an energy audit in order to find the energy saving opportunities and analyse the current status of the energy management in the company. Various energy saving measures were found such as pipeline insulation, steam trap replacement, compressed air leakage reduction, etc. The payback periods for these measures were found to be between 0.75 years to 3.62 years. Like other studies reported above, this study could had been more useful for the subject car manufacturing company if the potential of supplying the plant by using low carbon energy resources was explored.

A detailed thermal energy audit was conducted Kabir et al. (2010) in a pyro processing unit for dry process kiln systems in a cement plant. The study found that the thermal efficiency of the unit was 41%, which was low enough indicating the thermal energy saving potential.

A cement plant in Turkey was studied by Engin and Ari (2005). The authors conducted an energy audit in a dry type rotary kiln system with an output capacity of 600 ton-clinker per day in a cement plant in Turkey. They identified that energy was being lost in the form of waste heat and radiation through hot flue gas, kiln shell, and cooler stack, which amounts to around 40% of overall energy input to the kiln system. According to the analysis results, about 15.6 % of total energy input could be recovered by applying some recovery means.

An innovative study into energy efficiency in steelmaking was conducted by Tarrés et al. (2014). The authors investigated the potential of heat recovery by radiation in a cooling bed by conducting numerical simulations and experimental tests to recover heat with modified solar absorbers from the cooling bed in a Luxembourgish steelmaking plant. The authors found that 1 kW/m^2 could be recovered with a temperature of 70^{o}C at the side of the cooling bed with a thermal efficiency of approximately 40%.

Having reviewed macro-level studies, the following part will present the review of studies pertinent to renewable energy use.

2.3.3 RENEWABLE ENERGY/MICROGRID/ONSITE GENERATION/DEMAND RESPONSE

With the increasing concern on mitigating the effects of the energy challenge, there is a growing number of research around the world in renewable energy field. Most researchers studied the feasibility of electrification of islanded rural or remote areas by using a hybrid microgrid based on local renewable energy sources. The power requirements of these kind of places are generally met by diesel power plants which is a very costly and a highly polluting means. Moreover, grid extension to these off-grid areas require high capital investment. Therefore, a hybrid microgrid system with various energy sources such as wind, solar, diesel, etc.as well as energy storages can become a cost-effective and environmentally friendly solution for the electrification of off-grid areas in the developing and developed world. Thus, the number of research interest in application of hybrid microgrids have been growing recently. Although demand response participation and renewable energy based microgrid application are two different themes, as mentioned before, the automated EnMS system infrastructure of a microgrid can also assist the application of various demand response measures, which provides further energy cost savings. What is more, performing various demand response strategies can contribute to better utilisation of renewable based power generation which has intermittent and fluctuating nature. Bearing these in mind, this subsection reviews of the most recent research in renewable energy and microgrid applications as well as demand response.

Asrari et al. (2012) studied the techno-economic feasibility of powering a recently grid extended, before diesel powered, rural village in Iran in two hybrid power supply options They performed the analysis by using HOMER software: diesel-RES (diesel generator + renewables) and grid-RES (utility grid + renewables). The authors found that addition of renewable power generators to both diesel generator and utility grid cases could result in a more economic and climate-friendly power supply to the village. The results mean that the expenses spent for the grid-extension to the village could have been lowered if the diesel-RES and grid-RES hybrid systems had been considered before the grid-extension.

Sen and Bhattacharyya (2014) studied the techno-economic feasibility of the best hybrid power generation option from four renewable energy sources (i.e. small-scale hydropower, solar PVs, wind turbines, and bio-diesel generators) to meet the power needs of an off-grid remote village in India. They performed the analysis by using HOMER software (Figure 2-39). They found a least-cost combination of small hydropower, solar PV, bio-diesel and batteries could supply the power demand of the village in a reliable manner. Off-grid electrification of another region in India was studied by Kanase-Patil et al. (2010). The authors considered biomass, solar, hydro and wind as renewable sources and conducted a feasibility analysis by using LINGO and HOMER software.

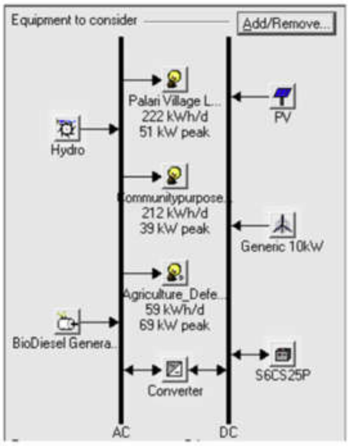


Figure 2-39: Hybrid microgrid design in HOMER by (Sen and Bhattacharyya, 2014)

Another study into the electrification of rural areas was carried out by Bekele and Tadesse (2012). By using HOMER software, they studied the feasibility of a small-scale hybrid power supply system comprises of Hydro/PV/Wind (Figure 2-40) for the application in a district in Ethiopia.

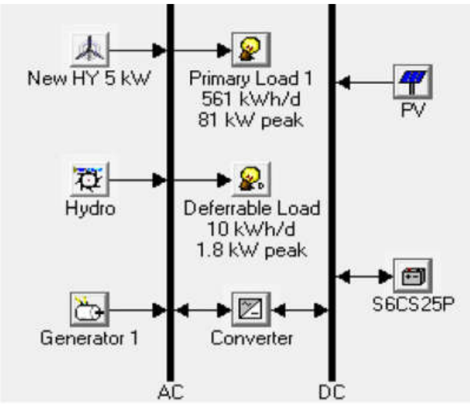


Figure 2-40: Hybrid microgrid design in HOMER by (Bekele and Tadesse, 2012)

Akinbulire et al. (2014) studied the application of hybrid renewable systems for a rural area in Nigeria. The authors investigated the techno-economic and environmental effect of applying demand side management activities to the rural loads in hybrid systems feasibility. They applied various energy efficiency measures as demand side management activities and reduced the power load 56.8%. The results showed 100% of renewable energy integration was possible through the demand side management activities which reduced the load. This study shows of importance of demand side management activities before sizing a hybrid power generation system. However, this study could have been more useful if the authors had considered the effect of the cost of energy efficiency measures.

Rehman et al. (2012) proposed a hybrid power system for a village in Saudi Arabia, which was normally powered by a diesel power plant consisting of 8 diesel generating sets of 1120 kW each. The proposed system comprised of 3 wind turbines each of 600 kW, 1000 kW of PV panels, and four diesel generator sets each of 1120 kW rated power. The authors simulated the proposed system by using HOMER software and the results showed that the proposed system was able to cover the energy demand of the village (i.e. 17043.4 MWh/year) with a cost of energy of 0.212 $/kWh. Further, the proposed system avoided 4,976.8 tons of GHG equivalent of CO_2 gas in t the local atmosphere and conservation of 10824 barrels of fossil fuel annually.

Lau et al. (2010) studied the techno-economic feasibility of hybrid PV-diesel energy generation systems for a remote location in Malaysia. The annual power demand, i.e. 421.94 MWh, was met solely by a diesel generating system. The study found that a hybrid system consisting of a 60kW PV array, two 50 kW of diesel generator units, and 12 units of battery could achieve a significant reduction in the solely diesel dependence of the location.

Kalinci (2015) investigated alternative energy scenarios for Bozcaada, a Turkish island, which is powered by the main grid although the island is rich in wind and solar energy potential. The author investigated the feasibility of grid-connected and standalone systems for the Island by using HOMER software. For this purpose, six scenarios which include grid, grid-wind, grid-PV, grid-wind-PV, wind-fuel cell, and wind-PV-fuel cell were simulated. The study found that the optimum grid-connected configuration was the grid-wind system generating the electricity at $0.103/kWh while the grid electricity price was $0.17/kWh. On the other hand, the optimum standalone system was found to be the wind-PV-Fuel cell system generating the electricity at $0.836/kWh.

Another Turkish Island, Gökçeada, was considered by Eskin et al. (2008). This study investigated the wind energy potential of the island at four different locations of the Island. They conducted field measurements of wind speed at 10 and 30m of height above the ground over a period of 3 years at two locations and 10 years at the other locations. The wind speed data then extrapolated to 50 m which had been considered as the wind turbine hub height. This study did not consider any economic assessment. The results of this study show the island under scrutiny has high wind speed and power potential.

As well as the research into the remote areas as presented above, applications of renewables in urban and residential areas and commercial facilities have been the interest of various researchers. For instance, Miranda et al. (2015) evaluated the techno-economic potential for installing PV in the Brazilian residential sectors. The results of the study indicated that about 2014 site would be ready to install PV panels while this number would reach 68,000 in 2016. The study also forecasted that around 29 million residential units would be able to have PV panels installed in 2026.

Strzalka et al. (2012) consider the building integration of PVs as a major issue in large scale implementation of PVs in the urban environment particularly because of the roof or façade surfaces with orientations which are not ideal for maximum energy generation. Therefore, the authors first investigated the PV-suitable roof areas in a residential district near Stuttgart, Germany by using a Geometric Information System and evaluated the performance of PV systems installed on these roofs. Then, they compared with the electricity use of building users. The results showed that the electricity produced by the roof top PV can meet 35% of the electricity consumption of buildings.

Peng and Lu (2013) investigated the potential installation capacity of roof top PV systems in Hong Kong. They estimated that the potential installation capacity was 5.97 GWp and the corresponding annual energy output potential was 5981 GWh hours which could supply the 14.2% of the total electricity demand in Hong Kong in 2011. The authors also addressed the climate change benefits of using PV electricity in Hong Kong.

Arslan (2010) investigated the techno-economic feasibility for renewable based electricity generation for a main grid-powered university campus in Kutahya province of Turkey. By using the measured wind data for a period of 3 years in the location, the author calculated the power production of different types of wind turbines and analysed the economic evaluation of the results using life-cycle cost analysis. The study showed that the meeting the electricity need of the university campus was technically and economically feasible.

Dalton et al. (2009a) conducted a feasibility analysis of a standalone renewable based power generation for a large-scale (i.e. over 100 beds) tourist hotel, in Australia. The study compared diesel generator-only, renewable energy-only, and renewable energy-diesel hybrid standalone system configurations. The results indicated that 100% of the power demand could be met by a renewable energy-only option while a hybrid renewable energy-diesel system configuration provides the least cost with a renewable energy fraction of 76%. The payback time of this configuration was 4.3 years. The study also found that large-scale wind energy systems over 1000kW are more efficient and economical than multiple small-scale ones.

An interesting study was conducted by Liu (2014). The author investigated the feasibility of solar PV powered street lighting systems in Hunan Province, China. The economic feasibility of two types of systems were analysed and compared: off-grid and grid-connected systems. He found that if the feed-in tariff was higher than a certain rate (i.e. 1.27 CNY/kW), the cost of energy of the solar powered lighting systems would be less than a pure grid powered lighting system. In terms of technical and environmental feasibility, the author considered two options of solar panel materials: single crystalline panel and polycrystalline panel. The results showed that for street lighting systems, single crystalline panel provided a larger number of annual electricity generation, less emissions, but single crystal panel is more expensive than polycrystalline panel.

Similar to Liu (2014), studied into the street lighting systems. The authors suggested that the commercialised standalone street lighting systems based on the classical configuration coupling solar PV cells and battery might not be efficient in regions far from the equators. To improve the classical configuration, the authors proposed a hybrid system that consists of a PV, a battery, and a fuel cell. To optimise and find out the least cost system, they used two optimisation methods: the generic algorithms and simplex algorithms. An optimal configuration, which consists of a 148 W PV generator, a 128 W fuel cell, and 2.54 kWh battery, showed that a 60 W street light would cost €7150 with a life time of 25 years. The authors conducted the analysis for Geneva in Switzerland.

Ucar and Balo (2009) investigated the annual electricity generation potential from four different wind turbines (600kW, 1000kW, 1500kW, and 2000kW) and their capacity factors (Cf) at six different locations of Turkey, namely, Erzurum, Elazıg, Bingöl, Kars, Manisa, and Nigde. This study was solely based on technical assessments and did not include any economic evaluation.

Besides the design and optimisation studies in remote and rural areas and urban applications, there are also studies into the performance analysis of existing systems. For example, Ma et al. (2013) presented the results of the performance investigation for a real-time standalone PV system of 19.8kW that was established on a remote island in Hong Kong which had been powered by diesel generators before. The performance evaluation that was carried out for the complete year of 2011 covered the PV array, inverters, battery bank, and overall system performance of the standalone PV system. The authors found satisfactory results for all system components and the overall system performance.

Another study into the analysis of existing systems was conducted by Yan et al. (2013). They investigated the performance of a PV array established in the University of Queensland, Australia based on the yearlong recorded data from the PV systems and then compared it with the theoretical estimations. The performance results based on the field measurements were found to be in good harmony with the theoretical estimation model which validates the theoretical model implemented for estimation.

The importance of industrial sectors, particularly of manufacturing sector, in terms of the energy challenge was highlighted earlier. As well as energy efficiency and management, using low carbon energy sources in manufacturing plant is of importance. There are some studies regarding the industrial scale application of renewables; however, few studies dealt with the application and integration of renewables in manufacturing plants.

For instance, by using HOMER software, Soshinskaya et al. (2014) studied the techno-economic feasibility of a renewable energy-based microgrid for a Dutch industrial-sized water treatment plant. They found that the water treatment plant could become 70–96% self-sufficient with renewable electricity based on wind and solar power. The Authors also found that demand response through shifting 29% of normal annual demand of the water treatment plant to be supplied during renewable energy generation increases the cost effectiveness of the microgrid application.

Al-Smairan (2012) also studied the power supply for pumping systems. The author compared the cost-effectiveness of a standalone PV and a diesel generating set for power supplying to a drinking water pumping system in a remote area of Jordan. The study found that, although the PV system requires quite higher capital investment, the cost of pumping one m^3 of drinking water was \$0.2 for the PV system and \$0.58 for the diesel generating set.

Similar to Soshinskaya et al. (2014) and Al-Smairan (2012), Ramos and Ramos (2009) analysed the potential of powering a water pumping system with local renewable energy sources of wind and solar in Portugal.

Nacer et al. (2014) carried out a feasibility analysis the application of grid-connected PV system to a dairy farm in Algeria to meet the electricity needs (i.e. 23.6 kWh/day) for milk production equipment and the cattle housing. By using HOMER software, the authors found that a grid-connected PV system of 5.98 kWp was the optimal system for the farm and satisfies that farm load with a 5.6% of annual surplus electricity generation.

Yuan and Dornfeld (2009) assessed the application potential of alternative energy technologies, including solar PV, wind turbine and fuel cells, to reduce facility emissions from automotive manufacturing plants in Detroit, MI, region in the US. The study found that wind power was more economically competitive than solar and fuel cells options; but, the authors pointed out the height requirements and noise generated from wind turbines in urban areas. This analysis was only based on the estimation of power generation potential based on local sources and comparing its cost with the local electricity cost.

Zhai et al. (2014) studied the cost benefit analysis of using clean energy systems to partially supply the power needs of global industrial productions to reduce GHG emissions. The authors conducted a case study on assessing ad benchmarking the application potential of four clean power systems at six selected represented locations of General Motors (GM)`s global production sites. The clean power technologies considered in this study included solar PV wind, hybrid solar-wind, and hydrogen fuel cell power systems. The findings of this study revealed that cost benefit performance of these power systems was dependent on multiple factors such as time, scale and location.

Regarding demand response participation, the previous research is mainly comprised of review and application studies focusing on the residential and commercial applications. For instance, Torstensson and Wallin (2015) investigated the potential for demand response among households of a Swedish town, Eskilstuna through conducting questionnaire survey with the aim of determining the attitudes and enablers for demand response among households. Darby and McKenna (2012) provided a review of some residential DR concepts. Robert et al. (2018) provided a critical review on the utilisation of demand response and storage for the implementation of renewable energy microgrids. The authors claim that storage and demand response can be a more cost effective and flexible solution than fossil fuel generation for stabilisation of the fluctuating power generation in renewable energy microgrids.

2.4 CHAPTER SUMMARY AND CONCLUSIONS

This chapter has reviewed the literature in terms of the global energy challenge and energy management in industry with a particular focus on marine manufacturing industry of a fast-developing country, Turkey. The literature review started with a detailed background on the global energy challenge and its two major dimensions, namely climate change and energy security. Unsustainable use of fossil-based energy resources was then considered to be the main cause of the energy challenge. The situation of the fast-developing countries with limited domestic fossil-based energy resources and how the energy challenge affects them were explained. The background section also briefly explained the emergent paradigm changes in two interrelated major energy consuming sectors, which are power generation and manufacturing industry. Among major modes of manufacturing industry, the importance and potential of marine manufacturing sectors such as shipbuilding and marine equipment manufacturers in terms of the energy challenge were noted. Following this, Turkey`s situation in terms of the energy challenge was presented as she is a good representative of developing countries with limited domestic energy resources, followed by explaining the potential of the fast-developing Turkish marine manufacturing sector. Thereafter, energy management and its various themes such as EnMS and energy auditing were reviewed. The ISO 50001 was also noted. The importance of the planning phase and top management commitment for energy management were highlighted. Bearing these in mind, the research efforts in the field of industrial energy management were critically reviewed.

The following deductions can be drawn from this chapter:

- The energy challenge requires manufacturing companies to improve their energy performance through three major drives: regulations & legislation; rising energy costs; market demand for green corporate image. In order for manufacturing plants to comherensively cope with the challenge and deal with the drivers, assessment and improvement of energy performance in manufacturing plant should be approached with holistic consideration to reduced energy consumption, reduced energy costs, and reduced GHG emissions. With this regard, a methodology framework with a holistic consideration of the following energy management themes should be developed for a compherensive assessment of the existing energy performance and its improvement potential in manufacturing plans: energy efficiency; renewable energy; and demand response. While considering improvement of energy efficiency, the human factors in energy efficiency should be considered together as well as technicalities. The state-of-the-art is missing in terms of such a compherensive methodology framework for improved energy performance.

- Although the subject of industrial energy management has experienced a recent surge of research interest as a result of the overwhelming concerns on the global climate change and energy security issues, regrettably, the state-of-the-art is missing the energy management issues in terms of the following perspectives in spite of their importance for the energy challenge as often explained in the entire chapter,:
    - Sectoral perspective: marine manufacturing industries
    - Developing country perspective: Turkey
- Bearing the above research gaps in mind, a compherensive methodology framework which formulates and adopts a holistic approach to the assessment and improvement of energy performance in manufacturing plants should be developed and implemented to a typical Turkish marine manufacturing SME.
- Such a research effort which develops a novel methodology framework for energy performance improvement and applies it to a Turkish marine manufacturing plant is really needed to achieve the aims and objectives of this thesis which are stated in Chapter 1 and can be justified with the major research gaps identified in the chapter.
- Furthermore, the development of such a holistic framework and demonstration of its applicability in a real-time case study will make an important contribution to the existing knowledge and to increase the energy management awareness among the Turkish marine and non-manufacturing industries, which is vital of in terms of establishing and dissemination of good energy management culture among them.

3

Development of a Holistic Energy Management Framework and Application Methodology

3.1 INTRODUCTION

The main objective of this chapter is to propose a holistic management framework for energy performance improvement and show its application methodology to meet the thesis objective 2. To meet the chapter objective, this chapter is structured in three major sections. Section 3.2 presents the proposed holistic energy management framework through answering the question "how to improve the energy performance of manufacturing plant?" and giving the grounds for the need for a holistic systematic approach for energy performace improvement. This is followed by Section 3.3 which presents the application methodology of the proposed framework. Finally, Section 3.4 concludes the chapter with a summary of the chapter.

3.2 HOW TO IMPROVE THE ENERGY PERFORMANCE OF A MANUFACTURING PLANT?

Conducting an energy audit prior to establishing an EnMS is essential to establish a baseline level of the energy performance of a plant and explore the improvement potential. In conducting an energy audit, a question arises: How can the energy performance of a manufacturing plant be improved? The answer to this question have been partly given in the previous sections addressing various measures and means. In this subsection, an overall picture of energy performance and relevant ways to improve it will be drawn to systematically approach for improved energy performance to pave the way for a holistic management framework.

3.2.1 THE NEED FOR A HOLISTIC APPROACH

As noted earlier, the main drivers of need for improved energy performance within manufacturing plants (Figure 2-13) are improved energy performance is defined as “low GHGs emissions and low energy costs through reduced energy consumption (i.e. increased energy efficiency) and low carbon energy use” to form a research basis in this thesis. Thus, it is aimed that the definition of improved enegy performance should correspond to these drivers. As it can be drived from this definition, three main dimensions of energy performance can be defined:

- energy consumption
- energy cost
- GHG emissions

Thus, energy consumption, energy cost, and GHG emissions are the key performance parameters to assess the energy performance improvement potential in a manufacturing plant. Any reduction in these parameters will contribute to improving the overall energy performance of the plant. Therefore, the following questions should be asked:

- How can energy consumption be reduced?
- How can energy cost be reduced?
- How can GHGs can be reduced?

To be able to answer these, the factors responsible for them must be studied. From energy management perspective, a manufacturing plant can be considered as a major energy system comprised of various sub-energy-systems such as production equipment and machinery, etc. The overall manufacturing plant must be powered by various forms of energy such as electricity or gas to power its energy using systems. The manufacturing plant and its energy demand represent the “energy demand side”. The energy demand of the plant must be supplied by utility providers or onsite generation, which represents the “energy supply side”.

Figure 2-31 depicts the relationship between energy performance parameters and their relationship with supply and demand sides of energy use. As it is well known, energy consumption cost and CO_2 emissions release can be simply calculated as follows:

- Cost of energy consumption (€) = energy consumption (kWh) * energy unit cost rate (€/kWh)

- CO_2 emission generation due to energy consumption (kg-CO_2) = energy consumption (kWh) * emission factor (e.g. kg-CO_2/kWh)

From the above, it is obvious that supply side of energy use is partly responsible for "energy performance" of a manufacturing plant as it is the determiner of the energy unit cost rate and emission factor. On the other hand, demand side of energy use, which is the manufacturing plant, is responsible for energy consumption. Energy performance of a manufacturing plant concerns both energy demand and supply sides as energy cost and energy related emissions are relavent to boths sides. Therefore, both demand and supply side of energy use must put under scope in an effort to improve the energy performance of a plant.

The major factor that influences the energy cost and energy-related emissions is the amount of energy consumption by the manufacturing plant. In the simplest terms, if there is no energy consumption, no energy cost and no emissions will involve. Therefore, any energy management approaches to improve the energy performance of a manufacturing plant, prior to establishment of an EnMS, should begin with searching the potentials to reducing the energy consumption of the plant. Then, further improvemet potential of energy performance can be sought out focusing on the supply side of energy.

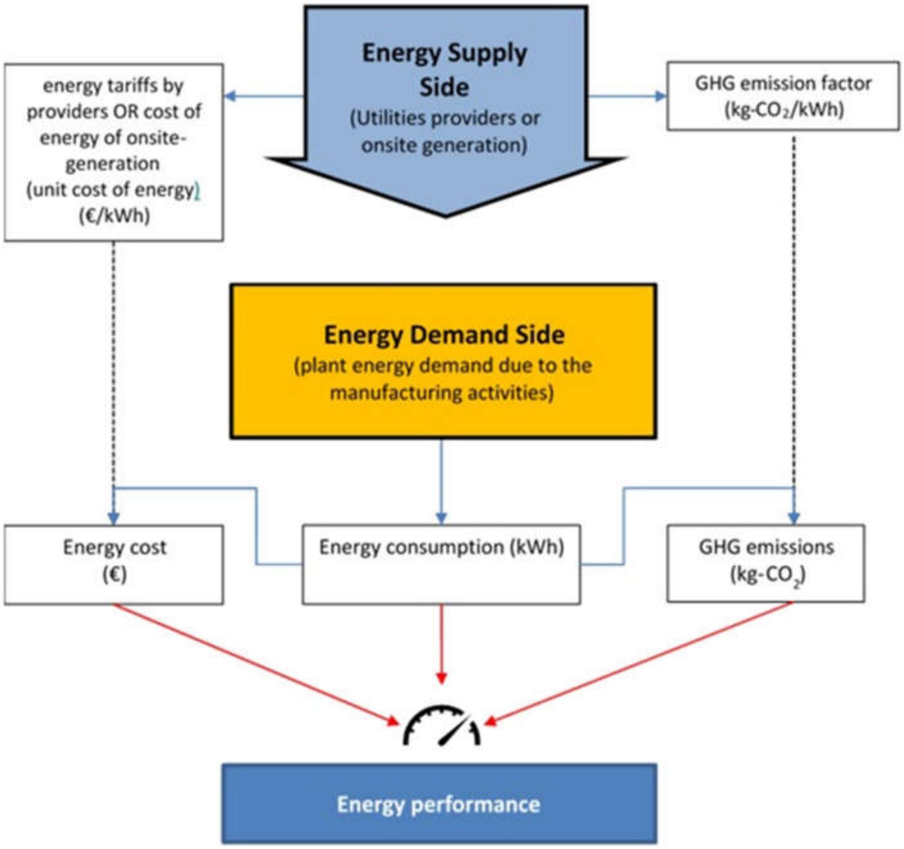


Figure 3-1: The relationship between energy performance parameters and their relationship with supply and demand sides of energy use

3.2.1.1 ENERGY DEMAND SIDE

3.2.1.1.1 Energy Efficiency

Energy consumption reduction potential in a manufacturing plant is related to how efficiently that plant uses energy. This is expressed as energy efficiency. In general, energy efficiency can be expressed as follows:

$$energy\ efficiency\ (EE) = \frac{useful\ \ workoutput}{energy\ input(energy\ consumption)}\ \%$$

From a manufacturing plant perspective, it can be expressed as follows:

$$EE = \frac{useful\ production\ output(kg)}{energy\ input(energy\ consumption)(kWh)}$$

To improve the energy efficiency of a manufacturing plant, total energy consumption by the plant to produce certain amount of production should be reduced. To reduce the total energy consumption, energy saving potentials within the manufacturing plant should be identified conducting an energy audit as noted before.

A manufacturing plant can be considered as a socio-technical system which incorporates various components such as technical equipment, human factors, and organisation (Figure 3-2) (Günter, 2009). The cooperation and synchronisation of these components (Dombrowski et al., 2014) affects the overall energy consumption of a manufacturing plant. Also, every improvement in these components in terms of efficient energy use will contribute to the overall reduced energy use and energy efficiency, and thus energy performance of the manufacturig plant.

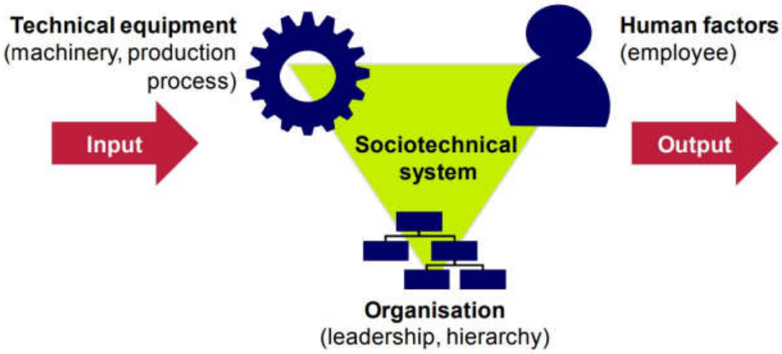


Figure 3-2: Manufacturing plant as socio-techical system (Günter, 2009)

Overall, energy efficiency of an energy using system will be affected by two major aspects:

- technical factors;
- human factors.

Techical factors

Technical aspects of a manufacturing plant in terms of energy efficiency are related to its energy consuming systems such as manufacturing machinery and equipment or processes. If these technical systems are efficient in terms of energy consumption, energy consumption will be lower than otherwise. Technical aspects of energy efficiency is mainly related to the energy efficiency of the energy using system itself which is related to its design and manufacturing phases and any energy efficiency retrofits which can be done in the usage phase.

Human factors

However, employing an energy efficient machinery or equipment for a specific task or process does not always ensure that it is efficiently and effectively use in terms of energy consumption. Using a machinery or equipment for an inappropriate task, using an undersized or oversized system, incorrect process parameters, and lack of proper maintenance of a system can be given as several examples that can lead to inefficient energy consumption by an energy consuming system even if it is an energy efficient one compared to its counterparts or alternatives. Therefore, energy efficieny of an energy consuming system itself as well as efficient and effective use of the system by the plant should be ensured.

Bearing the above in mind, closely related to energy efficiency, and of equal importance to Technical Factors is Human Factors. It concern the efective and efficient usage of the energy consuming system in terms of energy efficiency in the usage phase. The factors in this second aspect can be attributed to its usage by human factors such as employe awareness of energy efficiency and behaviour, and organisational aspects such as the commitment of top management.

Human factors is at the heart of energy management. For example, energy efficient technologies are already available in the market and any decisions as to purchase energy-efficient machine or equipment in a company is a matter of human factors since the decision will be given by the company management (i.e. human). A company management with high level of energy-awareness would opt for an energy efficient machine or equipment. Similarly, a decision regarding whether to implement an energy management program or energy management system is given by the company top management. As a matter of fact, as highlighted in Section 2.2.9, top management commitment for energy management is a prerequisite for establishing a successful energy management program or system and is a starting point of the endavours for improving the overall energy efficiency across a plant. Therefore, if a decision regarding the establishment an energy management program or system has been already taken and energy auditing phase has already commenced, it is quite likely that the top management commitment was ensured which means that the top management has already gained awareness of improved energy performance so that they have their plant audited for energy consumption.

Another human-factors related aspect with paramount importance in a plant is employee behaviour. Employees or labours neither consume energy and nor directly relate to energy efficiency; but, their behaviours or skills can affect the energy efficiency of energy consuming systems. For example, keeping the lightings on by a worker where lighting is not required is a wastage of energy associated with employee behaviour. As well as lack of awareness, there might be imperfect knowledge so that the employees` actions can result in excessive energy consumption. “An energy aware workforce (Vesma, 2011):

- has a less tendency to work in an energy-wasteful manner,
- is better at spotting signs of energy waste around them;

- knows what to do about suspected waste; and
- makes positivite suggestions for improving energy efficiency and preventing loss."

Despite the above facts, regrettably, human factors in energy management efforts are commonly neglected and the technicalities are given priority (Oung, 2013). There is also little research into the effect of human factors on the energy efficiency (Dombrowski et al., 2014).

Bearing these in mind, when investigating energy saving potentials within a system, employees` behavior on energy efficiency should be included in the energy auditing scope. If possible, impact of employee attitude or behaviour should be assessed and demonstrated "quantitatively" by quantifyig the energy saving potentials emaneting from employees' behaviour so that these can be used to create or increase energy efficiency awareness among them and enable their participation towards an energy efficient manufacturing plant.

In short, as well as technical aspects on the energy efficiency of energy consuming systems, human factors should be studied and analysed when conducting an energy audit.

3.2.1.2 ENERGY SUPPLY SIDE

To reduce energy costs focusing on supply side, a company can review the energy tariffs defined by its supplier or opt for another supplier for the cheapest unit cost rate. For example, electricity suppliers offer various energy tariffs such as fixed rate and time-of-use rates which requires the purchasers to perform demand response participation. Alternatively, a manufacturing company can generate its own energy by deploying distributed on-site power generation systems. If renewable generators are used, this will also contribute to the environmental dimension of improved energy performance of a plant since energy related emissions will be minimised.

A plant can generate its own electricity by deploying a microgrid. A microgrid consisting of distributed renewable power generators such as wind turbines and solar PV modules, and appropriate storage and control systems can provide electricity with lower environmental emissions in comparison to utility grid. Hence, the energy related emissions and costs for a manufacturing plant can be substantially minimised depending on the renewable energy technologies and energy potential in the plant location. Therefore, using renewable based clean energy source is essential in terms of decarbonising the plant operations and business competitiveness and the plant can be completely or partially self-sufficient depending on various factors such as solar and wind energy sources, and available plant area for accommodating renewables generators.

In addition to the integration of renewables, a microgrid application enables a plant to benefit from demand response measures. The power utility providers offer demand response programmes to their customers which create win-win situation for both sides. In general, demand response refers to "a specific tariff or program to motivate end-use customers respond to changes in price or availability of electricity over time by changing their normal patterns of electricity use. It can also be defined as incentive payment program to reduce usage of electricity when grid reliability is jeopardised (U.S. Department of Energy, 2006)". The power production in central power stations must closely meet the demand of energy. In other words, the supply and demand must be matched all the time. However, supply side has no direct control over the demand side which is not constant due to the consumer behaviour. There occur peak power demands which are higher than the average demand; but occurs for a short time. This imposes a major challenge on power plants. To ensure the security of power supply is maintained in peak periods, the total installed generation capacity has to be built so as to meet these peaks (Strbac, 2008). For this purpose, power companies employ back-up generators which have to be on stand-by to respond to instant power peaks but produces power for a short period of time. Running a generator for a short period is much less efficient than keeping a unit running at a regular output rate (Freeman, 2005). Therefore, their utilisation is very low, and this results in a very costly electricity generation. Furthermore, these back-up generators are generally powered by fossil fuels, which are environmentally harming. As such, utility providers encourage their customers to decreasing their power use during critical peak periods or shifting some of their peak demand usage to off-peak hours (Aghaei and Alizadeh, 2013) by offering low unit cost rates during off-peak hours or charging them for peak power demands. In this way, while demand response provides cost saving to the customer, it does not reduce the net energy consumption and not provide energy efficiency to the customer, it rather redistributes the load (Strbac, 2008).

Normally, some demand response measures such as load shifting can be carried out by manufacturing scheduling or shifting manufacturing activities to low-price hours offered by the utility. Alternatively, the electric loads by a plant can be shed at high-price hours. Similarly, a plant can avoid simultaneous operation of high power rated systems. However, this requires a very strict production planning and, even worse, it can disrupt production. Instead of these conventional ways of demand response practising, renewable-based power produced and stored in storage systems due to their intermittent nature in a microgrid application can be used to perform various demand response measures. For instance, the power demand of a plant in high-price hours can be met by the stored electricity considering the cost effectiveness of such as an application. Similarly, the stored electricity can be used for peak shaving by limiting the grid demand. To be able to perform these in a manufacturing plant, an innovative enabling technology is needed. An efficient infrastructure to implement these practically is an Energy Management System embodied a microgrid which is actually a fully automated electric power system which will involve some basic features such as a supervisory control and data acquisition (SCADA), advanced metering infrastructure, state estimation algorithms, and generation and load forecast system, etc. (Aghaei and Alizadeh, 2013).

Thus, putting demand response techniques and renewable energy integration in the same picture, a smart microgrid onsite the plant which will generate electricity sourced by a blend of renewable energy sources and dispatch it by deploying appropriate demand response strategies can have a profound effect for the demand supply match.

3.3 PROPOSED HOLISTIC ENERGY MANAGEMENT FRAMEWORK

Bearing the all facts presented thus far in mind, a holistic energy management framework which involves the following key energy management themes is needed as an initial key step for improved energy performance in a manufacturing plant:

- energy efficiency
- renewable energy use
- demand response

The Author of this thesis proposes an energy management framework which combines these three major pillars in one holistic platform as shown in Figure 3-3. The application of this framework, of which methodology is presented in Section 3.4, will enable an assessment of overall energy performance improvement potential from energy consumption, energy cost, and environmental perspectives.

In developing and implementing an energy management program or EnMS system such as ISO 50001 for a manufacturing plant, the holistic energy management framework considered in this thesis will be part of the planning phase (Figure 3-4). The results of the energy audit which will be a comprehensive energy report and the results of the techno-economic feasibility analysis of renewable energy use and demand response measures through the application of an onsite power generation (i.e. microgrid) can be used for an energy action plan. Based on the outcomes of the detailed energy analysis and microgrid feasibility, the subject plant can do a strategic energy management planning.

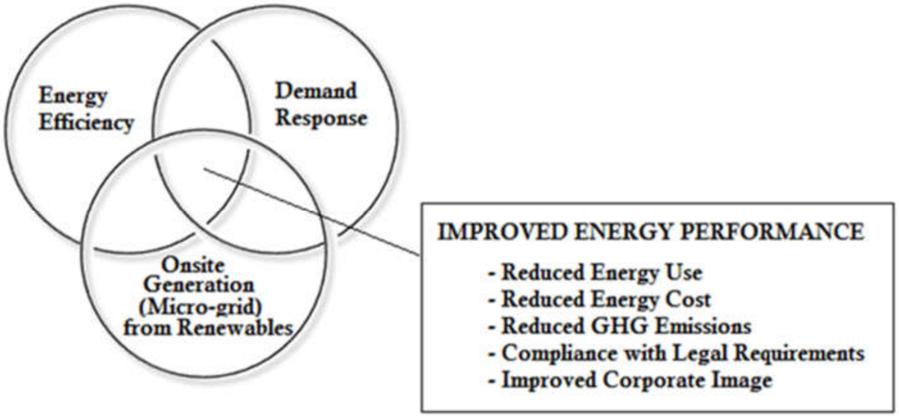


Figure 3-3: A holistic energy management framework proposed by the Author

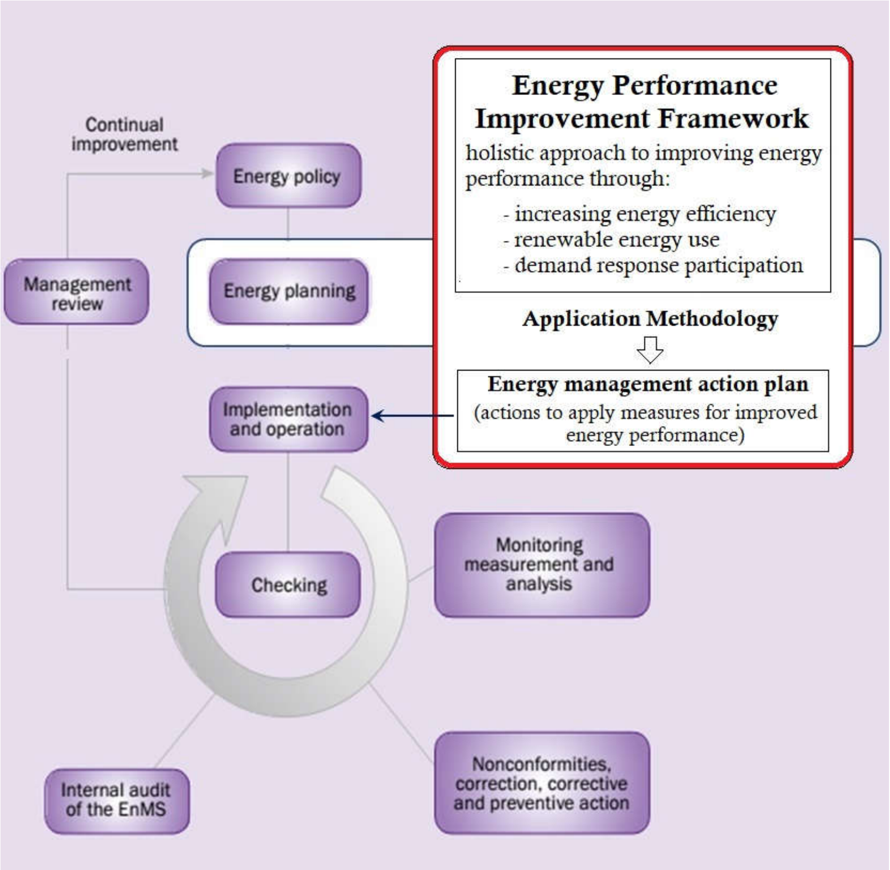


Figure 3-4: The relation between the proposed energy management framework and ISO 50001 energy management system model

3.4 APPLICATION METHODOLOGY

The first pillar of the proposed framework is Energy Efficiency. Any efforts towards energy performance improvement will begin with identifying the ESPs within the manufacturing plant which will increase the energy efficiency. Thereafter, other pillars of the proposed framework is put on the agenda.

A detailed energy audit is central to this framework and is a starting point for the target of "improved energy performance". This is because energy audit will reveal the ESPs of which application will improve the energy efficiency of the subject plant. In the meantime, the data required for further analyses of the feasibility of renewable energy integration and demand response participation through a microgrid is collected in the energy audit. Therefore, a feasibility analysis for microgrid application is required to see the techno-economic potential of renewable energy integration andd demand response participation. Hence, the following main steps can be identified to apply the proposed framework:

- Energy audit
- Microgrid application

The overall methodology framework is demonstrated in Figure 3-5. To demonstrate the applicability of the proposed energy management framework, it has been applied to a marine manufacturing plant in Turkey. A detailed introduction and description of the subject plant chosen for case study application is given in Chapter 4. The following subsections will explain the methodology to apply the proposed holistic energy management framework.

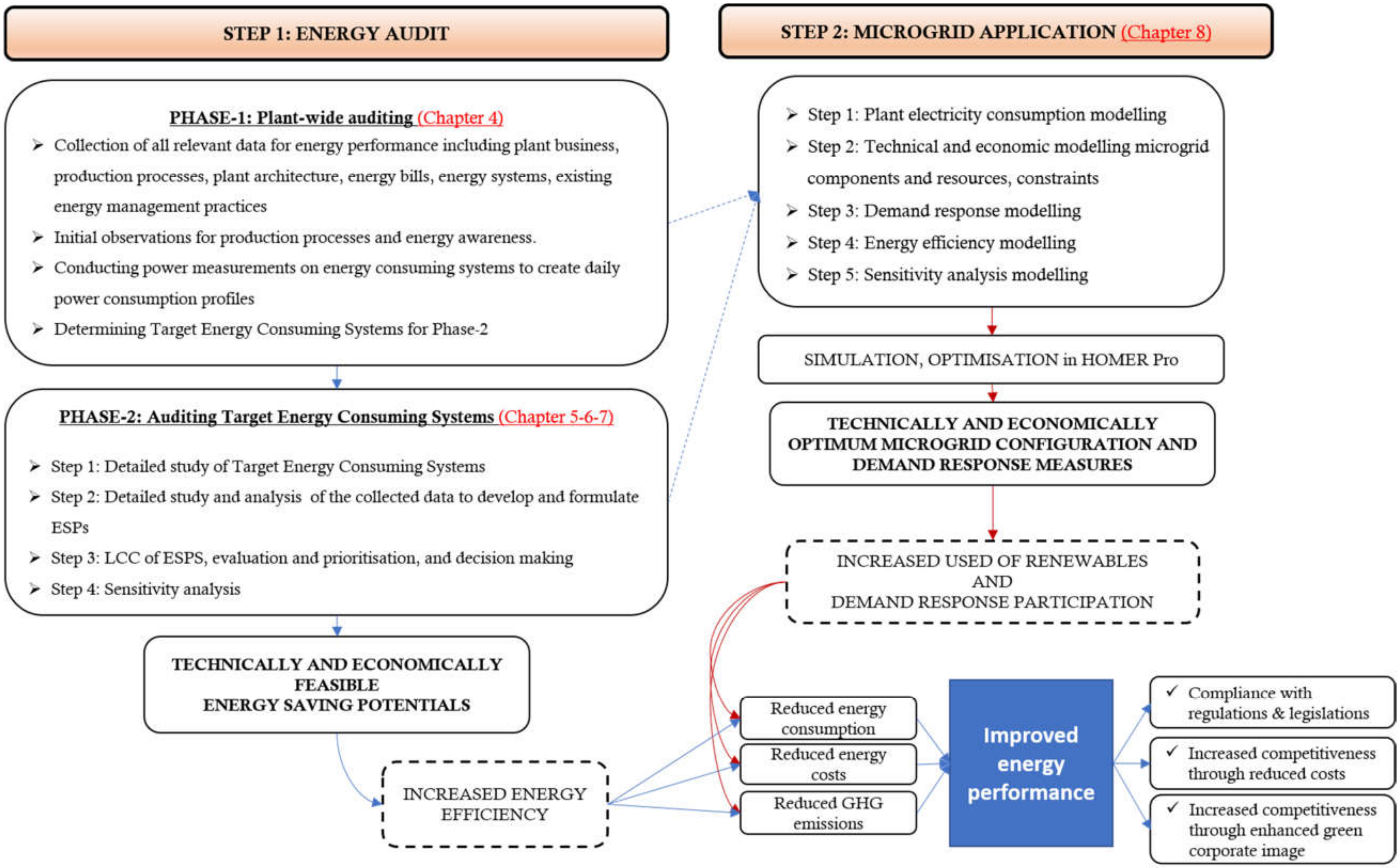


Figure 3-5: The overall methodology framework and improved energy performance

3.4.1 ENERGY AUDIT METHODOLOGY

As the literature review has showed in Chapter 2, there are generally two types of an energy audit: Preliminary Audit; and Detailed Audit. A preliminary audit generally involves simple analysis of energy use and performance of the plant and do not need exhaustive data collection and measurement (CIPEC, 2011). On the other hand, a detailed energy audit involves more detailed data collection and measurements on machine and equipment level as well as plant level. The results of a detailed energy audit are more comprehensive and provide more accurate understandings of the plant energy performance and improvement potentials (Hasanbeigi and Lynn, 2010). Furthermore, economic analysis for improvement potentials usually include the of Net Present Value (NPV), which gives more accurate results than a simple payback analysis which is employed in preliminary energy audit (Hasanbeigi and Lynn, 2010).

The energy audit scope in the proposed framework in this thesis comprises of two major phases:

1. Phase-1: Plant-wide Auditing
2. Phase-2: Auditing Target Energy Consuming Systems/Processes

3.4.1.1 PHASE 1: PLANT-WIDE AUDITING

The objectives of this major energy audit phase are to:

1. become familiarised with the plant and plant personnel.

2. collect the architectural and engineering plans of the plant.

3. collect all the relevant available data such as production flow diagrams, plant layouts, historical production records, energy using systems technical data sheets and their historical operation records.

4. understand plant manufacturing technologies, processes and flows, operating hours, operation schedule, type of products being manufactured, plant energy using systems, and energy flows.

5. observe and determine the existing or previously performed energy management practises performed by the plant and level of awareness in terms of energy efficiency.

6. observe and determine existing power/energy measurement devices in the plant and equipment, and collect if any achieved measurement records are available.
7. collect and analyse the plant energy bills to identify the energy types used in the plant and establish the overall energy consumption, energy cost, and CO_2 emissions figures.
8. determine the Target Energy Consuming Systems for further detailed auditing to find energy saving potentials to further auditing in the second phase of the energy audit.

In order to achieve the 8th objective, one needs to determine the relevant criteria for the Target Energy Consuming Systems/Processes to be chosen.

In general terms, a target in an energy audit can be any energy consuming system. For instance, a plant management may have a system audited in their facility because they deem that system is energy intensive or energy inefficient or because just for a reason. But, as also mentioned in Section 2.2.10, generally and in all reason, the systems/processes which have major impact on the overall energy consumption of a facility are chosen to be audited. In other words, major energy consumers are audited for their energy performance.

Concerning the Target Energy Consumers in the case study conducted in this thesis to demonstrate the application of the proposed framework in this thesis, this study aims to examine and audit all the energy consuming systems/processes in plant. The motivation behind this was explained in Section 2.2.10. To restate it briefly; covering all energy consumers in the energy audit rather than solely focusing on significant consumers will enable one to have a thorough picture of the baseline energy performance and the collective effect of energy savings potentials identified in less energy consumers can be worthwhile to consider. Such an attempt will also provide invaluable insights regarding the energy intensity of various manufacturing processes/systems, and the factors/aspects related to their efficient energy consumption as well as the appropriate energy saving measures and methods applicable to them. In addition to these, the level of detail of the data collected throughout the examining of each system is of importance as it will be used in the microgrid feasibility analysis involving technical and economical simulations; therefore, the more detailed and sophisticated data collected in the energy audit which covers the entire systems, the more accurate and realistic results.

All the energy consuming systems/processes are aimed to be covered in this thesis within the above motivation. However, including each energy consumer in the energy auditing may not be possible due to the various factors and constraints such as lack of data, technical constraints, and so on; as a result, covering the entire energy consuming systems/processes may be impractical. Thus, the following criteria for the Target Energy Consuming Systems/Processes to be chosen can be kept in mind throughout the energy audit:

1. The magnitude of the energy consumption by the System/Process: Major energy users are given priority to be focused on because any positive improvements in their energy performance will significantly contribute to the overall plant performance.

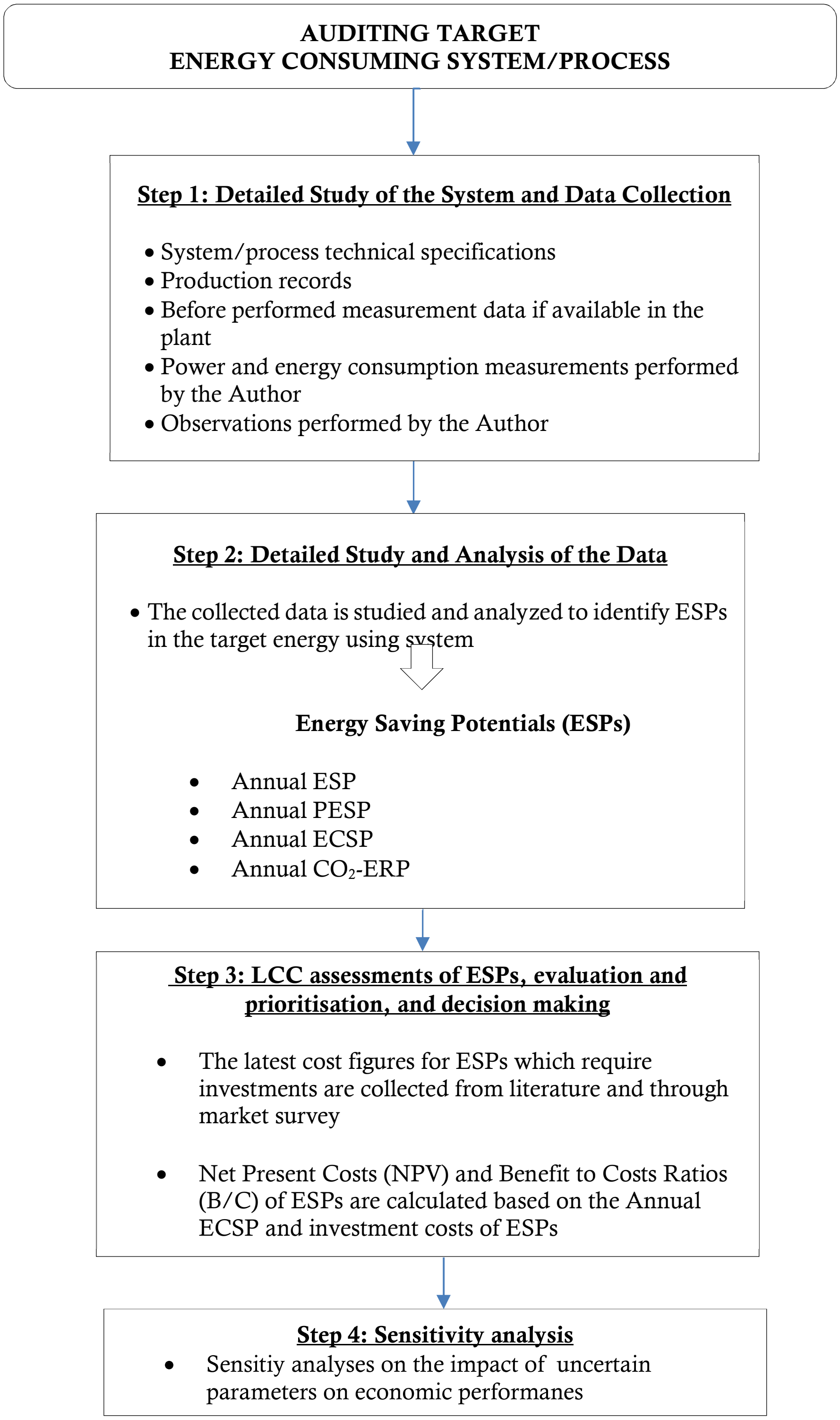
2. Availability and quality of the data: Availability and the quality of data on energy performance are crucial for choosing a system/process as a target because without data it is not possible to perform any analyses and accuracy of the energy performance analyses to a large extent depends on the quality of the available data. The more data available with high level of details easier to analyse the system performance and investigate the factors which influence the performance.

Also, it should be noted that electricity energy and electricity using systems/processes are primary focus of this study because it is the most valuable and expensive form of energy. Furthermore, the word “power” is also interchangeably used by “electricity” and “energy”.

3.4.1.2 PHASE 2: AUDITING TARGET ENERGY CONSUMING SYSTEMS

This phase aims to audit Target Energy Consuming Systems/Processes determined in the previous phase. The approach of the methodology for this phase is described in Figure 3-6 and it consists of three major steps within the following details:

- Step 1: Detailed study of the Target System/Process and data collection
- Step 2: Detailed study and analysis of the collected data
- Step 3: LCC assessments of ESPs, evaluation and prioritisation, and decision making
- Step 4 : Sensitivity analysis



AUDITING TARGET
ENERGY CONSUMING SYSTEM/PROCESS

Step 1: Detailed Study of the System and Data Collection

- System/process technical specifications
- Production records
- Before performed measurement data if available in the plant
- Power and energy consumption measurements performed by the Author
- Observations performed by the Author

Step 2: Detailed Study and Analysis of the Data

- The collected data is studied and analyzed to identify ESPs in the target energy using system

Energy Saving Potentials (ESPs)

- Annual ESP
- Annual PESP
- Annual ECSP
- Annual CO_2-ERP

Step 3: LCC assessments of ESPs, evaluation and prioritisation, and decision making

- The latest cost figures for ESPs which require investments are collected from literature and through market survey
- Net Present Costs (NPV) and Benefit to Costs Ratios (B/C) of ESPs are calculated based on the Annual ECSP and investment costs of ESPs

Step 4: Sensitivity analysis

- Sensitiy analyses on the impact of uncertain parameters on economic performanes

Figure 3-6: Approach of the methodology for identifying ESPs for the target energy consuming systems

3.4.1.2.1 Step 1: Detailed study of the target system/process

It is essential for an energy auditor to have a solid background information about an energy using system/process to be able to carry out an energy audit on it. For this reason, in this Step 1, the Target Energy Consuming System/Process is studied and understood.

To accurately identify and quantify any ESP on a system, it is first necessary to assess its present performance. For this reason, all the available data in the plant related to the target energy consuming system, which can be utilised for understanding and analysis of its baseline energy consumption performance, are gathered. Besides, if possible, power and energy measurements are conducted on the system. In fact, power and energy consumption measurement using a power and energy metering instrument is the most accurate method to directly quantify the baseline energy consumption of a system/process.

In this study, power and energy consumption profiles for the target system energy consumption for a certain period of duration, which is generally a production shift depending on the target energy consuming system, are conducted by using an advanced power and energy data logger, PEL 103 power and energy data logger from Chauvin Arnoux (CAP, 2017). PEL 103 uses a SD card for memory to record the measured data. This data is then transferred to a computer and can be visualised and processed through PEL transfer software Figure 3-7. It is also possible to export the logged data to MS Excell for further analyses. All power consumption measurements by PEL 103 in this study are conducted at 1 second resolution to gain a deeper understanding of the power consumption behaviour of energy consuming systems. In addition to PEL 103, the Author exploits any available power meters installed on the energy consuming system to be audited or the plant employs. These are mentioned in the relevant chapters.

Channel	Color	Cursor 1s MIN	Cursor MIN	Cursor AVG	Cursor MAX	Cursor 1s MAX	Window 1s MIN	Window MIN	Window AVG	Window MAX	Window 1s MAX
U12	■	400.8 V	401.8 V	401.8 V	401.8 V	403.2 V	381.1 V	393.9 V	401.8 V	408.1 V	412.4 V
U23	🟥	401 V	401.6 V	401.6 V	401.6 V	402.7 V	382.7 V	394.5 V	402.2 V	408.4 V	412.7 V
U31	🟦	403.7 V	404.6 V	404.6 V	404.6 V	405.6 V	383 V	397.2 V	404.9 V	410.9 V	415.2 V
I1	■	0 mA	2.377 A	2.377 A	2.377 A	9.653 A	0 mA	0 mA	42.42 A	137.4 A	445.1 A
I2	🟥	0 mA	3.442 A	3.442 A	3.442 A	19.24 A	0 mA	0 mA	41.13 A	123.4 A	367.1 A

Figure 3-7: A screenshot of PEL 103 transfer software

While conducting power/energy consumption measurement, the information of activity performed by the system/process is sometimes linked to the measured power/energy use to create a baseline performance indicator, such as kWh/kg.

In parallel to this, qualitative measurements such as observations on the operational practices that have a bearing on energy performance of the system/process and attitude/behaviour of the system operator towards energy efficiency are performed in order to see the impact of his/her impact on the enery efficiency. Thus, it is aimed to account for the impact of technical factors and human factors on the energy efficiency.

3.4.1.2.2 Step 2: Detailed study of the collected data and analysis

In this step, the collected data in Step 1 is studied and analysed. At this point, it is not possible to describe a specific analysis method because each system/process has different technical characteristics. In general, a pragmatic approach is followed in this thesis. In a sense, it can be said that brainstorming is performed on the theoretical information learnt from the literature about the system/process and the data collected in Step 1 to understand where, why, and how much energy is being consumed within the target and to create energy saving strategies. While doing this, some of the questions frequently asked can be listed as follows:

- Is the system/process using the available energy supply efficiently and how can this be determined?
- What is the theoretical energy use for this system/process?

- Is there any energy efficiency standard for this system/process?
- Are there any more energy efficient alternatives for this system/process?
- Is this system/process right sized for the application?
- Are there any energy efficiency technologies/measures for the system?
- Is benchmarking with any best practise values possible for the target system/process?
- Is the operator using the target system/process in accordance with the correct operating procedures?

The methods followed to identify an ESP in a target energy using system/process and the limitations and assumptions are explained in the corresponding chapters, in Chapter 6 and Chapter 7, devoted to the target energy using systems/processes in this thesis.

The outcome of the analysis in Step 2 is “Energy Saving Potential (ESP)”. An identified ESP is then converted to Annual ESP and Annual PESP (Primary Energy Saving Potential). Energy values are converted to Primary Energy based on the primary energy conversion factor (PECF) of the energy type. This is done so because it can provide comparison between different energy sources. For instance, 1 kWh electricity is equivalent to more than 1 kWh primary energy such as natural gas because some of primary energy is degraded and lost due to the irreversibility during power generation process. Also, it enables one to compare electricity values across countries. For example, primary energy value of the electricity generated by Turkey`s primary energy mix is different from that of another country. PECF of the electricity generated in Turkey is assumed as 2.43 (i.e. this value was determined by dividing Turkey`s primary energy consumption in a year to electricity generation in the same year) in the case study application of the proposed framework in this thesis. Annual PESP is calculated as follows:

$$\text{Annual PESP} = \text{Annual ESP} * \text{PECF} \tag{Eq. 3-1}$$

As it is well known, energy consumption means money for a plant. Therefore, saving energy will yield cost savings which motivates any energy intensive plant since energy cost makes significant share in the overall cost of the plant. Monetary benefits of an ESP are addressed as “Annual Energy Cost Saving Potential (ECSP)”. This is estimated as:

$$\text{Annual ECSP} = \text{Annual ESP} * \text{EUCR} \qquad \text{(Eq. 3-2)}$$

where;

EUCR is energy unit cost rate (€/kWh)

Annual ECSPs is then used in the Economic Evaluation of ESPs.

Environmental benefit of an ESP is addressed as “Annual CO_2 ERP (Emissions Reduction Potential)”. This is calculated based on CO_2-EF (CO_2-Emission Factor) of the energy type used. For CO_2-EF of electricity, a CO_2 -EF of Turkish electricity generation mix is assumed as 0.49 kg-CO_2/kWh is assumed based on (Enerdata, 2011). Annual CO_2-ERP is estimated as follows:

$$\text{Annual } CO_2 \text{ ERP} = \text{Annual ESP} * CO_2\text{-EF} \qquad \text{(Eq. 3-3)}$$

3.4.1.2.3 Step 3: Life cycle cost assessments of ESPs, evaluation and prioritisation, and decision making

Some of the identified ESPs, as a result of the energy audit, generally require an initial investment which will lead to future energy cost savings. For instance, replacing an electric motor with an energy efficient one will require initial capital cost while it will reduce future running costs (i.e. electricity cost) by using less energy. In addition to the initial cost, future maintenance and repair costs can be involved. In this respect, the cost-effectiveness of the investment should be assessed to see whether it will justify the initial expenditure or not. To do this, all the costs and benefits must be identified and added together.

While doing this, some cost and benefits can be tangible some can be intangible. Tangible costs are initial capital cost, operation or running costs and tangible benefits are energy cost savings. Intangible costs, on the other hand, can be company prestige, worker productivity increase, etc.

In this thesis, an economic analysis of the identified tangible ESPs which require capital investment will be carried out with net present value (NPV). NPV is the present value of all the benefits (i.e. energy cost savings) over the project life span minus the present value of all the costs of investment and operation. Future costs and savings over the project life time are discounted with interest to the today. Hence, the NPV provides an estimate of the net economic benefits if an investment is undertaken to save energy. The NPV is estimated as follows:

$$NPV = \sum_{t=1}^{T} (PVB - PVC)$$

(Eq. 3-4)

$$PVB = \sum_{t=1}^{T} \frac{(Annual\ ECSP, ARCs, SAVs, other\ savings)}{(1+i)^t}$$

(Eq. 3-5)

$$PVC = \sum_{t=1}^{T} \frac{(ICC, RCs, OC)}{(1+i)^t}$$

(Eq. 3-6)

where;

PVB is present value of the benefits (€).

PVC is present value of the costs (€).

ARCis avoided replacement costs (€).

RC is replacement cost (€).

OC is operation cost (€).

SAV is salvage values (€).

ICC is initial capital cost (€).

T is project life time (year).

i is discounted interested rate (%) .

PV is present value.

For an ESP to become economically feasible, NPV should be greater than zero. The ESPs with negative or zero NPV are deemed to be economically infeasible. Alternatively, Net Present Cost (NPC) can be used instead of NPV. The only difference between the NPV and NPC is in sign. The costs are positive while the benefits are negative within the NPC. Thus, the NPC for an ESP investment should be less than zero so that the revenues are greater than the costs throughout the project life span and the ESP with a negative NPC is deemed to be economically feasible. NPV is chosen as an economic feasibility parameter in this thesis.

To compare the economic performance of the ESPs with different initial capital costs, Benefit-to-Cost (B/C) ratio, which provides a ratio value by dividing the sum of the discounted benefits by the sum of the discounted costs, can be used to benchmark the alternatives. B/C ratio is expressed as follows:

$$\frac{B}{C} = \frac{PVB}{PVC}$$

(Eq. 3-7)

Regarding the case study application in this thesis, the basic economy parameters used in the NPV calculations are given in Table 3-1. A real interest rate, which is nominal interest minus the inflation rate, of 1.32 % is used. The initial cost and yearly savings are different for each ESP; therefore, they are given in Appendix D. The initial investment cost will be sum of the capital requirement to purchase the asset, installation labour cost, and transportation cost of the asset to the subject plant (if relevant), etc. Yearly savings will be the annual ECSP minus the operation costs. The operation cost is the sum of the repair and maintenance costs. These will be explicitly shown in Appendix D.

In addition to the above, the latest initial capital costs and operation costs together with the technical specification of the energy saving technologies are obtained from various suppliers by quotations. The Author of this thesis conducted a market survey and contacted to the technology suppliers. The suppliers will not be revealed. When it was not possible to get data from the suppliers, the estimations from the literature have been exploited. Also, the discussion with the subject plant management revealed that some works such as installation or repair of the equipment or technology could be carried out by the plant itself. Because the plant maintenance team are paid on a fixed month salary, the cost for such works is assumed to be zero. These are mentioned in the analysis in the corresponding sections.

Table 3-1**:** Basic parameters used in the NPV calculations in this thesis

Paremeter	Value	Source
Nominal interest rate (r)	8.82%	Central Bank of Turkey (TCMB, 2013)
Expected inflation rate (e)	7.40%	Central Bank of Turkey (TCMB, 2013)

3.4.1.2.4 Step 4: Sensitivity analysis

A sensitivity analysis is conducted to see the impact of following parameters on the economic feasibility of the ESPs:

- Discount rate: Because discount rate and expected inflation rate are assumed to be constant throughout the project life in LCC s, discount rate is chosen for sensitivity analysis.
- Electricity price: In NPV calculations in Equation 3-4, electricity prices are affected only by the inflation rate over the project lifetime despite the future of electricity prices is uncertain and it had an increasing trend over the last 8 years in Turkey. For this reason, a sensitivity analysis of increasing electricity prices is carried out.

3.4.2 MICROGRID APPLICATION METHODOLOGY

3.4.2.1 THE NEED FOR A HYBRID MICROGRID

A hybrid microgrid is a power generation system which incorporates at least two types of power technologies to supply power to local loads with the ability to operate either grid-connected or standalone (Fathima and Palanisamy, 2015; IEC, 2005).

Deploying microgrid, a local user can be partially or completely self-sufficient in terms of power supply. As discussed in Chapter 2, a manufacturing plant can generate its own electricity by deploying a microgrid onsite the plant which is comprised of distributed power generators such as wind turbines and solar PV modules, diesel generator, and appropriate storage and control system. Thus, they can integrate renewable energy into their power supply mix and reduce their dependence on the main electricity grid.

To understand and justify the need for a hybrid system, it is first necessary to comprehend the challenges arising from the renewable energy integration to a manufacturing plant. There can be defined two fundamental challenges: the first challenge arises from the intermittent nature of renewables which leads to a fluctuating power generation; while the second ensues from the highly volatile and dynamic nature of an energy intensive manufacturing plant that creates a very fluctuating power demand. Moreover, manufacturing plants often have limited space to accommodate distributed generation technologies such as wind and solar and this will limit the size of power generation capacity. Hence, supplying a highly volatile power requirement by using a fluctuating power source is a very challenging and complex task and needs additional technical and operational requirements. In this regard, the deployment of whether a single or multiple technology in a microgrid has a direct bearing on the cost structure and quality of the microgrid system. If a single technology is deployed, the power generator and other system components have to be sized big enough to ensure that the power generation always covers the power demand for a reliable power supply without any blackout. However, deployment of a single renewable technology can lead to an outsized system with an increased investment cost which will reduce the economic viability of the microgrid investment.

This is particularly of relevance in terms of renewable systems such as wind or solar. Renewable technologies, particularly in microgrids for industrial plant wide applications, will be subjected to space constraints. For example, the maximum PV system size for a manufacturing plant would be limited by the available roof space of the plant to array the PV modules. Therefore, a microgrid solely based on a limited capacity of PV system might not be enough to cover the required power demand.

Likewise, the available space in a typical manufacturing plant would usually allow only one or two wind turbines to be accommodated. Using multiple wind turbines to create power enough to satisfy the demand will require a great amount of space since there has to be a certain amount of clearance between wind turbines in order to minimise the mutual effect of rotor induced turbulence (Mathews, 2006). These can be overcome by using a very big wind turbine; however, its instant power production has to exceed the demand it is serving. This will require a gross over-capacity (Stott, 2010) increasing the investment cost significantly which will further adversely affect the cost of electricity generated. In addition to these, wind and solar energy are directly dependent on the location characteristics. Even if there is available space to accommodate PV modules or wind turbines, that particular location might not be rich enough in terms of wind potential, for instance. Even an oversized power system can deliver no electricity if there is not enough resource as it is case in PV power systems which cannot produce during night.

In addition to the above-mentioned aspects, an additional challenge with renewables is their variable and uncertain power output and non-dispatchability. As known, renewable power systems such as wind turbines and solar PVs generate electricity based on wind and solar energy which have a fluctuating and intermittent character in nature, producing a fluctuating power flow in the same way. For instance, a solar PV module reaches to its peak power generation during sunny hours whereas it produces zero electricity during night. Similarly, a wind turbine will not generate electricity if it is exposed to the wind slower than its cut-in speed while the power generation can reach to the turbine`s rated capacity at higher wind speeds. Besides, as neither the wind nor the solar radiation is available at a constant rate, the power output can be intermittent based on the wind speed or solar radiation value at a particular time interval. This means that the instant power and energy availability will be haphazardly volatile without regard to the demand it will supply. Owing to this, the variations in electricity generation do not match the time distribution of load demand on a continuous basis (Kaldellis, 2010). This causes the demand side to have almost no control over the power generation timing, presenting the non-dispacthable character of renewable systems. Dispacthable power systems such as utility grid or conventional systems like diesel generators, in contrast, are immediately available to dispatch power depending on their response speed whenever demanded or they can be scheduled to deliver electricity at a particular time. This is impossible in non-dispacthable renewable systems and creates another unique challenge of matching the supply and demand.

Further, if the power demand is volatile, too, as in manufacturing plants, this challenge is significantly increased and jeopardize the reliability of power supply. This calls for a management strategy to match power supply and demand and a technology option to stabilize the power generation based on renewables.

This challenge can be overcome by the integration of an energy storage technology into the microgrid. The fluctuations in electricity generation can be absorbed by storing the electricity when available and dispatched for use when demanded in a more stable way like conventional systems. However, especially in standalone (i.e. off-grid) applications where the microgrid is independent of the utility grid or it is destitute of some form of dispactable generation, there might be some situations where the electricity in the storage system are not enough to satisfy the demand and blackouts can take in place disturbing the manufacturing processes. The reliability of the system is questionable in such a case.

There are various operational and technical solutions to overcome these challenges. First, if using a single non-dispatchable renewable technology (or single source power unit) in a microgrid is not technically and economically feasible due to the aforesaid aspects, then reliance on a single technology should be avoided by diversifying the power supply mix. In spite of their intermittency and non-dispatchability, the renewables of solar and wind can be a quite complementary in terms of power generation fluctuations and installed capacity in most cases as shown by various studies (Gilau and Small, 2008; Katti and Khedkar, 2007; Mahmoudi et al., 2008). A mix of energy sources can accommodate seasonal and daily fluctuations (ARE, 2014). Therefore, hybridising a microgrid with the introduction of an appropriate blend of renewables complementing to each other may improve the technical and economic feasibility. However, this is still not enough to overcome the non-dispatchability that creates the problem of supply demand mismatch.

This is especially relevant for energy intensive manufacturing plants which hold space constraints for microgrid accommodation that will limit the installed power generation capacity but have a great energy requirement on the contrary. Thus, there is a conflict of high load demand and space constraints. For such applications, even though the space requirement is satisfied, a standalone system with 100% renewables needs an excessively large-scale system size in comparison to a conventional power system for the same application. By oversizing, large amounts of electricity exceeding the actual demand can be produced and stored to provide electricity when the power generators cannot produce electricity. A microgrid can be 100% self-sufficient in this way. However, energy storage systems and renewable energy technologies are already capital investment. Such a massive power system for an energy intensive application will require enormous capital cost and thus result in high electricity price. Therefore, a hybrid system should have some form of dispactable power supply which can be via a distributed power generator such as utility grid. With proper arrangements, a microgrid can be linked to the utility grid (i.e. main grid) whenever it is needed. It can also disconnect automatically and operate its own when necessary. In this regard, the systems which are integrated with the utility grid are named as "grid connected" whereas those which are independent from the utility grid are called as "standalone" or "off-grid systems".

In addition to the above, the presence of energy storage and a microgrid controller can facilitate the performing some demand response measures such as peak shaving or load shifting by taking the advantage of time-of-use tariffs. For instance, renewable based electricity can be stored and use to shave the peak loads by releasing peak load times. Likewise, grid electricity can be stored during low price times (off-peak hours) and used during high price – high demand times (on-peak hours). Therefore, demand response participation potential when investigating the microgrid application for a manufacturing plant should be considered, as well, as it may contribute to the feasibility of the application through reduced costs.

In line with the above explainations, microgrid design for a manufacturing basically includes a demand side (i.e. load) and a supply side (i.e. microgrid components including power generators, storage, and control system). The demand side represents overall energy consumption of the manufacturing plant. The supply side is comprised of microgrid components renewable generators and/or non-renewable generators such as a diesel generator, utility grid for grid-connected microgrid designs, and energy storage through the use of energy storage systems such as batteries. Besides, a control system, which can be considered as a component in the supply side, is required to provide communication between the load and microgrid components and dispatch the power to the load.

3.4.2.2 METHODOLOGY

As it has been discussed in the preceding subsection, renewable energy integration for a manufacturing plant through the imperative application of a microgrid for an energy intesive manufacturing plant is a very challenging task. In line with the grounds that have been explained in the preceding subsection, three major challenges can be given:

- uncertain and intermittent nature of renewables
- dynamic and volatile nature of the power demand of an energy intensive manufacturing plant
- limited plant space to accommodate distributed renewable energy generators

These challenges necessisiates the hybridising a microgrid with various energy forms either renewable or conventional forms. However, while the above challenges call for the application of a hybrid microgrid, those challenges, coupled with high number of technical and economic parameters that must be borne in mind for the optimum design, also increases the complexity in optimum designing a hybrid microgrid compared to a single energy generation system. As a result of these, the hybrid systems are more difficult to be designed and analyzed (Zhou et al., 2010).

Although there are a number of motivational drivers such as regulative & legislative pressurres and market demand for environmentally friendly products as explained before, an attempt to undertake a microgrid investment for a manufacturing company can be, first of all, motivated by economic considerations. Therefore, an investment to be made in a hybrid microgrid application that is capable of supplying power to a manufacturing plant on a reliable manner should be economically feasible. In other words, having ensured that a particular microgrid design is technically feasible for a particular application (e.g. manufacturing plant), its economic performance should also be feasible.

The optimum design in terms of cost-effectiveness and reliability of a hybrid microgrid with renewables, whether standalone or grid-connected, strongly relate to the load demand character of a plant (i.e. magnitude, constant or variable demand, and demand timing, etc.), renewable energy potential and availability at the microgrid site such as wind and solar power, the technical and economical specifications of power technologies used in the microgrid system, and the plant technical constraints such as the avaliable area to accommodate power generators. Depending on these factors, there can be a large number of microgrid configurations with different technical and economical performances. Each sub-system of the microgrid can highly vary in size and architecture which will affect the cost structure which in turn affect the price of electricity produced and the quality of the power supply. Accordingly, it can be said that there is no single microgrid solution for a particular application.

In line with the above, a sizing optimisation is required in order to determine and choose the most reliable and cost-effective microgrid configuration that can supply power for a manufacturing plant amongst a number of microgrid configurations. In other words, **a techno-economically optimal sized microgrid which will produce and supply power to the manufacturing plant on a reliable manner and satisfy the constraints at the lowest cost should be determined**. Because a hybrid microgrid is comprised of several components, the optimum size of each component should be determined in terms of the techno-economic feasibility of the overall microgrid design.

As well as the supply side which represents the power generation side (i.e. microgrid components such as the generators and storage), the optimisation study should also consider the demand side and operational strategy. As noted earlier, the load demand character of a plant is one of the important parameters that have a bearing on the optimum design of a microgrid as the generators and associated components of the microgrid will be sized so as to supply the demand on a reliable manner. Therefore, energy efficiency is of paramount importance and the energy efficiency potentials within the manufacturing plant should be factored into a microgrid investment planning as the reduction in load demand of the plant will contribute to the economic performance of the investment. In addition to these, the contribution of demand response participation as an operational strategy to the microgrid design optimisation should be assessed.

3.4.2.2.1 Optimisation problem and objective function

In line with the above, the overall objective is to minimize the life-cycle cost of the microgrid investment that is technically feasible. In other words, the objective is to identify the microgrid configuration with the lowest total NPC or the highest total NPV. Therefore, the optimisation problem is a cost objective optimisation and the objective function will be to minimise the total NPC or maximise the total NPV. Because NPV is used in this thesis as noted in Section 3.4.1.2.3, the objective function will be based on NPV.

As defined in Section 3.4.1.2.3, NPV is the present value of all the benefits such as energy cost savings and other avoided costs such as the replacement costs over the project life span minus the present value of all the costs of investment and operation. The equation to calculate the NPV for ESPs in the energy audit methodology was given by Equation 3-4. Equation 3-4 is used to evaluate the cost-effectiveness of investing in a single ESP which usually involves one or two energy saving equipment or device. As for the microgrid investment, a microgrid consists of several components with different technical and economic specifications, and economic performance of a microgrid configuration can vary with varying component sizes and techno-economic specifications. As such, the overall NPV of a microgrid system configuration will be the sum of NPV of each component in that microgrid configuration. In a microgrid investment, the costs will include ICCs, RCs, OC, fuel costs (FC), and cost of grid purchase (GP) (for grid-connected microgrid configurations). The benefits include, grid cost savings (GCS), grid sale incomes (GSI) (for grid-connected microgrid configurations), and SAV. Therefore, Equation 3-4 can be rewritten for a microgrid investment as follows:

$$NPV = -NPC = \sum_{i=1}^{N} PVB - \sum_{i=1}^{N} PVC$$

(Eq. 3-8)

Where; N is number of microgrid components such as generators. PVB and PVC can be expressed by using Equation 3-9 and Equation 3-10 as follows:

$$PVB = \sum_{t=1}^{T} \frac{(GCS, GSI, SAVs\ )}{(1+i)^t}$$

(Eq. 3-9)

and

$$PVC = \sum_{t=1}^{T} \frac{(ICC, RCs, OC, FC, GP\ )}{(1+i)^t}$$

(Eq. 3-10)

Thus, substituting Equation 3-9 and Equation 3-10 to Equation 3-8:

$$NPV = \sum_{i=1}^{N}(\sum_{t=1}^{T} \frac{(GCS, GSI, SAVs\ )}{(1+i)^t}) - \sum_{i=1}^{N}(\sum_{t=1}^{T} \frac{(ICC, RCs, OC, FC, GP\ )}{(1+i)^t})$$

(Eq. 3-11)

Thus, the objective function can be expressed as follows:

$$maximise\ (NPV) = maximise\ (\sum_{i=1}^{N}(\sum_{t=1}^{T}\frac{(GCS, GSI, SAVs\ )}{(1+i)^t}) - \sum_{i=1}^{N}(\sum_{t=1}^{T}\frac{(ICC, RCs, OC, FC, GP\ )}{(1+i)^t}))$$

(Eq. 3-12)

The objective function can be subjected to various contraints such as the number the number/size/capacity of microgrid components or maximum grid demand. The constraints can vary from one problem to another and they must be taken into account while modelling the system components as it is described in Section 3.4.2.5.

3.4.2.3 Simulation and optimisation with HOMER

Emaneting from the complexities already mentioned before, the techno-economic feasibility assessments of microgrid investments require very complex and extensive algorithms, and costly physical experiments. Instead of or together with these, advanced simulation tools that are proven to be reliable can be used for convenience (Al Garni et al., 2018). HOMER microgrid simulation and optimization software is the most popular tool used by many researchers (Al Garni et al., 2018; Bekele, 2009; Montuori et al., 2014; Sen and Bhattacharyya, 2014) in the field of renewable energy microgrid applications because it is capable of handling of different simulation scenarios and performing optimization and sensitivity analysis (Bahramara et al., 2016). These features of HOMER provide its users with the ability to model and compare very different microgrid configurations and thus overcome the challenges due to the large number of design parameters and uncertainties (Al Garni et al., 2018; Hafez and Bhattacharya, 2012). A variety of standalone and grid-connected microgrid design options with various combination of power generation technologies including wind turbines and PVs, diesel generators, batteries, etc. can be modelled and evaluated with regards to their technical and economic merits by employing HOMER. HOMER was evaluated as one of the most applicable computer tool for optimisation, feasibility, and sensitibity analysis of both standalone and grid-connected microgrid designs in a comparative study of 68 computer tools conducted by (Connolly et al., 2010).

Considering these facts, HOMER microgrid modelling, simulation and optimisation software is adopted in the proposed energy management framework in this thesis in order for manufacturing plants to model and determine the most reliable and cost-effective renewables-based hybrid microgrid configuration with/without DR participation that can supply clean power for them.

3.4.2.4 HOMER's approach

HOMER basically carries out three fundamental tasks: simulation; optimisation; and sensitivity analysis (Figure 3-8). Taking into the account of the inputs such as energy source data, system components together with their technical and economical specifications, constraints, and electric load demand, HOMER simulates 1 year of system production of all combinations of input technology/components sizes to supply the input electricity load. This is followed by the optimisation step which searches different microgrid configurations that meet the technical and economic criteria. The annual costs for the 1-year simulation of each technically feasible system is then extrapolated over the project lifespan and discounted based on the input discount rate. From this, the NPV for each technically feasible system are calculated. Then, the technically feasible microgrid configurations are ranked with regards their NPV (Lambert et al., 2006; Menictas, et al., 2014). Following the optimisation, the sensitivity analysis investigates the effects of different input parameters in the specified ranges on the system costs. This helps a modeller to see and quantify the effects of uncertainty or changes or different assumptions in the design variables such as component costs or the average wind speeds. (Lambert et al., 2006; Dalton et al., 2009).

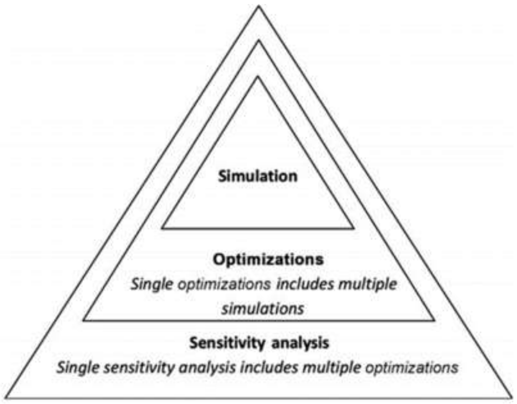


Figure 3-8: Relationships of HOMER simulation, optimizations, sensitiviy analysis (Menictas, et al., 2014)

HOMER lists the main optimization output results which include the size and combination of microgrid components (i.e. microgrid architecture), system renewable faction of load (%), system CO_2 emissions (kg/year), battery throughput, amount of energy purchased and sold to the grid (kWh), power generated by each generator (kWh), diesel generator hours (hr), and economic parameters such as cost of energy (COE) (€/kWh), initial capital (€), operating cost (€/year), total NPV (€). By means of system designs and tecno-economic outputs, one can evaluate and compare each system to other systems and the base case system (Dalton et al., 2009b; Lambert et al., 2006; Soshinskaya, 2013).

To compare the microgrid options with different initial investment cost, B/C ratio given in Equation 3-6 can be used.

The levelized cost of energy (LCOE) is an important economic parameter that indicates the cost of energy generated by the microgrid. This value can be compared with the existing unit cost of energy (i.e. utility grid LCOE is calculated by the following equation (Lambert et al., 2006):

$$LCOE=,Cann,tot-Etot+Egrid,sale.$$

(Eq.3-13)

where;

Etot is the total amounts load which the microgrid serves per year.

Egrid, sales is the amount of energy sold to the grid per year.

3.4.2.4.1 Optimisation Variables

An optimisation variable is a variable of which optimal value is determined during the course the optimisation process (HOMER, 2018). The simulation is run for each different value of each decision variable. Based on this fact, different values (i.e. size, number, or capacity) of microgrid components (i.e. decision variables) can be specified so that the simulation is run for each of the specified values of each decision variable in each time step of simulation (i.e. each hour of the year) so as to find the most efficient microgrid configuration amongst all possible configurations.

The optimisation variables in HOMER microgrid modelling are:

- the number/size/capacity of microgrid components.
- the number/size/capacity of each generator.
- the number/size/capacity of converter.
- the maximum grid demand (for grid-connected microgrid configurations).

A modeller using HOMER can specify various values for each decision variable by defining a set of decision variable values in Search Space Option of component modelling in HOMER (Figure

3-9) so that HOMER searches to locate the optimal system (HOMER, 2018). Alternatively, insead of defining values in the Search Space, the HOMER Optimizer can be enabled and used. The modeler needs to define only the upper and lower bounds so that the HOMER Optimizer compares the quantities between those limits and finds the optimum (HOMER, 2018).

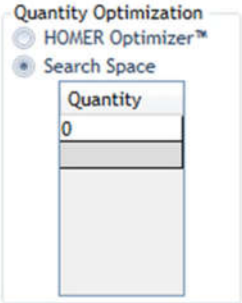


Figure 3-9: Defining values in Search Space (HOMER, 2018)

3.4.2.5 Methodology followed with the proposed framework

The flow diagram of the methodology to achieve the most reliable and cost-effective microgrid configuration as a part of the proposed energy management framework is summarised as shown in Figure 3-10 within the following steps:

1. Electricity consumption of the plant is modelled based on the power measurements conducted by the author and various data collected during the energy audit.
2. Energy supply options to the plant are identified and microgrid components are modelled based on their technical and economic specifications. Microgrid components include renewable generators, a wind turbine and PV modules, an energy storage system, a diesel generator, converter, grid, micro controller systems.
3. Demand response measures that suits for the subject plant are selected and modelled.
4. Various energy efficiency scenarios are defined and modelled to see the impact of energy efficiency on technical and economic feasibility of the project.
5. Project economics and system constraints are defined.
6. Microgrid simulations are performed based on the various scenarios grid-connected and standalone microgrid scenarios modelled based on the design data
7. Results: techno-economic potentials are obtained from simulation and optimisation results.
8. Sensitivity analyses are conducted to see the uncertainties of some parameters.

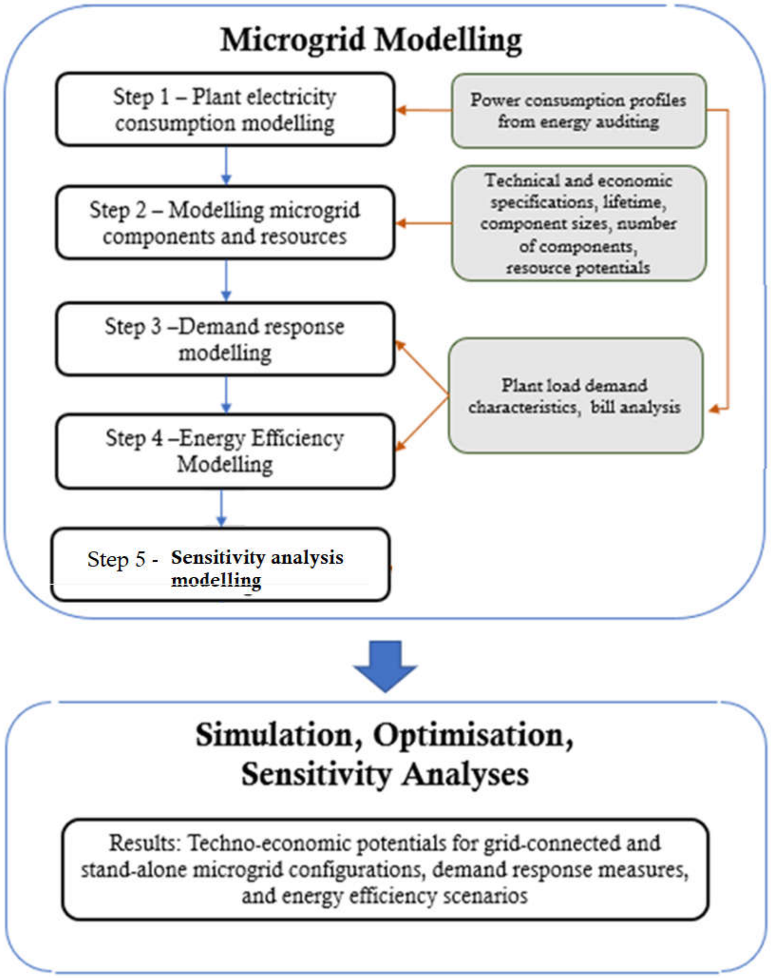


Figure 3-10: Methodology flow diagram for microgrid feasibility

3.4.2.5.1 Plant electricity consumption modelling (STEP 1)

The accuracy of power demand data both in terms of magnitude and distribution is very important as this will directly affect the feasibility of the microgrid investment. Therefore, it is essential to produce a typical electricity load curve which represents the entire manufacturing plant power demand.

The power demand of a manufacturing plant that the microgrid in design will supply power to can be modelled based on the real-time consumption measurement as this is the most accurate data. The real-time power demand over a certain period (i.e. a typical production day of 24 hours) can be obtained through recording the instantaneous power demand of the entire plant. If this is technically not possible, a bottom-up approach can be followed by recording the power demand of each energy consuming systems of the plant over a day and their sum will give the overall plant power demand.

In the proposed framework, power demand of the entire manufacturing plant is modelled using a bottom-up approach. All specific load curves of individual users are generated by conducting power consumption measurements of each individual users for a typical production day over a 24-hours period during the energy audit. They are then augmented together, and a high resolution aggregated electric load representing the manufacturing plant daily power demand is generated (Figure 3-11). This data is then defined in HOMER as "load" that the microgrid will serve.

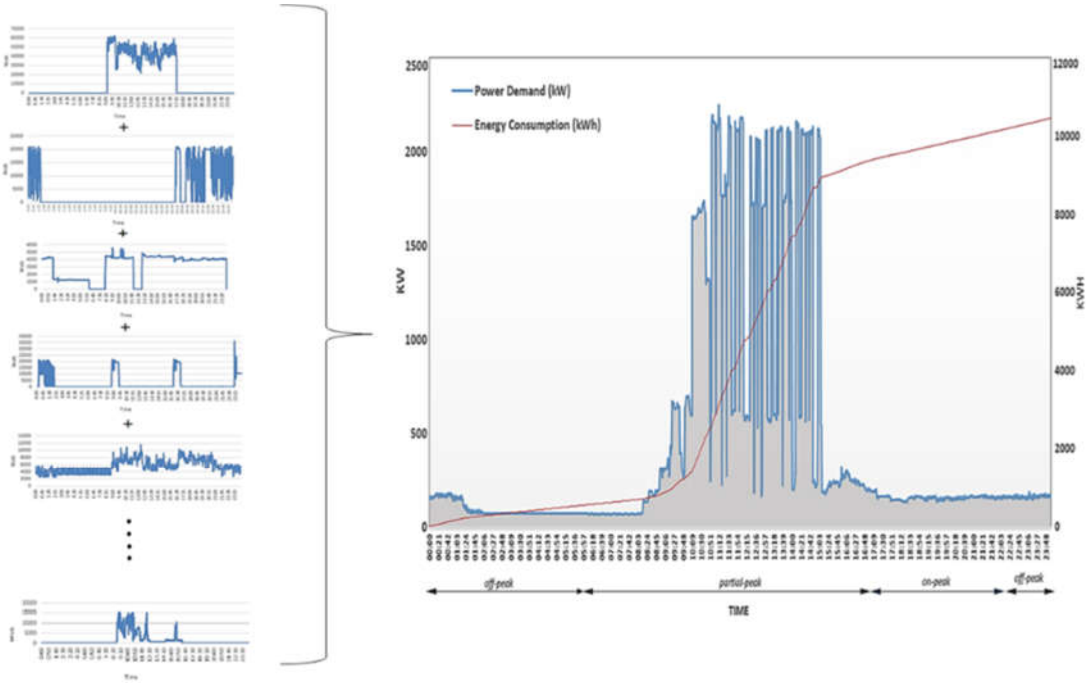


Figure 3-11: Creating a representative plant load demand from measured individual loads

3.4.2.5.2 Modelling microgrid components and sources (STEP 2)

A component in a microgrid is any element of a microgrid which generators, delivers, converts, or stores energy (Lambert et al., 2006). The generators can be renewable energy generators such as a wind turbine and non-renewable generators such as a diesel generator. Besides, as stated earlier above, a microgrid can be either grid-connected or standalone. Therefore, a grid is needed as a component in grid-connected microgrid design configurations.

The optimum microgrid system will produce power based on the best combination of renewable and non-renewable energy resources. Two renewable energy resources are chosen for implementation in the proposed framework: wind and solar power indigenous based on local resources. Therefore, PV modules and wind turbines are considered as system components and be modelled accordingly. As non–renewable energy resources, diesel generator and utility grid are considered and modelled. The hope would be a power generation system based on solely renewable energy resources in terms of environmental considerations. However, as discussed previously, the intermittent nature of renewable sources can result in inadequate power supply with respect to the demand and require capital intensive storage/battery requirements. To avoid this problem, it may be required to consider conventional power supply options of diesel generation and utility grid based on non-renewable resources. The simulations of the microgrid configurations will try to find out the most reliable and cost-effective blend of these options with regards to NPV as described previously.

Thus, the following components are required to build a hybrid microgrid:

1. renewable energy generators (to integrate renewable energy (i.e. wind turbine, and solar PV)).
2. utility grid (for grid-connected microgrid configuratons).
3. diesel generator (as a backup generator in case of shortages).
4. energy storage (for a stable power output and demand response participation).
5. microgrid controller system.

3.4.2.5.2.1 Wind power and wind turbine

The kinetic energy available in the wind is harvested by the wind turbines with a rotor and blades and it is transferred it to a rotating shaft in the form of mechanical energy. The mechanical energy in the rotating shaft is then used to drive an electric generator to produce electricity energy. This conversion process is highly dependent on the efficiency of the rotor. The power available in the wind flow passing through a wind turbine rotar is calculated as follows:

$$Pw = ½ * \rho * A * {V^3}_{wind}$$

(Eq. 3-14)

where;

ρ	is air density (kg / m^3).
V$_{,wind}$	is wind speed (m/s).
A	is cross sectional area (or swept area) of the wind turbine rotor(m^2).

Equation 3-14 gives the theoretical power available in the wind flow. As seen, the available power in the wind stream is directly dependent to the parameters of the air density, area of the wind turbine rotor, and the wind velocity. Among these parameters the wind speed has an outstanding effect over the available power because the power increases as the cube of wind speed. If the wind speed is doubled, the power increases 8 times. This clearly shows the importance of wind speed, thus the location, in wind power projects. For the same power, rotor area can be reduced by a factor of 8 when the wind turbine is installed in a location with double wind speed (Ackermann, 2012; Mathews, 2006). This results in significant cost saving.

While predicting the theoretically available wind power by using Equation 3-14, it is of importance to note that average wind speed cannot be used directly. This is because of the nonlinear relationship between power and wind speed as seen in Equation 3-14. The average of the cubes of wind speeds will be greater than the cube of the average wind speed. Rather than calculating the power corresponding to the average speed, the power corresponding to individual speeds should be calculated and the average power should be taken (Ackermann, 2012; Mathews, 2006).

The theoretically available power in the wind flow cannot be completely harvested by the wind turbine. The maximum energy that can be captured from the wind flow is expressed by Betz`s limit which is 59.3% of the available wind power. Betz`s limit cannot be achieved by a wind turbine due to the rotor efficiency, frictional losses, blade surface roughness, etc. It can only be approached. Actual energy captured from the wind and converted by the turbine rotor is determined by the wind turbine efficiency which is named as the power coefficient (Cp). It is defined as the ratio of power extracted by the wind turbine rotor to the available power in the wind (Ackermann, 2012; Mathews, 2006):

$$Cp = \frac{Pt}{Pw}$$

Hence,

$$Pt = Cp * Pw$$

(Eq. 3-15)

Substituting Equation 15 in 16 gives:

$$Pt = Cp * ½ * \rho * A * V^3{}_{wind}$$

(Eq. 3-16)

As seen in Equation 3-15 and 3-16, the actual energy extracted from wind flow depends on wind speed, rotor swept area, air density and turbine power coefficient which is always less than Betz`s limit. Cp is provided by wind turbine manufacturers.

Another important factor affecting the performance of a wind turbine is its response to various wind speeds. The overall power performance of the wind turbine is shown by its power curve. In other words, the power curve reflects the power output in response to various wind speeds based on the aerodynamic, transmission and generation efficiency of the wind turbine.

Modelling a wind turbine in HOMER

HOMER calculates the power output of a wind turbine in a four step process (Lambert et al., 2006):

- The average speed for the hour at the anemometer height is determined by refering to the wind resource data. Wind source data at the anemometer height is specificed to HOMER by the user/modeller.

- HOMER converts the wind speeds at the anemometer height to the wind speed at the turbine`s hub height. Such conversion is required due to the fact that wind speed increases with height due to wind shear (friction of the air with the earth`s surface) and this will improve the power input to the turbine rotor depending on the surface roughness of the ground (Mathews, 2006). The wind speed at the turbine`s hub height is calculated using the logaritmic law. HOMER uses the following equation for wind speed adjustment between two different heights (Lambert, 2009).

$$\frac{U_{hub}}{U_{anem}} = \frac{\ln(Z_{hub}/z_0)}{\ln(Z_{anem}/z_0)}$$

(Eq. 3-17)

where;

U_{hub} is the wind speed at the hub height of the wind turbine (m/s).

U_{anem} is the wind speed at the anemometer height (m/s).

Z_{hub} is the hub height of the wind turbine (m).

Z_{anem} is the anemometer height (m).

zo is the surface roughness length (m)

ln (..) is the natural algorithm.

- After determining the wind speed values at the hub height, HOMER calculates the power output of the wind turbine referring to its power curve. Power curves are supplied by manufacturers.

- Power curves typically specify wind turbine performance under standard temperature and pressure conditions. The air will have a standard density of 1.225 kg/m^3 at these conditions. As discusses previously, density is one of the factors that have a direct bearing on the kinetic energy of wind. At higher altitudes air will be less dense and the available power in the wind will decrease. This difference between the actual air density and the air density at which the power curve applies has to be taken into account. To account for this, HOMER multiplies the power value predicted by the power curve by the air density ratio, using the following ratio (Lambert, 2009):

$$P_{WTG} = \left(\frac{\rho}{\rho o}\right) . P_{WTG,STP}$$

(Eq. 3-18)

where;

P_{WTG} is the wind turbine power output (kW).

$P_{WTG,\,STP}$ is the wind turbine power output at standard temperature and pressure (kW).

ρ is the actual air density (kg/m^3).

ρ_o is the air density at standard temperature and pressure (kg/m^3).

In order for HOMER to follow the above described procedure and calculate the wind power output, the data presented in Table 3-2 are specified as input to HOMER`s wind turbine modelling window.

Table 3-2: Wind turbine technical specifications (HOMER, 2018)

Parameter
Wind turbine power curve data
Hub height
Turbine losses
Turbine life time
AC or DC output

A user/modeller can collect these data from a manufacturer/supplier and enter these data to model a wind turbine to be used in his/her microgrid design. Alternatively, a wind turbine can be chosen from HOMER`s component library. It is possible to enter several quantities of wind turbine in HOMER`s search space so that HOMER can consider these for system optimisation by simulation the microgrid performance for each quantity. If the wind turbine generates DC power, a converter should be added to the system to convert the power to AC. In addition to the technical specifications, economic parameters for each wind turbine are specified for economic modelling. These are presented in Table 3-3.

Table 3-3: Economic modelling parameters for wind turbine (HOMER, 2018)

Parameter	**Description**
Capital cost	the initial purchase price of the wind turbine
Replacement cost	the cost of replacing the wind turbine at the end of its lifetime
O & M (operating and maintanence) cost	the annual cost of operating and maintaining the wind turbine

In addition to the wind turbine technical and economic specifications modelling, wind resource data with any time step (down to 1 minute) is required to be imported to HOMER while modelling the wind turbine component. Therefore, it is essential to determine the wind power potential in the plant location where the microgrid is to be established. According to Manwell et al. (2009), locations with average annual speed of more than 5.6 m/s are suited for wind power generation. The wind speed data can be obtained through onsite measurements or readily available wind speed data can be obtained from meterological stations in close promixity to the plant location. Meanwhile, the plant constraints should be determined so as to identify how many turbines can be accommodited in the plant.

Furthermore, the altitute in meters above sea level and anemometer height above the ground at which the wind speed data were measured must also be defined in HOMER (HOMER, 2018).

3.4.2.5.2.2 Solar PV and PV systems

In solar PV technology, the sun`s radiating energy (radiated light) is directly converted into electricity. This is achieved by means of PV modules (or panels) composed of solar PV cells which contain photovoltaic materials that generate electricity when exposed to the sunlight. When the sunlight is absorbed by a PV cell, the sunlight gives energy to some electrons in the PV cell, thereby increasing their energy to an adequate level and freeing them. These electrons produce a voltage which in turn used to drive a current through a circuit because of the built in potential barrier in the cell (Parida et al., 2011).

PV cells are connected in series so as to form a PV module. By this means, power generation capacity is increased as PV cells on their own have limited capacity to produce electricity. When they are connected in series, their voltage are added up, but the current remains the same as that of a single cell. Also, PV modules are connected in series and parallel in order to obtain an adequate or desired installed power ideal for the intended application. Modules connected in series build up a string and strings are joint in parallel to make an array.

<u>*Modelling PV in HOMER*</u>

Solar PV system in a microgrid project in HOMER is modelled as a component. HOMER estimates the power output of a PV module by using the following equation (Lambert, 2012):

$$P_{PV} = Y_{PV}.f_{PV}.\left(\frac{G_T}{G_{T,STC}}\right).[1 + \alpha P.(T_C - T_C)]$$

(Eq. 3-19)

where;

Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions [kW].

f_{PV} is the PV derating factor [%].

GT is the solar radiation incident on the PV array in the current time step [kW/m^2].

GT,STC is the incident raditation at standard test conditions [1kW/m^2].

αP is the temperature coefficient of power [%/°C].

Tc is the PV cell temperature in the current time step [°C]

Tc, STC is the PV cell temperature under standard test conditions [25°C]

Tc, the PV cell real temperature in the current time step is calculated based on the following equation (Lambert, 2012):

$$Tc = \frac{Ta + (Tc,NOCT - Ta,NOCT)\left(\frac{GT}{GT,NOCT}\right)\left[1 - \frac{\eta mp,STC.(1 - \alpha pTc,STC)}{\tau\alpha}\right]}{1 + (Tc,NOCT - Ta,NOCT)\left(\frac{GT}{GT,NOCT}\right)\frac{\alpha p.\eta mp,STC}{\tau.\alpha}}$$

(Eq. 3-20)

where;

Ta is the ambient temperature [°C].

Tc, NOCT is the nominal operating cell temperature [°C].

Ta, NOCT is the ambient temperature at which the NOCT is defined [20°C].

GT, NOCT is the solar radiation at which the NOCT is defined [0.8 kW/m^2].

ηmp, STC is the electrical conversion efficiency of the PV array at maximum power [%].

τ is the solar transmittance of any cover over the PV array [%].

As seen in Equation 3-10, the actual power output of a PV module depends on various factors. The major factor among them is the solar radiation incident on the PV module surface, GT. HOMER simulates GT from the global radiation (G) data which is the total amount of solar radiation striking the Earth`s surface (Lambert, 2009). More information as to how GT is calculated can be found in (Duffie and Beckman, 2013; HOMER, 2018).

In order for HOMER to simulate the performance of a PV system, appropriate data for technical and economic parameters are required to be specified as input in HOMER`s PV system modelling window. For example, the technical and economic specifications for PV panels chosen for microgrid design are needed. A modeller can search for a PV panel from the market and its specifications can be used. Alteratively, a PV panel can be chosen from HOMER`s component library together with its technical and economic specifications. The required parameteres for PV panel modelling are summarised in Table 3-4. There parameters can be obtained from the manufacturer of the chosen PV panel or there are readily available in HOMER if the PV panel is chosen from HOMER`s libray.

In addition to the above parameters, other parameters required to be specified and their descriptions are presented in Table 3-5. Panel slope and panel azimuth are dependent on the place geometry where the PV panels are to be arrayed. As well as technical parameters, economic parameters are needed. These are summarised in Table 3-6.

Table 3-4: PV system technical specifications (HOMER, 2018).

Variable	Description
Temperature Coefficient of Power	A number indicating how strongly the power output of the PV array depends on cell temperature, in %/degrees Celsius
Nominal Operating Cell Temperature	The cell temperature at 0.8 kW/m2 and 20°C ambient temperature in degrees Celsius
Efficiency at Standard Test Conditions	The maximum power point efficiency under standard test conditions, in %
Life time	The number of years before the PV panels must be replaced

Table 3-5: Parameters to be specified in HOMER PV modelling and their desription (HOMER, 2018)

Variable	Description
Ground Reflectance	The fraction of solar radiation incident on the ground that is reflected, in %
Tracking System	The type of tracking system used to direct the PV panels towards the sun
Use default slope	If this input is checked, the slope input is disabled, and the slope is set to match the latitude
Panel Slope	The angle at which the panels are mounted relative to horizontal, in degrees
Use default azimuth	If this input is checked, the azimuth input is disabled, and the azimuth is set to 0 or 180 degrees for projects in the northern or southern hemisphere, respectively
Panel Azimuth	The direction towards which the panels face, in degrees

Table 3-6: Parameters to be specified in HOMER PV modelling and their desription (HOMER, 2018)

Parameter	Description
Capital cost (€)	the initial purchase price of the PV system
Replacement cost (€)	the cost of replacing the PV system at the end of its lifetime
O & M cost (€/year)	the annual cost of operating and maintaining the PV system

PV panels produce DC power. Therefore, an inverter is required to convert DC to AC, thus a converter is required to be added to the system and modelled. As stated above, HOMER uses the solar global horizontal irradiation (GHI) to calculate the PV array power output. Therefore, the GHI resourse data is required to be specified as input to HOMER.

3.4.2.5.2.3 Energy storage

Electricity cannot be directly stored. However, it can be converted to another storable energy form and then it can be reconverted to electricity whenever it is demanded. Electricity energy can be converted into various storable energy forms such as chemical, electro-chemical, mechanical, electromagnetic, thermal, etc.; therefore, there exists a variety of energy storage technologies. Each storage technology has relative advantages and disadvantages over each other. "The power (kW) and energy capacity (kWh) of the system normally dictates how well suited a particular technology is for specific applications (Menictas, et al., 2014)". While some are more suitable for energy applications, some are suitable for power applications. There are also some storage technologies who can satisfy the both applications. Therefore, energy storage applications fall basically into two main categories: power applications and energy applications. (Carnegie et al., 2013).

Power applications usually require high power output in relatively short timescale such as a few seconds to a few minutes so as to perform basic functions such as sag compensation, power smoothing, grid stabilisation and frequency regulation. Energy storage technologies in this category usually have capacity to store fairly modest amounts of energy per kW of rated power output (Eyer and Corey, 2010). In other words, while power output is high in short time, energy output is modest. On the other hand, energy applications require relatively large amounts of energy in charge/discharge cycles of long time scale such as many minutes to hours so as to fulfil energy management functions such as peak shaving.

This research tries to find out to what extend the subject plant can be self-sufficient for electricity by integrating renewable energy into a microgrid as well as which demand response techniques can be used. For a microgrid, the energy storage system should be capable of high power in a long time scale (Xin Qiu et al., 2014) as it is the partial or sole energy supplier for a load. Furthermore, the plant wide application requires an energy storage system not to be site specific like hydro or compressed air storage technologies. Therefore, an energy storage technology capable of providing both energy and power application is relevant for the aim of this study.

Electrochemical energy storage technologies basically convert electrical energy into chemical energy and stored within the batteries. Electrochemical batteries are traditionally classified into two main groups based on whether they can be recharged or not: primary and secondary batteries (Menictas, et al., 2014). Primary batteries cannot be recharged after discharge; and therefore, are not considered as energy storage devices. On the other hand, a secondary battery can be recharged; therefore, considered as energy storage device. Hereupon, a battery will refer to the type of secondary battery in this study.

Batteries offers many advantages. For instance, they can be sited anywhere, and they are modular, so they can be used in applications ranging from a few kWh to several MWh. They have millisecond response times; thus, they can be used simultaneously for both power quality and energy management applications (Skyllas-Kazacos et al., 2011).

The most common battery types available in the market are:

- lead-acid batteries.
- lithium-ion batteries.
- sodium sulphur batteries.
- flow batteries.

Flow batteries, also called as Redox Flow Batteries, are highly efficient and flexible electrochemical energy storage devices. As seen in Figure 3-12, a redox (reduction-oxidation) flow battery comprises of flow type cell, electrolyte storage tanks, pumps, and piping (Shibata et al., 2013).

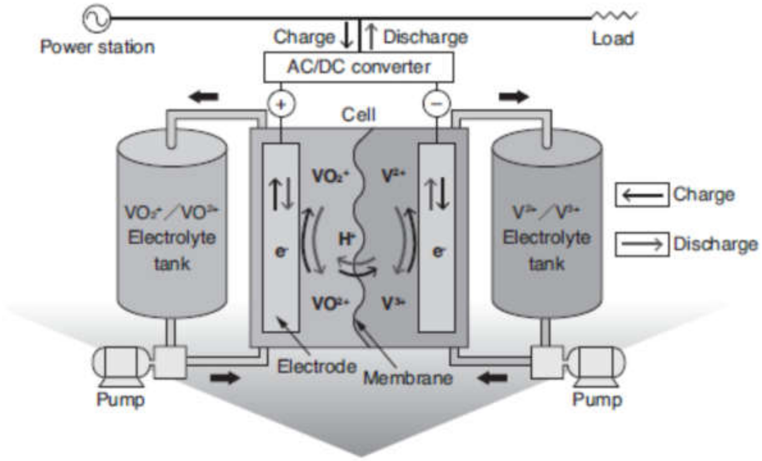


Figure 3-12: Redox Flow Battery Schematic (Skyllas-Kazacos et al., 2011)

Battery charging and discharging in these batteries is realised by a couple of reversible redox processes between two liquid electrolytes stored in separated storage tanks outside the cell. The electrolytes are pumped through the electro-chemical cell where electricity is generated as a result of a chemical redox reaction and vice versa (De Boer and Raadschelders, 2007; Skyllas-Kazacos et al., 2011). Multiple cells are combined in series to build up a cell stack so that serviceable voltage can be obtained (Shibata et al., 2013).

Storing the electrolytes in the storage tanks outside the cell stack in flow batteries provides a flexibility to define the energy and power specifications of the system. The energy (kWh) capacity of a battery system is determined by the size of the electrolyte volume while the power depends on the design and number of the electrochemical cell stacks (IEC, 2011). In conventional batteries such as lead-acid or sodium-sulphur batteries, power cell and electrolyte storage are coupled so that their energy and power ratings are fixed and cannot be modified (De Boer and Raadschelders, 2007). An upgrade in energy capacity in conventional batteries requires a complete overhaul of the existing electrical and physical system to accommodate (Qiu, 2014).

On the contrary, power and energy capacity of the flow batteries can be specified independently of each other. That is, the energy capacity of a flow battery can be increased very easily by simply increasing the amount of electrolyte by additional storage tanks, and the power rating can be increased by increasing the number of the cell (De Boer and Raadschelders, 2007; Droste-Franke et al., 2011; IEC, 2011). This feature allows the flow batteries to be designed and applicable for both power and energy applications (De Boer and Raadschelders, 2007) and to be optimised for storage applications of any specific size. This also facilities any future capacity upgrades.

In addition to this application flexibility, flow batteries provide lower capital cost per energy (kWh) and lowest operating costs for the high storage capacity applications in comparison to the other battery technologies. This is owing to the fact that the storage capacity of flow batteries is easily augmentable by simply increasing the capacity of storage tanks and the incremental cost of each additional storage capacity is lower than other battery types (Skyllas- Kazacos et al., 2009). This is a very important advantage for the applications which require high storage capacity. For instance, it would be a cost-effective option to opt for flow batteries for a microgrid application based on renewable sources or grid connected electricity storage at wind farms as these will typically require 8-10 hours of storage capacity so as to provide a reliable power supply (Skyllas-Kazacos et al., 2011).

Another cost related advantage of the flow batteries is the fact that the replacement cost for the battery system when it reaches to the end of its useful life would be only a fraction of the capital cost of the overall battery system. This is because the replacement cost for a flow battery would be either the capital cost of cell stack or servicing the stack and there will be no electrolyte-related costs as the electrolytes have an indefinite life span. On the other hand, the replacement cost for a lead-acid battery system will be close to the capital cost of the overall battery system (Skyllas-Kazacos et al., 2011).

In light of the foregoing explanations, flow battery type is chosen to be employed in the microgrid design.

Modelling battery bank in HOMER

HOMER uses the idealized power-capacity storage model to simulate flow batteries as this model is suitable for the storage systems of which energy and power capacities can be sized independently as it is the case for flow batteries (HOMER, 2018). The technical parameters given in Table 3-7 are required to be specified in HOMER for modelling a flow battery. In addition, the economic parameters presented in Table 3-8 are defined.

Table 3-7: Technical variables to be specified in HOMER PV modelling and their desription (HOMER, 2018)

Variable	**Description**
Cell stack lifetime (year)	The lifetime of the cell stack. The cell stack replacement cost occurs at the end of the cell stack lifetime
Electrolyte lifetime (year)	The lifetime of the electrolyte. The electrolyte replacement cost occurs at the end of the electrolyte lifetime.

Table 3-8: Economic variables to be specified in HOMER PV modelling and their desription (HOMER, 2018)

Variable	**Description**
Capital cost (€)	The initial purchase price
Replacement cost (€)	The cost of replacing the storage at the end of its lifetime
O & M cost (€/year)	The annual cost of operating and maintaining the storage

3.4.2.5.2.4 Diesel generator

As explained in the succeeding part, electricity storage technologies are used to store the intermittently generated power from renewable sources and to supply it constantly when demanded. However, especially in standalone (i.e. off-grid applications) where the microgrid is independent of the electricity grid, there might be some situations where the electricity in the battery system are not enough to respond to the demand. In case of these situations, a standby diesel generator is needed.

A diesel generator in a microgrid application for a manufacturing plant will have to provide a range of power requirement as the power demand will be varying. This will require the generator to run at various load ranges which means that the diesel generator will rarely operate at its rated capacity and will be mostly partly loaded. Even though it has been used as the sole power supplier for the subject plant, the generator will have had to operate spontaneously at varying speeds since the load demand is extremely fluctuating.

However, this kind of operating conditions will significantly affect the performance of a fixed speed diesel generator since the fixed speed diesel generators work most efficiently at full load. Reduction in load on a diesel generator does not result in a proportional reduction in fuel consumption; therefore, it is often recommended by manufacturers to operate fixed speed diesel generators above 40-60 % of their rated load in order to maintain an acceptable efficiency (Manwell et al., 1992; Wang et al., 2010).

Running fixed speed diesel generators at partial loads will reduce its operating efficiency which will further result in high fuel consumption, higher harmful emissions, and higher running cost. What is more, running at partial loads may even cause harmful and destructive conditions to the diesel engine itself owing to the fact that the unburned fuel dilutes the oil in the cylinder which will shorten the engine life (Waris and Nayar, 2008) and result in more maintenance.

Different from a fixed speed diesel generator, a variable speed diesel generator can run more efficiently at part loads and consume less fuel. In variable speed generators, the output voltage and frequency of the engine is regulated by using a power electronic converter based on a variable-speed, constant-frequency technology (Leuchter et al., 2007). This electronic interface decouples the frequency of the generator and that of the connected load, so that the speed of the generator can be varied to reduce the fuel consumption and emission level (Chen and Hu, 2003). While the minimum load for fixed speed diesel generators are about 40-60% of the rated power, this value for variable speed ones is around 23% (Waris and Nayar, 2008) or less giving a generator more flexibility to operate over a broad range of load conditions more efficiently in comparison to a fixed speed generator.

Overall, a DG in a hybrid microgrid with renewable energy for a manufacturing plant has to spend most of its time at partially loaded. In such an environment, deployment of a variable speed diesel generator will improve the economic and environmental performance of the microgrid by virtue of the aforementioned advantages. Therefore, variable speed DG is used in the proposed framework in this thesis.

Modelling DG in HOMER

HOMER allows a user to add and model diesel generator in a microgrid design. A generator can be added to the microgrid design from the several alternative diesel generators available in the component library of the HOMER and the data readily available for the chosen diesel generator can be used. Also, the associated information for the diesel generator can be managed (HOMER, 2018) so that a modeler can build a specific diesel generator. To do this, the information presented in Table 3-9 and Table 3-10 must be defined to the model.

Table 3-9: Parameters for diesel generator modelling and their descriptions (HOMER, 2018)

Parameter	Description
Fuel Resource	Specify the fuel used by the generator, set the cost, and optionally set a maximum consumption.
Fuel Curve	Set fuel consumption parameters.
Emissions	Enter the emission factors for the generator.
Maintenance	Set a maintenance costs and downtime for the generator.
Schedule	Set the generator to be forced on, forced off, or optimized (default)
Lifetime	the number of years before the DG must be replaced

Table 3-10: Economic modelling parameters for wind turbine (HOMER, 2018)

Parameter	Description
Capital cost (€)	the initial purchase price of the diesel generator
Replacement cost (€)	the cost of replacing the diesel generator at the end of its lifetime
O & M cost (€)	the annual cost of operating and maintaining the wind turbine

3.4.2.5.2.5 Converter

As mentioned before, a converter is needed to convert DC power to AC if a generator such as wind turbine and PV panel produces DC power. Similarly, AC power is converted to DC to be stored in an energy storage system. A converter consists of an inverter which converts DC to AC and a rectifier which converts AC to DC (HOMER, 2018). In such cases where DC-AC and AC-DC transformations are required, a converter model can be added to the microgrid design from the component library of HOMER. The technical specifications for each converter model are readily available in HOMER`s library. Also, a user can modify those parameters to create or define a new model. The data presented in Table 3-11 are required to be specified. As well as technical parameters, economic parameters are needed. These are summarised in Table 3-12.

Table 3-11: Technical parameters required to be specified for converter modelling and their description (HOMER, 2018)

Parameter	Description
Lifetime	The expected lifetime of the converter, in years.
Efficiency for inverter	The efficiency with which the inverter converts DC electricity to AC electricity, in %.
Parallel with AC generator? (inverter)	Check this box if the inverter can operate at the same time as one or more AC generators. Inverters that are not able to operate this way are sometimes called switched inverters.
Relative Capacity rectifier	The rated capacity of the rectifier relative to that of the inverter, in %

Efficiency for rectifier	The efficiency with which the rectifier converts AC electricity to DC electricity, in %

Table 3-12**:** Economic parameters required to be specified for converter modelling and their description (HOMER, 2018)

Parameter	**Description**
Capital cost (€)	the initial purchase price of the converter
Replacement cost (€)	the cost of replacing the converter at the end of its lifetime
O & M cost (€/year)	the annual cost of operating and maintaining the converter

3.4.2.5.2.6 Grid

Grid is needed as a power source in grid-connected microgrid configurations. Grid is modelled in HOMER as a component. The specifications given in Table 3-13 are specified in the grid component modelling in HOMER.

Table 3-13: Grid modelling parameters and their description (HOMER, 2018)

Parameter	**Description**
Grid Power Price (€/kWh)	The cost of buying power from the grid, in 4/kWh.
Grid Sellback Price (€/kWh)	The price that the utility pays you for power you sell to the grid in €/kWh.
Grid Demand Rate (€/kWh)	The monthly fee charged by the utility on the monthly peak demand, in €/kW/month
Grid Power emission rate (€/kWh)	The amount of carbon dioxide released per kWh of grid power consumed by the system, in grams/kWh

3.4.2.5.2.7 Microgrid controller

A specific microgrid hardware and information technology control system is needed in a microgrid to provide all the required information communication and control, and electricity dispatching between loads and supply. Therefore, it will be assumed that a microgrid controller is embedded into the proposed microgrid. Because microgrid controller has a capital cost, it must be taken into account. The parameters in Table 3-14 are required to be specified to model a micro controller.

Table 3-14: Economic parameters for microgrid controller modelling (HOMER 2018)

Parameter	**Description**
Capital cost (€)	the initial purchase price of the controller
Replacement cost (€)	the cost of replacing the controller at the end of its lifetime
O & M cost (€/year)	the annual cost of operating and maintaining the controller
Lifetime (years)	Life time of the controller

3.4.2.5.2.8 System economics

Because HOMER finds the optimum system based on NPV, economic parameters are needed. In this study, nominal discount rate, expected inflation rate, and project life time are assumed to be 8.82%, 7.40% (as defined in Section 3.4.1) and 25 years, respectively.

3.4.2.5.3 Demand response modelling (STEP 3)

It is possible to model some demand response techniques by using HOMER. To see which demand response measures can be employed in a manufacturing plant and to see the potential of corresponding monetary and environmental benefits, it is necessary to understand the consumption behaviour of the plant. In this regard, the first task is to understand how the plant is billed and see unit cost rates as well as to determine the tariff options offered by the utility provider. Thereafter, the plant load curve must be seen.

3.4.2.5.3.1 Load factor (LF)

A very useful indicator to understand the demand character of a plant is Load Factor (LF). LF is the energy consumed relative to the maximum energy that could have been used if the maximum demand had been maintained throughout the billing period and can be estimated as follows (CIPEC, 2011):

$$LF(\%) = \frac{kWh\ used\ in\ period}{(peak\ kW * 24hrs.per\ day * number\ of\ days\ in\ period)} * 100$$

(Eq 3-21)

A low LF indicates that there occur dramatic power demand peaks while higher values of it implies that power demand is more stable throughout the billing period. A plant with high LF can benefit from performing Peak Shaving demand response.

As it will have been explained in Chapter 8, Peak Shaving and Grid Arbitrage Using Energy Storage are considered for the subject plant studied in this thesis. Alhtough HOMER does not have a direct way to model a demand response measure, some features of Advance Grid Module of this software can be exploited to model some demand response measures. The methodology followed by the Author for modelling of these demand response measures in HOMER is explained in the following parts.

3.4.2.5.3.2 Peak shaving modelling

The rationale behind performing peak shaving is to reduce to demand charges. The peak grid demands of a manufacturing plant are supplied by using a cost-effective power source instead of the grid power. Thus, the demand charges during peak times are alleviated. In this point, the unit cost of the alternative power supply to cover the peak demands should be cheaper than the grid unit cost which is the sum of demand charge and consumption charge.

Peak shaving can be modelled and simulated in HOMER by limiting grid power capacity. As noted in Section 3.4.2.4.1 maximum grid demand, which is expressed as "grid purchase capacity (kW)" in HOMER grid modeling, is an optimisation variable. Therefore, while modelling a grid in HOMER, grid purchase capacity can be specified by the user in the grid component menu and multiple values for grid purchase capacity can be specified in the search space. While simulating the performances of each microgrid configuration for each specified grid purchase capacity in the search space, HOMER does not allow the system to purchase grid power more than that specified grid purchase value. In other words, the maximum grid demand cannot be more than the specified values in the search space in each simulation. The plant load demand more than a grid purchase capacity defined in the search space in a particular simulation can be met by batteries or DG (if included in the model) depending on which one is more cost-effective at that time step of the simulation. If the grid purchasing capacity is too low and the alternative power supply is not cost-effective, then, there might be no feasible solution in that particular simulation.

To apply the above described peak shaving modelling method, the optimum microgrid configuration that will have been identified as a result of microgrid simulations will be chosen and applied to see the contribution of demand response through peak shaving to the economic and technical potential of microgrid feasibility and plant energy performance.

3.4.2.5.4 Grid arbitrage (GA) using energy storage

In this demand response measure, grid electricity can be purchased during low-cost off-peak hours and stored by a storage system and can be consumed during expensive on-peak hours or to cover peak demands. Therefore, the aim of performing this demand response measure is to benefit from cheap electricity offered by the utility provider. To benefit from this, a plant must be billed based on TOU (Time-of-use)-based electricity tariff.

To model GA in HOMER, TOU-based electricity consumption unit cost rates offered by the utility are defined in the grid component HOMER. TOU-based unit cost rates are obtained from the electricity bills or the utility provider. Grid electricity will be purchased and stored in the microgrid batteries during grid off-peak periods when the grid power is cheapest and will be discharged and used during on-peak periods.

3.4.2.6 Energy efficiency modelling (STEP 4)

As explained in Section 3.1, energy efficiency is one of the pillars in the proposed energy management framework. The potential of energy efficiency in a manufacturing plant is to be explored by conducting an energy audit in the plant prior to the microgrid application. Therefore, the impact of energy efficiency on the feasibility of the microgrid application is investigated.

For this reason, using the energy efficiency options in HOMER, 4 main EE scenarios are defined. These are 5%, 10%, 15%, and 20%. HOMER reduces the plant power demand by these rates and repeates simulations for each energy efficiency options.

3.4.2.6.1 Sensitivity analysis (STEP 5)

There are various parameters which remain uncertain and can affect the economic potentials of the microgrid application. Because of this, a sensitivity analysis is conducted for the following parameters.

- Discount rate: HOMER assumes that the economic parameters of nominal discount rate and expected inflation rate do not change throughout the project life. Therefore, a sensitivity analysis is required to see the economic potential of the microgrid invesment is affected from the real discount rate.
- Electricity price: As inHOMER uses a fixed electricity price of which increase is affected only by the inflation rate over the project lifetime. However, the future of electricity prices is uncertain, and it had an increasing trend over the last 8 years in Turkey. For this reason, a sensitivity analysis of increasing electricity prices is carried out.

- Sell-back rate: The sellback rate applied by the Turkish Government is valid for 10 years after the project is commenced. After 10 years, it will be reviewed and whether it will be increased, or decreases is not clear. Due to this uncertainty, a sensitivity analysis is needed to see the effect of increasing and decreasing sellback rate on the project feasibiliy. Also, there is an extra support price for the use of domestically manufactured renewable generators. If domestic renewable generators are used in the project, the sellback rate increases by 50% from the current sellback rate. Thus, the effect of using domestically produced renewable is needed to be analysed.

- Technology lifetime: The lifetimes of the microgrid components are assumed based on the manufacturer specifications. However, there can occur unrecoverable breakdowns or failures. Also, the lifespans of some technologies can last more than expected. For instance, a recent (Myers, 2014) showed that wind turbines can last their full life of about 25 years before they need to be upgraded whereas the lifespan for wind turbines are generally regarded to be 20 years. Considering these uncertainties, a sensitivity analysis is done on the lifetimes of the microgrid components.

3.5 CHAPTER SUMMARY

The objective of this chapter was to provide a description of the proposed energy management framework and its application methodology. To meet the chapter objective, the question “how to improve the energy performance of manufacturing plant?” was answered . Based on this and keeping the challenge that manufacturing plants face, a holistic energy management framework was developed giving the reasons for the need for a holistic systematic approach for energy performace improvement. The application methodology of the proposed framework, which consists of two major steps, Energy Audit and Microgrid Application, were described. Finally, a summary of the chapter was given.

4

Description of the Subject Manufacturing Plant

4.1 INTRODUCTION

The objective of this chapter is to introduce and describe the subject manufacturing plant chosen as a requirement of the thesis methodology to be used for the main application case study in this PhD study. For this purpose, Section 4.2 explains the rationale for choosing the subject plant for study. Section 4.3 gives some background information about the subject plant including the plant location, the industrial estate that the plant is based in, the business line in which the plant operates, product types and the customer profiles of the plant, and production volumes. The production flows and processes are scrutinised in detailed in Section 4.4. Energy consuming systems of the plant, energy types and plant-wide energy consumption values, and energy balance and energy flows are given in Section 4.5, Section 4.6, and Section 4.7, respectively. Also, as a requirement of the application methodology presented in Chapter 3, Target Energy Consuming for detailed energy auditing are chosen in Section 4.8. Finally, Section 4.9 concludes the chapter with a summary of the chapter.

4.2 THE RATIONALE FOR CHOOSING THE SUBJECT PLANT

In line with the aim and objectives of this study, a typical Turkish SME (Small and Medium Size Enterprise) with an energy intensive manufacturing plant operating in marine industry was chosen. The grounds for why this plant was chosen as a case application can be listed as follows:

- It operates in marine industry and produces marine machine and equipment as one of the main requirements of the application case study.

- Metal casting is one of the most energy intensive industries of the manufacturing sector. The plant practises metal casting. Therefore, it is an energy intensive manufacturing plant where energy use is a critically important factor in terms of global energy challenge defined in Chapters 1 and 2. It is also appropriate in terms of the competitiveness of the plant itself which is subjected to high energy costs and operates in marine industry that is an internationally open and competitive market.

- The plant consists of a foundry, machine shop, and heat treatment unit. Thus, there involves a number of different energy consuming systems, which gives an opportunity to gain insights and compare energy consumption of different systems as well as ESPs.

- It is located in Turkey which is a fast developing, energy intensive country and more specifically it is situated in the most industrialised region of Turkish manufacturing industry. Thus, the plant is a good application case study for a representative Turkish manufacturing plant since most plants in this region are subjected to the same regulation and/or policies for energy efficiency issues and the same geographical conditions that are decisive for renewable energy potential.

- The plant is a SME. This aspect is important because most of the 3.5 million enterprises (99.8%) in Turkey are SME, which represents a paramount importance for Turkish economy and social life. Furthermore, focus of the most studies into the themes of plant-wide energy savings, energy efficiency, and energy management in the literature review were on big industries. Hence, focusing on a SME plant in this thesis study is a wise and rational option within the above stated reasons.

Key aspects of the subject manufacturing plant are shown in Figure 4-1.

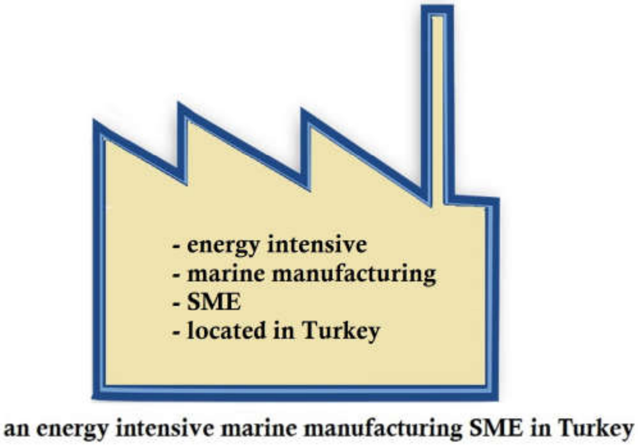


Figure 4-1 : Key aspects of the subject manufacturing plant

4.3 BASIC INFORMATION ABOUT THE SUBJECT PLANT

The plant under investigation is an energy intensive manufacturing plant established in Turkey in 2007. It consists of three main production units: a foundry, a heat treatment unit, and, a machine shop. The gross area of the plant is 5705 m^2 while a 5530 m^2 of this area is a closed site. The plant operates on two-shift system 6 days a week. Each shift is 8.75 hours and the number of workdays in a year is about 295. A general view of the plant is shown in Figure 4-2. The plant layout is given in Appendix A.

Figure 4-2: General view of the subject plant

4.3.1 PLANT LOCATION

The subject plant is located in an organised industrial estate called TOSB (Tayland Organize Sanayi Bolgesi) which is one of the 13 industrialized zones of the Kocaeli province. Kocaeli is documented as the most industrialized city of Turkey. It accounts for the 13% of the country`s industrial production. There are 2200 important industrial companies in Kocaeli. Moreover, 26 of the 100 largest companies of Turkey are based in Kocaeli, and 87 Kocaeli-based companies are in the top 500 list of Turkey (GRBD, 2015). Kocaeli City is located in the Marmara region of Turkey, 50-70 kilometres away from Istanbul, which is one of the most strategic metropolitan cities in the world. Istanbul is a logistics centre that appeals to all markets by virtue of its several small size and industrial size ports bordered by the Black Sea and the Marmara Sea (GRBD, 2015). Furthermore, it is very close to the major shipyards of the country: Tuzla and Yalova. The location of TOSB industrial estate and the view of the plant on Google Earth can be seen in Figure 4-3.

TOSB is a very modern industrial estate certified with ISO 9001-2000. Currently 87 factories operate in the estate. TOSB pays ultimate attention to environment. A 20 % of the total estate area consists of green places. All the factories located in TOSB are inspected for their environmental impacts. However, environmental impacts related to the energy consumption are not included. Furthermore, the state yet lacks a renewable energy supply, and its possible effects have not given enough consideration (TOSB, 2014).

Figure 4-3: Location of the TOSB industrial estate and view of the plant on Google Earth

4.3.2 LINE OF BUSINESS, PRODUCTS, AND CUSTOMER PROFILE

The plant performs three major manufacturing activities: Foundry operations; heat treatment; and machining. Foundry operations form the core production activities of the plant and thus, the company defines itself as a foundry. As such, the casting, which is the production of shaped articles by melting the raw material and pouring molten metal into moulds, is the major manufacturing process in the plant. Casting type performed in the plant is sand casting. Other foundry processes include mould making, grinding, and shot blasting. In addition to the foundry processes, there are two major processes performed in the plant: heat treatment and machining.

The subject plant handles orders from various customers of different sectors. Products are made-to-order. Once the order is received, casting design is made accordingly. Both the customers' orders and the product range are quite sizeable. This results in a very diverse product mix and thus diverse casting designs.

Regarding the industrial profile, the plant does most of its business with the marine and offshore industry. But, it also takes order from several industrial branches such as mining industry, cement industry and the automotive industry, owing to its manufacturing skills and capabilities. Yet the Marine and offshore industry is the major customer amongst them. The plant can manufacture a variety of machines and equipment for the marine and offshore industry. These include deck machinery and equipment such as mooring, towing, anchoring elements, propulsion and manoeuvring machines and equipment such as propellers and rudders. Some marine and offshore products manufactured in the plant can be seen in Figure 4-4.

Figure 4-4: Some examples of marine & offshore products produced in the plant

4.3.3 PRODUCTION VOLUMES

The production volume of the plant is defined in casted metal tonnes. The average monthly and annual production volumes for the plant are about 120 tonnes/month and 1420 tonnes/year, respectively. These are presented in Table 4-1.

Table 4-1: Production volumes of the plant, tonne

Total casted metal	1420 tonnes/year
Monthly average	120 tonnes/month

4.4 PRODUCTION PROCESSES

The production process flow of the plant is shown in Figure 4-5. Once the order is approved, the casting design team designs the casting and simulates the melting process as given in the flow diagram in Figure 4-5. After the optimum casting design is achieved, the metal and moulding requirements are calculated and sent to the moulding and furnace sections. In terms of the energy efficiency measures of the plant, the use of appropriate simulation software is of great importance since the simulation results can foresee the defects that are likely to occur in the casting. Thus, the design team takes the necessary preventive actions and tries to reach the optimum casting design. If the defects cannot be prevented, the castings will require additional work for correction, which will result in an increase in the energy consumption or even the whole casting can be lost.

Following the casting design, the moulding section commences the moulding process. The sand is prepared by a sand mixing machine and the moulding is performed by moulders manually. Finished moulds are conveyed to the moulding zone by overhead travelling cranes.

Meanwhile, the furnace operators prepare the molten metal and pre-heat the ladles. The plant uses 3 induction furnaces for melting process, which are the most efficient type of melting furnaces. Before charging the scrap metal, the furnace is pre-heated for sometimes in order to heat the furnace lining. The scrap metal is charged to furnaces by shovels. While the scrap is melting, the ladles are heated. Ladles are used to carry molten metal from the melting furnace to the pouring zone. The aim of ladle preheating is to prevent heat loss when molten metal is poured into the ladle.

When the molten metal is ready, a sample piece of melt is extracted from the furnace and analysed by a spectrometer in order to ensure that it has the right constituents. More constituent is added to molten metal if required based on the analysis results.

When the molten metal is finally ready, the preheated ladles are brought to the pouring station and molten metal is poured onto the preheated ladles. The molten metal is then carried to the moulding zone by ladles and poured into the moulds.

After pouring, the moulds stay in the moulding zone for cooling for some time. At this point, enough waiting time should be allocated for the moulds cool. Otherwise, conveying a mould which still holds hot melt can cause defects on the castings, and correcting defects means more energy consumption.

After cooling, the moulds are carried to mould dismantling station. They are loaded onto the sand reclamation machine and dismantled by vibration. The castings are separated by the operator and moulding sand is reclaimed mechanically by sand reclamation system.

After dismantling, the castings are carried to the fettling station, where casting rises, patterns and feeders are trimmed and removed by using oxy-propane flame.

Following the fettling, the remaining roughness from the fettling station and other surface bulges are grinded in the grinding station. Heavy works require a purpose built grinding machine while a small hand grinding machine is used for small works.

When the grinding process is completed, the castings are subjected to heat treatment process in heat treatment furnace which is powered by natural gas. There are various heat treatment processes such as normalisation, stress relieving, annealing. They all have different purposes. The heat treatment is followed by quenching processes, which can be considered as a part of heat treatment. It can be air or liquid quenching depending on the specifications of the castings; therefore, there is one liquid quenching pool and air fans for air quenching. After heat treatment, the castings can be transferred to the machine shop if they need machining.

Thereafter, the castings are sent to the shot blasting machine, which is a mechanical one. The purpose of the shot-blasting is to provide a smooth finishing surface to the castings. Following the shot blasting, the quality controls are done. If any defects are found, necessary actions are taken depending on the type of the defect. Some of the production processes can be repeated to correct the defect. For example, if the hardness of the casting does not satisfy the required level, then an appropriate heat treatment process is performed.

Finally, the castings are prepared for shipment and delivered to the purchaser.

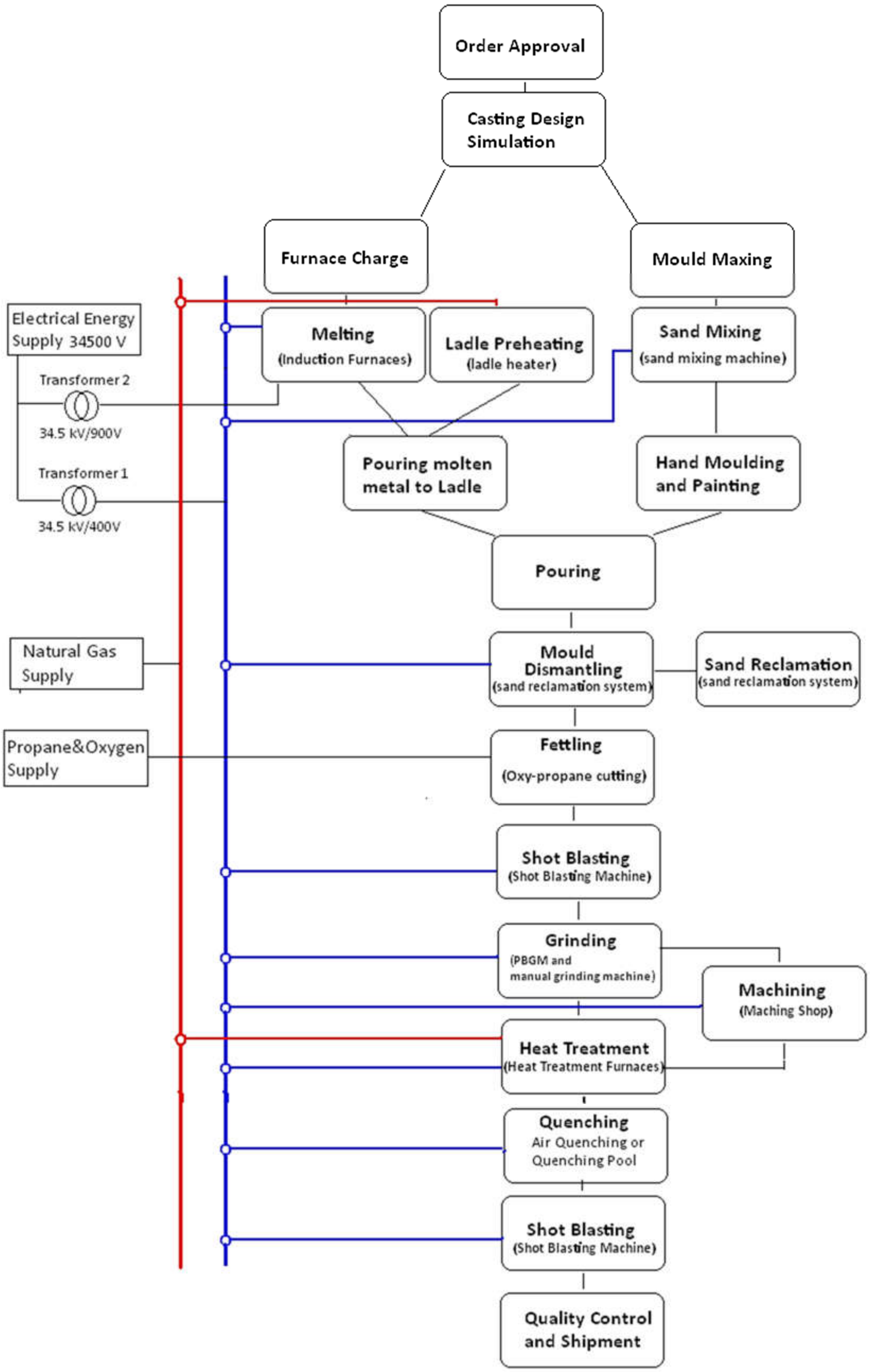


Figure 4-5: Production processes and corresponding energy flows in the subject plant

4.5 ENERGY CONSUMING SYSTEMS

Energy consuming systems in a manufacturing plant can be split in to two major categories: Production process systems; and production support systems (Trygg and Karlsson, 2005). Production support systems are related to those systems which support the production such as ventilation, space heating, compressed air, lighting, material handling, etc. On the other hand, production process systems are related to the systems which actually perform the production. The subject plant has a number of various production process systems and production support systems. Table 4-2 lists the energy consuming production process systems and production support systems. The subject plant has a variety of production process systems because it consists of the following major production areas:

- foundry.
- heat treatment unit.
- machine shop.

Foundry is the core section of the subject manufacturing plant and all the manufacturing begins here. It consists of various subsections where various foundry processes are performed as it will be described detailed in the forthcoming parts. Some of the castings produced by foundry section can need heat treatment or machining by virtue of their final physical and geometrical specifications, so these processes are performed in the heat treatment unit or machine shop. As Table 4-2 shows, there are 9 energy using systems in the foundry which include 3 induction furnaces for melting process, a sand mixing system, a sand reclamation system, a ladle preheating system, oxy-cutting systems, grinding systems, an abrasive blasting system, a core production unit, and a model production unit. The major energy consuming systems in Heat Treatment Unit are heat treatment furnace, liquid quenching system, and air quenching system whereas 4 vertical lathes constitute the machine shop of the subject plant.

As for the production support systems of the subject plant, there are ventilation system, compressed air system, cooling towers, material handling systems (i.e. 5 overhead travelling cranes), lighting systems, a laboratory, and plant offices.

Table 4-2: Energy consuming systems and energy types in the subject plant

System Type	**Plant section**	**System**	**Energy Type**
Production Systems	Foundry	Induction furnaces	Electricity
		Sand mixing system	Electricity
		Sand reclamation system	Electricity
		Ladle preheating system	Natural Gas
		Oxy-cutting system	Propane
		Grinding systems	Electricity
		Abrasive blasting system	Electricity
		Core production unit	Natural Gas
		Model production unit	Electricity
	Heat Treatment	Heat treatment furnace	Natural Gas
		Liquid quenching system	Electricity
		Air quenching system	Electricity
	Machine Shop	Machine Tool 1 – Vertical lathe	Electricity
		Machine Tool 2 – Vertical lathe	Electricity
		Machine Tool 3 – Vertical lathe	Electricity
		Machine Tool 4 – Vertical lathe	Electricity
Production Support Systems		Ventilation system	Electricity
		Compressed air system	Electricity
		Cooling tower 1	Electricity
		Cooling tower 2	Electricity
		Material handling systems	Electricity
		Lighting systems	Electricity
		Plant offices	Electricity

4.6 ENERGY TYPES AND PLANT-WIDE ENERGY CONSUMPTION

Three types of energy sources power the subject plant: electricity; natural gas; and propane. The annual electricity consumption of the subject plant is 2,970 MWh. The associated annual primary energy consumption, energy cost and CO_2 emissions values are 7,217.1 MWh, €194,535 and 1,452,330 kg-CO_2, respectively. The annual natural gas consumption of the plant is 2,274 MWh and the associated annual energy cost and CO_2 emissions values are €51,118 and 411,446 kg-CO_2, respectively (i.e. 0.1812 CO_2 factor for natural gas, 0.2152 for propane (EIA, 2017)). Thus, the annual primary energy consumption of the plant is 9,444.5 MWh whereas the associated total energy cost and the overall indirect and direct CO_2 emissions release are €250,590.3 and 1,876,512.9 kg-CO_2, respectively. These values are based on the year 2013 and will be assumed as the overall plant baseline values as tabulated in Table 4-3.

Table 4-3: Subject plant energy types and annual energy consumption values

Energy types	**Annual consumption (kWh/year)**	**Unit cost (€/kWh)**	**Annual energy cost (€/year)**	**Annual CO_2 (kg-CO_2/year)**	**Annual primary energy use (kWh/year)**
Electricity	2,969,566.70	0.06554	194,625.40	1,455,087.70	7,334,829.70
Natural gas	2,273,898.80	0.0225	51,162.70	412,030.50	2,273,898.80
Propane	43,656.00	0.11	4,802.20	9,394.80	43,656.00
Plant total			250,590.30	1,876,512.90	9,652,384.50

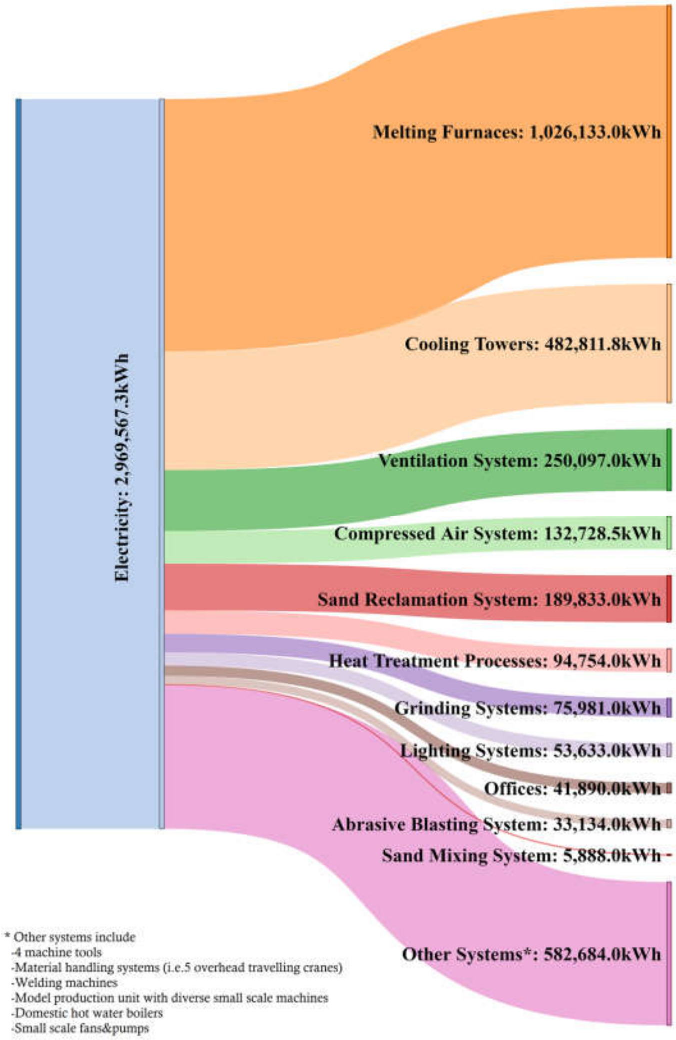
It is evident from Table 4-3 that electricity is the major energy source of the plant since it is the most expensive one and has the highest share in overall consumption. It constitutes the 75% of overall annual plant primary energy use. Also, it accounts for 77% of the overall annual plant energy cost and for 77% of the overall annual plant CO_2 emissions. Therefore, the focus of the energy audit is given to the electricity consuming systems. As also noted in Section 3.3.2 of Chapter 3, natural gas and propane consumers are not included in the audit; and energy, electricity and power terms are used interchangeably from now on.

4.7 ENERGY BALANCE AND ENERGY FLOWS

An energy balance for the overall annual electricity consumption has been prepared based on the power consumption measurements and presented in Sankey diagram as shown in Figure 4-6. The energy balance shows the contribution of each audited energy consuming system to the overall annual plant energy consumption. How the annual energy consumption of each system estimated is given in the associated subsequent sections of Chapter 5 and Chapter 6 devoted to different energy consuming systems.

As seen in Figure 4-6, the most significant energy consumer in the subject plant is Melting Furnaces. Their annual energy consumption is 1,026,133 kWh accounting about 35% of the overall plant energy consumption. The second major energy consumer is Cooling Towers by consuming 482,811.8 kWh per year. Their contribution to the overall plant energy consumption is 16.3%. The annual energy consumption of Ventilation System is 250,096.8 kWh which makes 8.4% of the overall plant consumption. Compressed Air System consumes 132,728.5 kWh contributing for 4.5% the overall plant annual use. Sand Reclamation System is another major energy consumer consuming 189,833 kWh per year and accounts for 6.4% of the overall plant consumption. The annual energy consumption of other users, Heat Treatment Systems (i.e. heat treatment furnace, air quenching system, and liquid quenching, Grinding Systems, Lighting Systems, Plant Offices, Abrasive Blasting System, and Sand Mixing System are 94,754 kWh, 75,981 kWh, 53,633 kWh, 41,890 kWh, 33,134 kWh, and 5,888 kWh, respectively. Their contribution to overall consumption are 3.2%, 2.6%, 1.8%, 1.4%, 1.1%, and 0.2%, respectively.

In addition to the above said systems, there are other energy consumers of which individual annual energy consumption estimation was not possible. These systems include machine tools, material handling systems (i.e. 5 over head travelling cranes), welding machines, model production unit with diverse small-scale machines, domestic hot water boilers, and small-scale fans and pumps. Their collective energy consumption is 582,684 kWh per year as presented in Figure 4-6 and Table 4-4.



* Other systems include
-4 machine tools
-Material handling systems (i.e.5 overhead travelling cranes)
-Welding machines
-Model production unit with diverse small scale machines
-Domestic hot water boilers
-Small scale fans&pumps

Figure 4-6: Energy flows in the subject plant

Table 4-4: Annual energy consumption of energy consuming systems of the subject plant and their share on overall plant energy consumption

Energy consuming system	**Annual energy consumption (kWh)**	**Share on overall plant energy consumption (%)**
Melting Furnaces	1,026,133	35%
Cooling Towers	482,811.80	16.3%
Ventilation System	250,096.80	8.4%
Sand Reclamation System	189,833	6.4%
Compressed Air System	132,728.50	4.5%
Heat Treatment Systems	94,754	3.2%
Grinding Systems	75,981	2.6%
Lighting System	53,633	1.8%
Offices	41,890	1.4%
Abrasive Blasting System	33,134	1.1%
Sand Mixing System	5,888	0.2%
Others	582,684	19%
Total Subject Plant Consumption	296,956.30	100%

4.8 AUDITED SYSTEMS: TARGET ENERGY CONSUMING SYSTEMS

As a requirement of the objective of Phase 1-Plant-Wide Auditing, which is to determine the Target Energy Consuming Systems for detailed auditing to find ESPs on them, keeping the criteria given in Section 3.4.1 in Chapter 3 in mind, the following energy consuming production process systems and production support systems are chosen as Target Energy Consuming Systems.

Production process Systems (presented in Chapter 5):

- Melting Process Systems
- Grinding Process Systems
- Abrasive Blasting Process System
- Machine Shop
- Heat Treatment Systems
- Sand Mixing System
- Sand Reclamation System

Production process Systems (presented in Chapter 6):

- Ventilation System
- Compressed Air System
- Cooling Tower Systems

- Lighting Systems
- Offices

The collective energy consumption of the above Target Energy Consuming Systems are 2,386,882.7 kWh per year. This is about 81% of overall plant energy consumption. Therefore, one can say that a major part of the energy consuming systems is covered in the energy audit in this thesis.

As for the systems/processes which are not included in the energy audit are as follows:

- Material Handling Systems (i.e.5 Overhead travelling cranes).
- Welding machines.
- Model production unit which consists of small scales machine and tools with very low running hours.
- Domestic hot water boilers.
- Small-scale pumps and air fans.

The above systems which are not included in the energy audit accounts for about 19% of the overall plant energy consumption. The reasons as to why they are not considered as a target can be listed as follows:

- It was not possible to conduct power consumption measurement on overhead travelling cranes and welding machines.
- Lack of data regarding their energy consumption figures such as power ratings, etc.

4.9 CHAPTER SUMMARY

The objective of this chapter was to introduce the subject plant, which will be used as the main application case study in this PhD study. Initially, the rationale for choosing the subject plant for study was explained by giving main characteristic features of the subject plant. Some introductory background information regarding the subject plant such as its production units, employment periods, number of workers, number of working days, and so on were provided. This was followed by providing more detailed information regarding the plant such as the business line of the plant, product types, and customer profiles. The production volumes were also provided, and the production flows and processed were scrutinised. The energy balance and energy flows for the subject manufacturing plant was introducing by providing an inventory of the all energy consuming systems of the subject plant together with their energy input types. The overall annual energy consumption of the subject plant with regards to energy types and the associated CO_2 and energy costs were presented. Because this thesis focuses on electricity consuming systems, annual energy consumption of these systems and their share on the overall plant annual energy consumption were presented. Also, a Sankey diagram which shows the overall energy balance and energy flows across the energy consuming systems was given. As a requirement of the application methodology presented in Chapter 3, the Target Energy Consuming Systems were determined.

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5

Energy Saving Potentials Production Process Systems

5.1 INTRODUCTION

The objective of this chapter is to present the energy auditing analyses conducted on the target energy consuming systems of the production process systems of the subject plant to identify the appropriate ESPs using alternative methods and their application. To meet this objective, this chapter is structured in five sections:

- Melting System (Section 5.2)
- Grinding System (Section 5.3)
- Abrasive Blasting System (Section 5.4)
- Machine Shop (Section 5.5)
- Sand Reclamation System Offices (Section 5.6)
- Sand Mixing System (Section 5.7)
- Heat Treatment System (Section 5.8)

Finally, a brief summary of the chapter and concluding remarks of the overall chapter are given in Section 5.9.

5.2 MELTING PROCESS

Melting is the key and most energy intensive process in the subject plant. It can be considered as the main engine of the subject plant because it triggers all the manufacturing. The foundry section of the subject plant is equipped with 3 induction furnaces for melting process. Their melting capacities are 5000 kg, 2500 kg, and 600 kg. The furnaces of 5000 kg and 2500 kg are powered through the same inverters of 1500 kW. The small induction furnace of 600 kg is fed by 350 kW.

In the subject plant, the melting process, so the induction furnaces, represents the significant energy consumption in the plant. Based on the calculations from the plant furnace records, the annual electricity consumption of the induction furnaces in a year are 739,522 kWh for 1500 kW induction furnaces and 286,611 kWh for 350 kW induction furnace. In total induction furnaces consumed 1,026.133 MWh of electricity, which makes about 34.6 % of total annual plant electricity consumption. This percentage varies over the months as seen in Figure 5-1. For instance, the induction furnaces accounted for 53 % of the total electricity consumption in September while this value was 18 % in June. This is due to the highly varying production volumes nature. All in all, the melting process is the most significant energy consumer and major energy cost factor and requires primary consideration to identify ESPs.

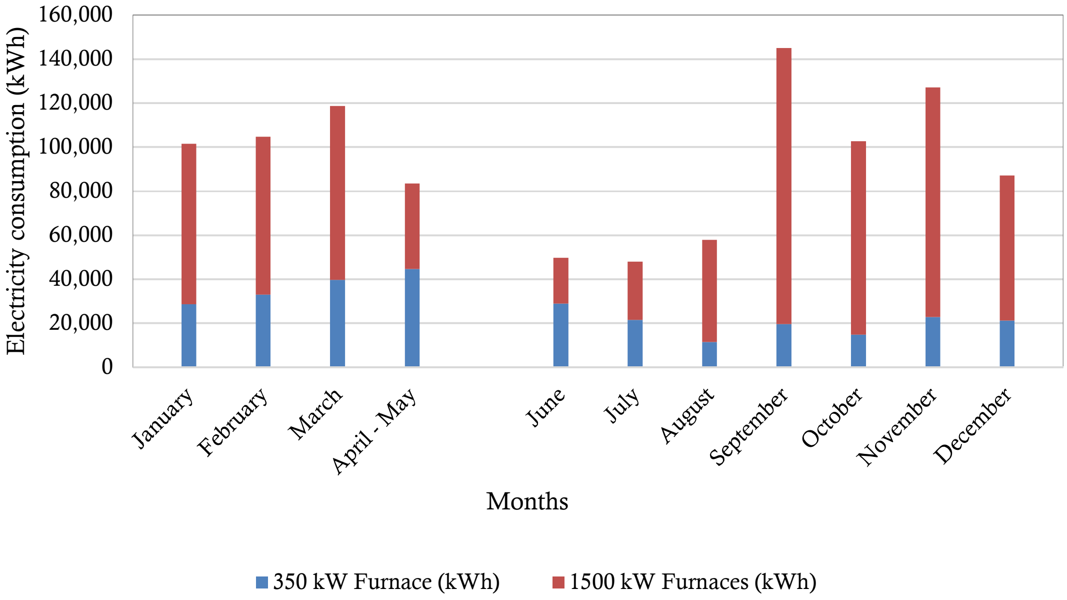


Figure 5-1: The induction furnaces monthly electricitty consumption in the plant in a year

5.2.1 IDENTIFYING ESPS IN THE MELTING PROCESS

Energy efficiency of a melting process is dependent on a lot of factors because of the complex nature of melting process. Assessing all these factors to identify ESPs is an extremely challenging task in an energy audit process. Some factors are qualitative while some are quantitative. The Author exploited the following data to explore ESPs in the melting process of the subject plant:

- Melting process specific energy consumption data: 600-kg-induction-melting furnace was chosen a representative and energy consumption measurements were conducted for 70 melting furnace cycles.
- Annual rejected casting rate of the subject plant.

These data have been collected, compiled, tabulated and used to quantitatively identify ESPs in the melting process of the subject plant. In addition to these, the Author carried out observations on melting and furnace practises of the subject plant to find out possible reasons on inefficient energy consumption. Having analysed the above-mentioned data, the following ESPs have been identified:

1. ESP by Improving Melting Practise.
2. ESP by Reducing Casting Defect Rate.

These will be explained in the following subsections. The analysis methods and steps have been described where appropriate.

5.2.1.1 ESP BY IMPROVING MELTING PRACTISE

Specific melting energy consumption, that is energy consumption per melted metal amount (i.e. kWh/kg), will be used as an energy efficiency indicator in the melting process of the subject plant and benchmarked against best practice values available in the literature to identify ESPs.

To determine the specific energy consumption (SEC) of the melting process and ESPs, the Author conducted a number of power consumption measurements and the 600-kg furnace was chosen as representative for this purpose since it is the most frequently used one by the plant. Energy consumption values (i.e. kWh) from the furnace power meter unit (can be seen in Figure 5-2) before and after each furnace charge were logged and electricity consumption was calculated as the difference between each charge. While doing this, the associated furnace charge data (i.e. product details such as weight, tapping temperature, etc.) were also recorded. In total, a data set of energy consumptions of 70 furnace cycles were determined and the average value has been calculated to be used as plant specific melting energy consumption (i.e. kWh/tonnes). This will be used to benchmark against Best Available Practices (BAP) values collected from the literature. In the literature, there are various values regarding the minimum energy consumption of melting process performed in a modern coreless induction furnace. Table 5-1 shows these minimum values found in the available literature. The surplus energy consumption will be determined from the benchmarking and possible reasons and factors causing to unnecessary energy consumption will be discussed based on the Author`s observations on the melting practise carried on the subject plant.

Figure 5-2: Melting Furnaces Power Meter and Control Unit in the Subject Plant (Photo taken by the Author)

Table 5-1: Minimum energy requirements of induction melting practise found in the literature

Reference	Value (kWh/ton)
(EC, 2005)	550 – 650
(Brown, 2000)	550 – 650
(IFC, 2011)	544* – 566**
(DETR, 2000)	600
(Schifo and Radia, 2004)	538.1
(CIPEC, 2003)	595 for iron 620 for steel
** average, * best practise for Europe	

Figure 5-3 shows the electricity consumptions of 70 furnace cycles of various weights of the same metal (i.e. steel) and the minimum best practise value found in the literature. The average specific melting energy consumption of the subject plant based on the power consumption measurements was found to be 770.01 kWh/tonne. This value is compared with the European Best Practise value which is 544 kWh/tonne as shown in Table 5-2.

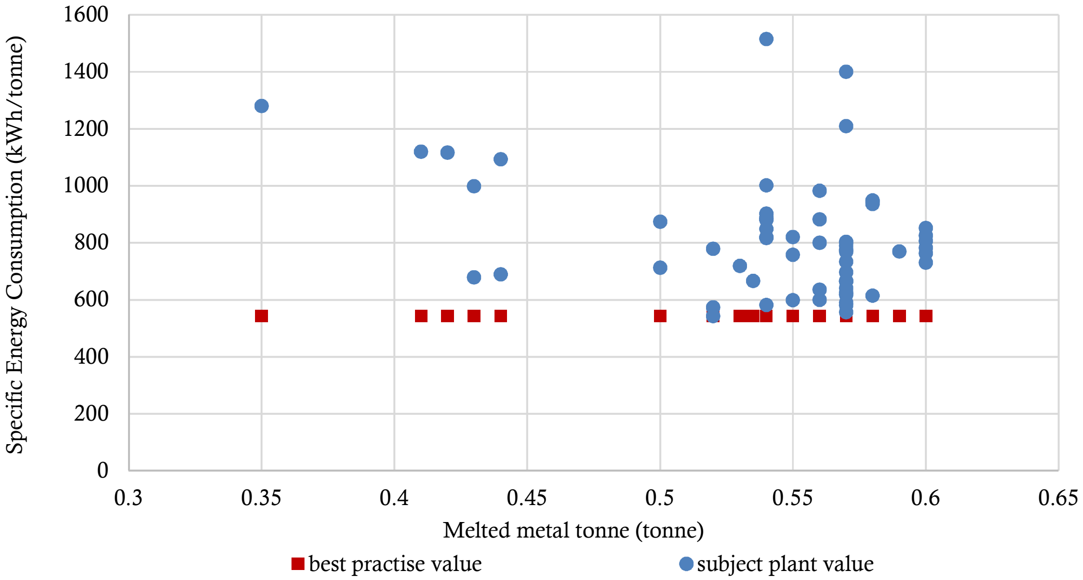


Figure 5-3: Specific energy consumption of melting process in the subject plant

Table 5-2: Benchmarking and energy saving potential of melting process in the subject plant

Subject Plant (kWh/t)	**Europe Best Practise (kWh/t)**	**Improvement Potential (difference) (kWh/t)**	**ESP %**
770.01	544	226.01	29

As one can see in Table 5-2, the difference between the plant melting specific energy consumption (i.e.770.01 kWh/tonne) and the Europe Best Practise value (i.e. 544 kWh/tonne) is 226.01 kWh. This means that subject plant can save 226.01 kWh per tonne, that is about 29% of plant melting specific energy consumption, on the condition that the plant improves their melting process and follows the level of Europe Best Practice value.

As shown in Table 5-3 ESP scenarios have been defined to express the energy savings in the subject plant melting process by improving the melting practise. These are 7.25%, 14.25, 21.7%, and 29% which corresponds to 25%, 50%, 75%, and 100%, respectively, of 226.01 kWh/tonne melting SEC difference. To give an example, if the subject plant can approach to 25% of Europe Best Value by improving their melting process, an ESP of 7.25% can be achieved.

Table 5-3: Scenarios of ESP by improved melting practices

SEC with 25% ESP ((kWh/t)	**SEC with 50% ESP (kWh/t)**	**SEC with 75 % ESP (kWh/t)**	**SEC with 100% ESP (kWh/t)**
7.25%	14.25%	21.70%	29%
713.5	657	600.51	544

In this study, *ESP by Improving the Melting Process* will be assumed based on the assumption that the plant will achieve 50% of the specific improvement potential (i.e. 226.01 kWh/tonne) identified above. In this case, the plant can achieve a 14.25% ESP in the melting process owing to an improved melting practice. This will be assumed as a representative ESP for the melting process of the subject plant. As it was given earlier, the total annual energy consumption of the melting furnaces was 1026.133 MWh. Assuming that the plant can achieve the above-found 14.25% ESP rate in all furnace cycles and other furnaces as well, 14.25% of 1,026.133 MWh which makes 146.22 MWh, can be saved. This is equivalent to approximately 5.7% of the overall plant electricity consumption. If the plant can approach to 100% of Europe Best Value, the corresponding ESP in melting process will be 29%, which means that 297.57 MWh of electricity can be saved in a year. This is equivalent to approximately 9.7% of the overall plant electricity consumption. This ESP is designated as **ESP 5-1, ESP by Improving the Melting Practise.**

There are various factors affecting the energy consumption of a melting process in a melting furnace. There might be various factors and inefficiencies that lead to the above found energy consumption waste for the subject plant. Investigating and quantitative assessment of these factors and inefficiencies are arduous task and beyond the scope of this thesis. However, the Author of this thesis observed inefficient melting practises of the plant furnace operators while conducting the energy audit to find out possible reasons of inefficient energy consumption. These will be discussed in the following subsection.

5.2.1.1.1 Energy Saving Measures for Induction Melting Process and Possible Reasons for Inefficient Energy Consumption of the Subject Plant

Considering that the specific melting energy requirement is the same for all furnace charge because the types of melted metal are the same (i.e. steel), one can expect that SEC values of them should be close to each other. It is not realistic to expect a very strong consistency among SECs in a batch melting process because it is not performed continuously so that energy consumption versus production melting output will not be constant. Moreover, melting is a highly complex process which involves a lot of energy efficiency factors. These factors can change from one furnace cycle to another. For this reason, some degree of variation in melting SECs of the furnace cycles with the same metal can be acceptable. However, the SECs of the melting process in the subject plant shows extreme volatility as can be seen in Figure 5-3. While the average SEC is 770.01 kWh/tonne, the standard deviation is 241. The wide scatter of results indicates that the subject plant employs diverse operational practises and highlights the scope of improvement.

For instance, the quality of scrap raw material to be melted affects the melting energy requirement. The type and efficiency of the melting furnace are other parameters affecting the energy consumption. Depending on the furnace type, the furnace operator has also an effect on the efficiency of the furnace and energy consumption. Therefore, it is important whether the furnace control (loading, charging, etc.) is efficiently practiced or not. Some of these factors together with the observations conducted by the Author on the melting practice of the subject plant will be given in the following subsections.

Furnace

Furnace type is one of the most important parameters in energy efficiency of a melting process. There are three basic furnace types, which are frequently used in melting industries: cupola furnace, electric arc furnace, and induction furnace. Induction furnaces are the most efficient type of melting furnaces. They are suitable for batch-melting process where the furnace is charged with scrap metal and emptied after melting for pouring. This makes a furnace cycle.

The subject plant performs batch-melting because the product mix is very diverse. Various products with different alloying specifications are casted in a typical production day. Each melting cycle is devoted to the castings with the same alloying specifications. This must be done as such because it enables the utilization of maximum furnace capacity. In this regard, the subject plant uses the most suitable and efficient furnace type.

The efficiency of the induction furnaces which the subject plant poses can be compared with that of the best practice melting performing plants` furnaces. However, data for neither the subject plant nor the best practice induction melting furnaces specifications are available; thus, such a comparison was not possible in this study.

In fact, once a furnace is already purchased and installed by a plant, the most important energy efficiency aspect in induction melting is operational practices. Replacing a furnace unit with a new one after installing it will be very costly and time-consuming; therefore, specific features, size and capacity, power characteristics, connection with pouring line of furnaces and melting shop layout must be understood prior to the procurement of the furnaces (ECC, 1998).

There are two groups of energy losses in an induction furnace melting: electric losses and heat losses. Electric losses are due to the power system elements of an induction furnace and cannot be adjusted by the furnace operator. On the other hand, heat losses arise from mainly poor furnace practices where furnace operator/user has a direct impact.

Energy efficiency of power system elements (i.e. electric losses) of an induction furnace cannot be optimised or managed by furnace users because these components are related to the design and manufacturing phase of the furnace. However, a furnace user has an impact on heat losses so that he or she can increase energy efficiency in a melting process by optimising the factors that lead to heat losses. Some of these factors include keeping furnace lid open, scrap charge size, scrap charge cleanliness, superheating of molten metal and tapping temperature, and furnace lining (DETR, 2000a; Donsbach and Trauzeddel, 2006; ECC, 1998). These factors will be discussed in terms of the subject plant in the following subsections.

Keeping the furnace lid open

Keeping the furnace lid open during melting is a very inefficient furnace practise because it causes excessive heat losses in the form of radiated energy emitted from the surface of the molten metal bath. Normally, the furnace lid needs to be opened for charging, tapping, slag removal, metal composition analysis, and temperature control. During these periods, there occur significant radiation heat losses. Table 5-4 shows radiation energy losses of typical induction furnaces of 6-tonne and 10 tonne capacities. As one can see from Table 5-4, the radiated power loss of an open-lid 6-tonne furnace is 70 kW while it is 9 kW when the lid is closed. This means that 61 kWh of energy can be saved without open lid in an hour, which is a significant potential. Therefore, it is of paramount importance that furnace lids are kept closed during melting process. Unnecessarily opening of them should be avoided. Slag removal and sample taking should be done as quick as possible. As an alternative to open lid method, sampling for analysis and temperature measurement can be performed through a hole with stoppered opened on the furnace lid (CIPEC, 2003). Also, it should be ensured that furnace lids are well fitted and maintained in good condition so that potential leaks can be minimised, and the personnel should be trained about this (DETR, 2000b).

Table 5-4: Effectiveness of furnace lids on radiated heat losses (DETR, 2000)

Furnace capacity (tonnes)	**Energy loss (kW)**		
	Lid open	**Lid closed**	**Difference**
6	70	9	61
10	130	13	117

During the power measurements in the subject plant, it was very often seen that the furnace lids were unnecessarily being kept open during melting process. This was sometimes due to a massive scrap material (usually in the form of gate and runner returns from fettling process) placed into the furnace to melt it as seen in Figure 5-4 and sometimes due to the ignorant behaviour of the furnace operator as seen in Figure 5-5. The furnace operator did not bother to close to the furnace lid many times. This issue was discussed with him, but he was unaware of energy losses due to the open lid. This is one of the reasons why the SEC of melting energy consumption is higher than the best practise value and shows very strong volatility. The radiation energy loss leads to extended melting period to complete the melting process and thus the lost energy has to be replaced by drawing more electricity.

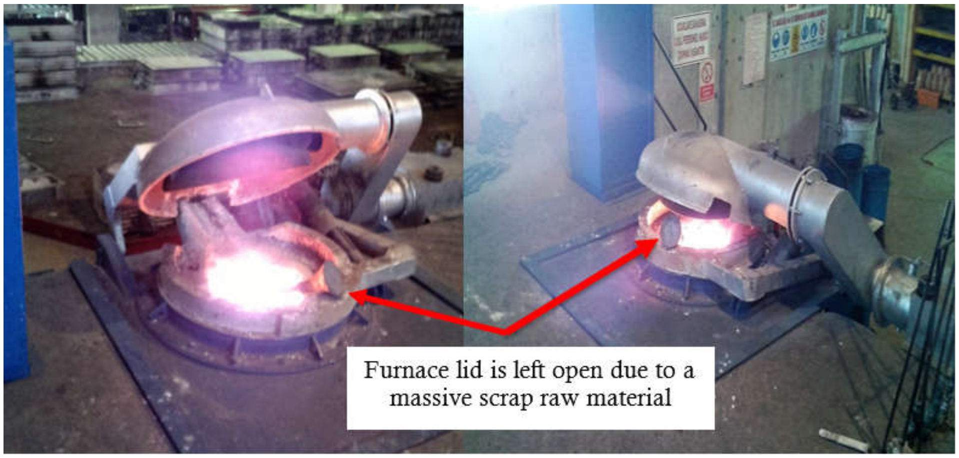


Figure 5-4: Inefficient furnace operation causing to energy losses in the subject plant (Photo taken by the Author)

Figure 5-5: Unnecessary opening of the furnace lid causing to energy losses in the subject plant (Photo taken by the Author)

<u>Scrap charge cleaness and slag removal</u>

Scrap charge cleanness is another important factor affecting melting process energy use and efficiency. Sand casting performing foundries usually use a combination of new scrap and foundry returns such as gates, runners, defected castings. Generally, high content of foundry returns in the scrap charge is usually preferred by foundries to save raw material. However, foundry returns are usually in dirty condition coated with moulding sand. The presence of sand in the scrap charge in induction melting is not desired because sand causes slag formation, which will consume just as much specific energy as needed to melt the iron (Donsbach and Trauzeddel, 2006) presenting heat loss, hence energy inefficiency. Some of energy input to furnace is used to heat the sand in the scrap charge and this heat must be compensated by drawing more power extending the melting period.

If the slag is not removed from the molten metal bath surface, then it will get mixed in the molten metal and be poured into the moulds. This will change the metal composition and cause to casting defects or even product failures in service. In addition, if slag is not skimmed and removed, it causes to slag deposition on furnace lining with time reducing furnace volume and coil efficiency. Slag deposition on furnace lining will reduce the lining life so that lining maintenance will be performed earlier than usual and coil efficiency will decrease due to the poor coupling between lining and furnace coils. To avoid such cases, the slag has to be removed before pouring. However, removing the slag needs the furnace lid to be open during melting which will cause instant radiation heat losses as explained in the preceding sections. All in all, slag means loss and inefficiency and the most efficient way to deal with it to use clean scrap charges (CIPEC, 2003; DETR, 2000a; Padan, 2011).

Concerning the subject plant, unfortunately, they use very high amounts of dirty foundry returns from fettling station such as feeders, gates, and runners. Some examples of these can be seen in Figure 5-6. The furnace operator is aware of the slag formation due to dirty scrap charges and he said that he had reported this situation to the plant management and demanded the scrap returns to be cleaned, for instance, by shot blasting them, but he had got no affirmative response. The subject plant should pay attention to the scrap charge raw material quality for energy efficiency. Using clean scrap charge will not only provide energy efficiency, it will reduce work losses and improve furnace life by reducing the melting operation time.

Figure 5-6: Uncleaned returns used as scrap metal in the subject plant (Photo taken by the Author)

Scrap charge size

The scrap charge should be as dense as possible for faster melting and less SEC. The denser charge material will contain less air between scrap pieces so the heat conductivity will be higher (Padan, 2011). Low density can also cause to oxidation problems in molten metal (DETR, 2000a). Baled scrap is another aspect which should be avoided because baled scraps often involve undesirable moisture and contaminants, which will reduce melting efficiency and quality (DETR, 2000). In addition, small size scrap material will be better in terms of efficient melting. It is generally recommended that the maximum length of any individual scrap piece should be one-third of the crucible diameter (DETR, 2000a).

As for the subject plant, the scrap charge material geometrical specifications are not standard, and the scrap sizes vary. The plant purchases the new scrap charge in the form of baled scrap as seen in Figure 5-7. This is not efficient in terms of melting efficiency and energy consumption as stated in the preceding subsection. As mentioned earlier, the subject plant also uses foundry returns as scrap charge as well. They are in desirable form in terms of density; however, most times they are massive in size, which takes long time to melt and hinders closing the furnace lid.

Figure 5-7: Baled scrap used in the subject plant (Photo taken by the Author)

Sampling, analysing, and adjustment of chemical composition

In melting process, it is necessary to analyse the composition of the molten metal so that adjustments if necessary can be done to acquire the required composition. For this purpose, once the molten metal is ready, the furnace lid is opened, and a piece of melt is taken from the furnace and transported to the laboratory to chemically analyse by a spectrometer. According to the results, appropriate additions are added to the molten metal to acquire the correct composition. The subject plant uses a spectrometer shown in Figure 5-8.

Figure 5-8: Spectrometer in the subject plant (Photo taken by the Author)

It is of importance that sampling, analysis and subsequent composition adjustment are performed with minimum delay (DETR, 2000b). This is because the molten metal must be kept at constant temperature meanwhile the analysis is being conducted. If sampling, analysis, and adjustment processes are prolonged and not performed swiftly, power consumed by the furnace to keep the molten metal at the required temperature will increase. The subject plant is aware of the unnecessary energy expenditure due to a prolonged sampling, analysis, and adjustment processes and they try to complete them with minimum delays. For instance, when the analysis is done in the laboratory, the laboratorian informs the furnace operator by phone as soon as possible. Despite this, as the subject plant management is also aware of, the laboratory where the spectrometer is placed is very far away from the furnaces as shown in Figure 5-9. This has been planned accordingly during the initial layout planning and design of the subject plant. If it was close to the furnace bay, these processes would be less time consuming and less powered would be spent.

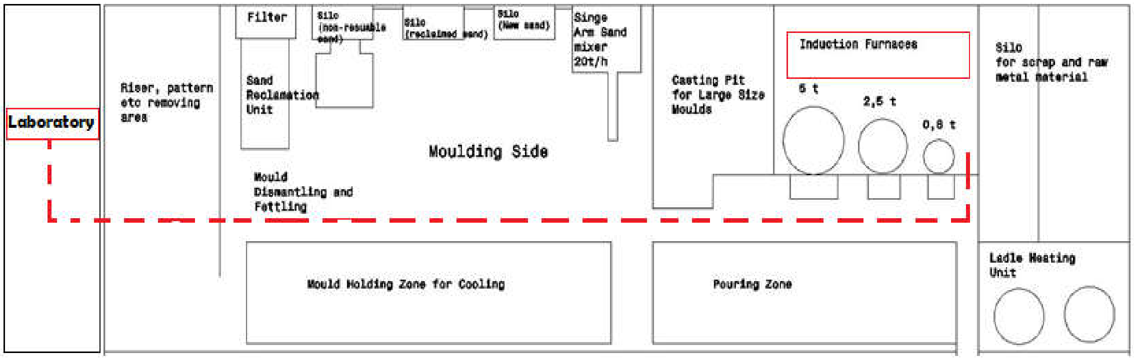


Figure 5-9: The locations of the induction furnaces and laboratory on the plant layout and the route between the furnace bay and laboratory shown in red dashed line

A faster alternative to the above method with a spectrometer in a laboratory is to measure and analyse the metal composition directly in the furnace by using a Laser-Induced Breakdown Spectroscopy (LIBS) technology (De Saro et al., 2005), which does not require a laboratory. This technology uses a laser and a spectrometer and measures the melt composition in real-time in-situ; thus, it provides a faster process. In this system, the compositional data is continuously provided to the operator through a probe placed in the melt so that he can adjust the melt composition faster than previously, which will result in less power use and increase production efficiency (De Saro et al., 2005). More information about LIBS technology can be found in (De Saro et al., 2005).

Employing a LIBS technology can be considered as an ESP for the subject plant. For this purpose, a dedicated research effort is needed to quantify the magnitude of ESP by using a LIBS and see the cost-effectiveness of such an investment. However, it should be born in mind that both the spectrometer used in the laboratory and LIBS technologies are capital investment devices. Therefore, it would had been a wiser decision for the subject plant to opt for a LIBS technology at the design stage of the factory. Alternatively, the proximity of the laboratory to the furnace bay could had been optimised at the layout design stage so that the sampling, analysing, and composition adjustment could have been less time-consuming and thus more energy efficient.

Superheating of molten metal

Superheating refers to heating of molten metal to temperatures slightly higher than the pouring temperature. The objective of this is to compensate temperature losses that will occur during transfer of molten metal by ladles from furnaces to pouring zone. Taking the required final pouring temperature in pouring zone into account, temperature loss should be determined and required superheating needs to be performed to compensate the temperature loss (Padan, 2011) so that the required final pouring temperature will be realised at the pouring zone. This is needed because otherwise can cause to earlier cooling and solidification of the molten metal due to the temperature loss and affect the melting and final product quality. However, unnecessary superheating more than the actual requirement will be energy loss and increase the melting SEC.

The subject plant performs superheating of the molten metal, as well, to recover the heat losses which take places during transfer of the molten metal. Based on their experiences and measurements, the approximate temperature loss during transferring the molten metal is 40°C and they superheat the molten metal +40°C in each furnace cycle as a standard melting rule. When the charge in the furnace gets molten, the operator reads the molten metal temperature by using a thermocouple and takes the necessary actions. The Author`s observations on the superheating practises of the subject plant during the energy audit revealed that unnecessary superheating above +40°C was not observed. Thus, based on the Author`s observations and assuming that +40°C superheating-temperature-rule of the subject plant is technically correct, one can conclude that the plant performs superheating practise correctly in terms of energy efficiency.

Transfer of molten metal

When the molten metal is ready for tapping, carrying ladles should be ready in front of the furnaces to be poured. Any delays in it means energy losses because energy must be continuously supplied to the molten metal to keep at tapping temperature (plus superheating temperature if needed as explained in the above subsection) (Padan, 2011). This will increase the overall energy use of melting process. Besides, carrying ladles must be preheated before tapping. The underlying reason for this is to avoid heat losses when the molten metal is poured to a colder carrying ladle. Therefore, co-operation between the furnace operators and ladle heating department is very important to achieve a timely arrival of preheated carrying ladles at furnace bay.

The subject plant performs ladle preheating (Figure 5-10). They have 3 ladle preheating station. They preheat the ladles approximately to 800°C and keep there about 40 minutes. This temperature and duration are based on their technical knowledge and experience in melting process. During the energy audit, the Author observed that the plant failed to strictly follow this temperature and duration rule. For instance, it was often seen that the ladle preheating department did not heat the ladles up to the appropriate temperature and they had to abort the ladle heating not to delay tapping because the furnaces were already ready for tapping. The ladle heating should had been scheduled paying attention to the tapping time anticipated by the furnace operator. This indicates a lack of cooperation between furnace operators and ladle pre-heating.

Figure 5-10: Ladle preheating in the subject plant (Photo taken by the Author)

Furnace lining

The molten metal bath is in touch with a refractory lining layer of which function is to provide good thermal insulation, adequate mechanical protection of the coil, and good electromagnetic coupling of the coil and the metal charge (Donsbach and Trauzeddel, 2006). Depending on the thermal and construction characteristics of the refractory lining material, there will be a conductive heat transfer from molten metal bath to furnace coil side through the refractory lining. The heat is then absorbed by cooling circuit from the coils.

As Figure 5-11 shows, the rated power of a furnace can be supplied to the furnace only when the lining is at optimal thickness. Above or below the normal thickness, SEC (kWh/t) increases. Heat transfer through the lining can be reduced by increasing the lining thickness, however, the thickness has a bearing on the coupling between the metal charge and coils for an efficient melting (DETR, 2000). In that, coil efficiency increases with thin lining, hence, specific energy consumption reduces. However, heat loss (i.e. conductive heat transfer) also increases through the lining wall due to thin lining and specific energy consumption increases. Therefore, reducing conductive energy loss through increasing the lining thickness is not realisable.

However, it should be borne in mind that the condition of refractory lining deteriorates by time due to erosion and slag accumulation. It wears and losses its thermal characteristics and thickness. Because the optimal thickness and functional characteristics of the lining are lost, this leads to a poor coupling between the coil and metal charge resulting in a poor electric efficiency and this leads to an increased specific energy consumption. Therefore, lining maintenance should be effectively performed, and the lining should be renewed properly when needed. When selecting a lining refractory, it is important to choose one with good quality and low thermal conductivity.

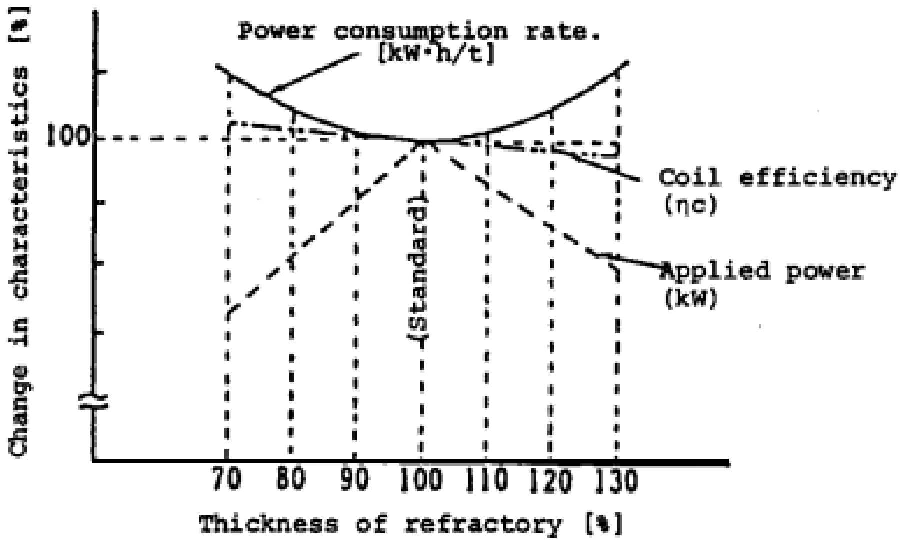


Figure 5-11: Furnace characteristics versus furnace lining thickness (ECC, 1998)

Based on the information given by the plant management, the subject plant is aware of the importance of good lining practise and they perform lining for each furnace when the furnaces complete a certain number of cycles. During the energy audit, the Author came across the lining of a furnace which can be seen in Figure 5-12.


[redacted]

Figure 5-12: Furnace lining in the subject plant (Photo taken by the Author)

5.2.1.2 ESP BY REDUCING CASTING DEFECT RATE

Unrecoverable defect refers to any castings which do not meet quality specifications, cannot be recovered by any repairing process and must be discarded. As said earlier, casting is a very versatile manufacturing process and involves various complex interactions among a lot of process parameters such as mould design, charge metal quality, pouring temperature, and so on as some of them discussed in the preceding subsection.

Defects are almost unavoidable in many casting processes due to the uncertain nature casting involving various disciplines of science and engineering and there is always a chance that casting defect can occur. In fact, casting has a reputation with high defect rates (Zeng, 2013) and almost all foundries suffer from casting defects. As (Ransing et al., 2013) reports that there are more than 100 parameters which affect the quality of the final product and there are multiple optimal conditions in a casting process. As such, there can occur defects at every stage of the casting process due to a number of different factors and they can cause to additional works to repair the defects or sometimes even the whole casting can be lost and rejected. If the casting cannot be recovered through reparing, then an unrecoverable defect is associated and the casting is rejected.

Whether a defect can be repaired, and the casting can be recovered or not will depend on the type and magnitude of the defect. Some casting defects can be recoverable by repairing while some cannot be recovered. Both recoverable and unrecoverable casting defects cause to energy losses. Repairing the casting defects means further processes such as grinding and welding or performing additional heat treatment depending on the defect and these results in additional energy use. As for unrecoverable casting defects, these means that the casting must be reproduced and the entire melting and casting processes which are highly energy intensive have to be repeated. This is a significant energy loss as well as material and work losses.

Rate of the defects in a foundry reflects how skilful that foundry is in casting process. A foundry can reduce the rate of defects by improving their casting skills and taking appropriate actions. The root causes of the defects should be investigated and studied to prevent the reoccurence of defects.

Regarding the subject plant, historical defect rate logs were collected during the energy audit. The subject plant keeps the record of each major defects, defect types, and possible reasons. Figure 5-13 shows the casting scrap rates in the subject plant between 2008-2012. While the subject plant had a very high defect rates in 2008 and 2009, the average defect rate between 2010 and 2012 was 1.2%. Considering that the plant started to operate in mid-of 2007 and the high scrap rates in 2008 and 2009, one can say that the plant improved its casting skills by time and achieved lower defect rates.

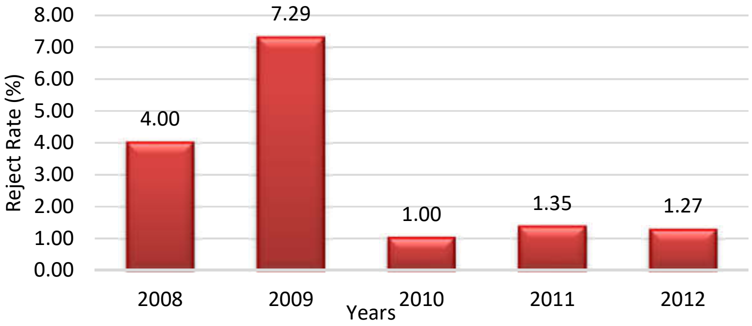


Figure 5-13: Casting Reject Rates due the Unrecoverable Defects

From the historical records, the detailed list of castings defects, defect types, and possible reasons for a year were collected. The total amount of the rejected castings (unrecoverable castings) in the subject plant in a year is 18,3 tonnes. Considering that the average SEC of the melting process is 770 kWh/t, the total energy loss due to the rejected castings makes about 14,091 kWh as can be calculated as follows:

$$energy\ loss = SEC\ x\ amount\ of\ casting \qquad (Eq.\ 5\text{-}1)$$

$$energy\ loss = 770\ \ kWh/t\ {*}18.3t$$

$$energy\ loss = 14{,}901\ kWh.$$

This amount includes only melting energy consumption; however, there are many other processes such as moulding, ladle preheating, fettling, etc. which cause to additional energy use in manufacturing of the rejected casting. Therefore, the total energy loss will be more than 14,091 kWh. Despite this, it is still a significant energy waste and higher than energy consumption of the many other processes of the plant. Table 5-5 lists the casting defect types which resulted in unrecoverable castings and the possible cause of them based on the investigations of the subject plant in a year.

Table 5-5: Defect types and their root causes in the subject plant

Defect	**Root Cause**
Surface cracks	core fraction during pouring
Inappropriate dimension	-
cavities in casting	-
deep cracks in feeder region of the casting	-
faulty shape (eccentricity)	eccentric assemble of drag and cope
cavities on casting surface due to slags	rapture of filter during pouring
molten metal leakage between drag and cope	eccentric assemble of drag and cope
fracture of casting while grinding	excessive heat exposure on casting while grinding
fracture of casting while liquid quenching	over-quenching
damage on casting by oxyfuel cutting while removal of feeder, gates, and risers	labor factor
surface defects on casting	pouring at low temperature
casting cavities and surface cracks on the casting	-
surface and deep fracture on the casting	-
cracks and cavities on the casting	-
cavities in the casting	pouring at low temperature due to the furnace failure
surface cracks on casting	-
inadequate hardness	

As stated above, the energy waste due to the unrecoverable casting rate of 1.27% 2012 is 14,091 kWh. If the plant had improved its casting skills and taken necessary actions to prevent the casting defect occurrence, at least 14,091 kWh of electricity consumption would have been avoided in a year. This can be accepted as an ESP by avoiding the casting rejects for the subject plant. Taking the challenging nature of casting processes in terms of defects, it is not rationale to expect a foundry to completely achieve a zero level of defect and reject rate. However, as mentioned earlier, a foundry can improve its casting skills and reduce the defect rates and and associated unnecessary energy consumption. Therefore, 4 different reject rate reduction scenarios have been defined for the subject plant. These are 25%, 50%, 75%, and 100% reductions of the base case unrecoverable defect rate of the subject plant (i.e. 1.27%). The corresponding scrap rates based on the reduction scenarios are 0.96%, 0.63%, 0.31%, and 1.27%, respectively. These are presented in Table 5-6.

Table 5-6: Scenarios of ESP by reducing reject rates

	Base case Scenario	**25% reduction of base case scenario reject rate**	**50% reduction of base case scenario reject rate**	**75% reduction of base case scenario reject rate**	**100% reduction of base case scenario reject rate**
Reject Rate (%)	1.27%	0.96%	0.63%	0.31%	1.27%
Rejected Castings (t/year)	18.3	13.8	9.1	4.6	18.3
Specific energy use (kWh/t)	770	770	770	770	770
Unnecessary Energy Consumption due to rejected castings (kWh/year)	14,901	10,678	7,063	3,531.50	0
Melting energy consumption					
ESP, %	-	28%	52%	76%	100%
ESP, kWh/year	-	4,223	8,642.60	11,370	14,901

In this study, ***ESP By Reducing the Casting Defect Rate*** for the subject plant will be assumed based on the scenario that the plant will achieve a 50% reduction of the base case reject rate. In this case, subject the plant can achieve a reduction of 52% of the unnecessary energy consumption due to the unrecoverable defects. This will be assumed as a representative ESP owing to the defect rate reduction for the melting process of the subject plant.

If the plant can reduce its unrecoverable defect rate at 50%, the scrap rate will be 0.63% and the corresponding scrap casting will decrease from 18.3 t to 9.1 t. Hence, the new energy loss because of the unrecoverable defects will be 7,063kWh in a year based on the specific melting energy consumption which is 770 kWh/t. Thus, the corresponding annual ESP (kWh) is 8,642.6 kWh. As it was given earlier, the total annual energy consumption of the melting furnaces is 1,026.133 MWh.

Hence, ESP% by Reducing the Defect Rate can be calculated as follows:

$$\%\ \text{ESP} = \frac{Annual\ ESP\ reducing\ the\ defect\ rate}{Annual\ melting\ energy\ consumption} \frac{8{,}642.6\ kWh}{1{,}026.133\ MWh} = 0.82\%$$

Thus, ESP% will be 0.82%. Despite it seems a low percent, it is greater than the electricity consumption of many other energy using systems in the plant. Therefore, it is worthwhile to consider. This ESP is designated as ESP 5-2.

5.2.2 REVIEW OF THE EPS IDENTIFIED IN THE MELTING PROCESS AND TOTAL ESPs

As a result of the energy audit analysis focusing on the melting process of the subject plant, two major ESPs have been identified:

1. ESP 5-1, ESPs by Improving Melting Process
2. ESP 5-2, ESP by Reducing Casting Defect Rate

These ESPs are summarised and documented in Table 5-7. Overall, the total annual ESP in the melting process of the subject plant will be the sum of ESP 5-1 and ESP 5-2. Thus;

$$ESP\_melting = ESP\ 5\text{-}1 + ESP\ 5\text{-}2$$

$$ESP\_melting = 146{,}220 + 8{,}642.6 = 154{,}862.6 \quad kWh/year$$

Table 5-7: ESPs in melting process of the subject plant by improving their melting practise

ESP No:	**ESP Measure**	**EPS (%)**	**Annual ESP (kWh/year)**	**Annual PESP (kWh/year)**	**Annual ECSP (€)**	**Annual CO_2 ERP ($kg\text{-}CO_2$)**
5-1	ESP by Improving Melting Process	14.25 %	146,220	361,163.7	€9,577.41	70,523.58
5-2	ESP by Reducing Casting Defect Rate	0.82 %	8,642.6	21,347.2	€566.1	4,168.42
Overall $ESP_{melting}$		15%	154,862.6	382,511	10,143.5	74,692

Considering that the annual melting energy consumption is 1,026.133 MWh, the % $ESP_{melting}$ will be:

$$\%\ \mathrm{ESP}melting = \frac{Overall\ ESPmelting}{Annual\ energy\ consumption} \frac{154{,}852.6\ kWh}{1{,}026.133\ MWh} = 15\%$$

Using Equations 3-1, 3-2, and 3-3, the associated overall annual PESP, annual ECSP, and annual CO_2 ERP are 382,551 kWh, €10,143.5, and 74,692 kg-CO_2, respectively.

5.3 GRINDING SYSTEM

The plant uses two types of grinding machines. One is a pendant pendulum-grinding which consists of a rotating grinding wheel driven by an electric motor and the other is a manual type electrical grinding machine (Figure 5-14). There are 3 main grinding stations with pendulum-grinders and 3 small scale grinding stations with manual electrical grinding machines. Figure 5-15 illustrates a typical grinding action in the subject plant while Figure 5-16 shows the simplified diagrams of the three grinding stations.

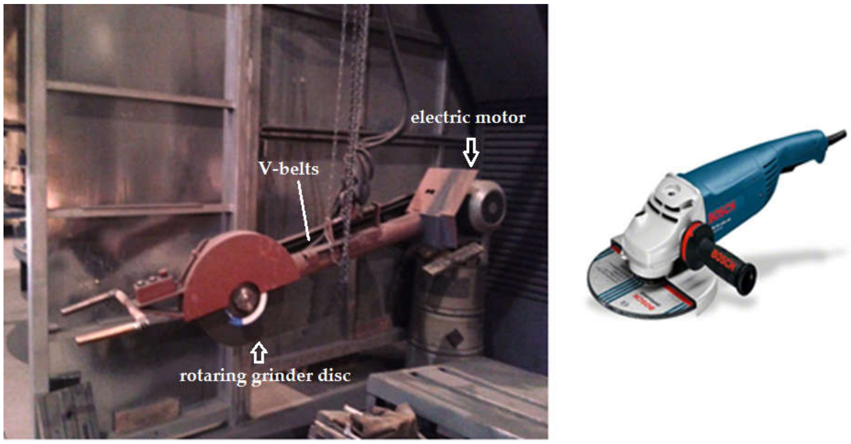


Figure 5-14 Pendant pendulum-grinder (left) and manual grinding machine used in the plant

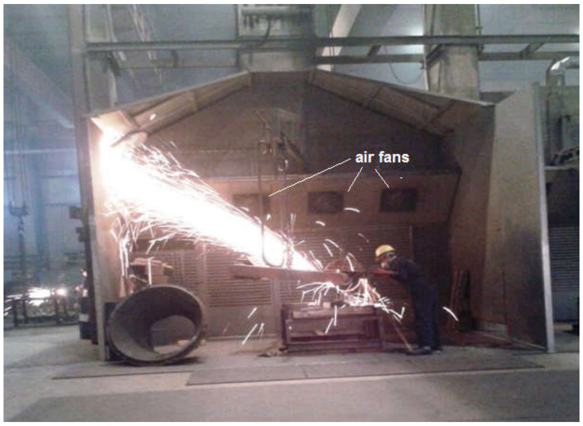


Figure 5-15: A worker while grinding with the pendulum-grinder (Photo taken by the Author)

The pendulum-grinders are equipped with a rotating grinding wheel which is driven through an electric motor. Power transmission between electric motor and rotating grinding wheel is achieved through 2 V type belts. The technical specifications for the electric motor is given in Table 5-8 below. The technical specifications for manual grinding machine is given in Table 5-9.

Table 5-8: Specifications of the electric motor used in pendulum grinders (source: manufacturer`s data)

Maker/Type	CAMAK/ AGM 132 S 4
Energy Efficiency Rating	EFF2
Power Rating	5.5 kW

Table 5-9 Specifications of the manual grinding machine (manufacturer`s data)

Maker	BOSCH
Type	GWS 26-180 JH Professional
Power Rating	2.6 kW

As seen above, a pendulum-grinder has a power rating of 5.5 kW while a manual grinding machine has 2.6 kW. There are 3 pendulum-grinders in totals which makes 16.5 kW. Also, working hours for pendulum-grinders are quite long in comparison to the manual grinding machines where only small surface corrections are performed on the casting surface which were previously grinded by the pendulum-grinders. Therefore, energy audit in grinding systems will be focused on pendulum-grinders.

5.3.1 IDENTIFYING THE ESPS IN THE GRINDING SYSTEM

Because the pendulum-grinders are driven through electric motors, their power performance will be evaluated and the impact of using more energy efficient electric motors on the energy consumption will be assessed. Furthermore, because V type belts are used for power transmission, using energy efficient belts will be assessed. Replacement of the whole pendulum-grinder obviously will be a pointless action because the electric motors and V-belts are the main elements that determine the energy efficiency of the machine.

The grinding stations in the subject plant are equipped with ventilation fans which are absorbed and transfer the dust air resulting from grinding processes to the central ventilation system. As indicated in Figure 5-16 there are 14 fans with the same size and specifications and each one has a power rating of 0.75 kW. The total installed power capacity of fans for grinding and welding zone is 10.5 kW, which is worth to consider for energy saving. In addition, there are 3 different fan systems, and each have an electric motor with 3 kW power rating, hence total installed power of 9 kW. The allocation of these fans over the grinding stations is as follows:

- Grinding Station 1: 4 fans
- Grinding Station 2: 2 fans
- Grinding Station 3: 2 fans

- Grinding Station 4: 2 fans
- Grinding Station 5: 2 fans
- Grinding Station 6: 1 fan

More detailed information regarding the fans specifications and installed electric motors could not be obtained because the fans and electric motors are embedded in a closed medium.

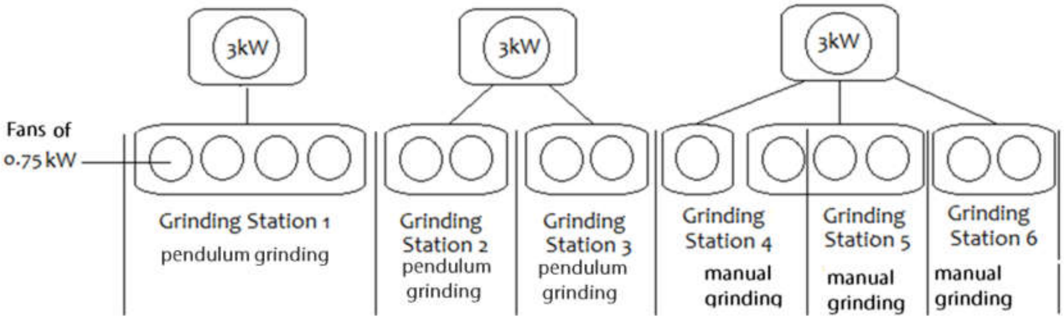


Figure 5-16: Simplified diagram of grinding stations and installed ventilation fans

5.3.1.1 EXISTING PERFORMANCE OF THE GRINDING STATIONS

The grinding process performed in Grinding Station 1 in a typical production shift has been chosen as a representative for the analysis. Thus, power consumption measurement was done for a typical production day. Figure 5-17 shows the power demand (kW)-time graph for the pendulum-grinder used in Grinding Station 1 in a grinding process in a typical production shift.

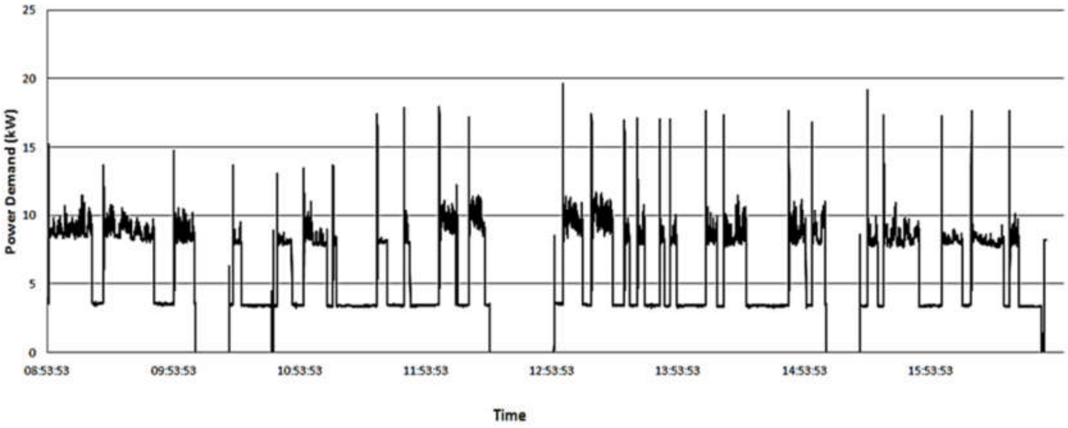


Figure 5-17: Power demand -time graph for a pendulum-grinders in a grinding process in a typical production shift

Power and energy consumption details are calculated from the tabulated power consumption data obtained through PEL 103 and listed in Table 5-10. The total energy consumption in the production shift based on the power measurement was 42.927 kWh.

Table 5-10: Power and energy consumption measurement results

		Source/equation/calculation
Total time energy consumed (a)	6.848 hours	Based on power measurement
Total energy consumption in a production shift (b)	42.927 kWh	Based on power measurement
Average power demand in energy consumed time duration (c)	6.276 kW	c=b/a

The overall energy consumption of the subject plant grinding system is sum of the energy consumption of consumptions of Grinding Station 1, Grinding Station 2, and Grinding Station 3. Based on the recommendation by the plant management, it is assumed that all three stations approximately consume the same amount of electricity per production shift. This assumption is quite rational because these stations perform the same kind of works and workload per shift for each station are somewhat the same, as reported by the plant management. Also, the same type of grinding machine (i.e. pendulum-grinder) is used in all grinding stations. Accordingly, calculation of the energy consumption of grinding process in the subject plant can be presented in Table 5-11 below.

Table 5-11: Energy consumption calculations of grinding process

		Source/ equation/ calculation
Energy consumption of a station in a production shift (a)	42.927 kWh	
Number of grinding stations in a dayshift (b)	3 stations	
Number of grinding stations in a nightshift (c)	3 stations	
Daily energy consumption of grinding process (d)	257.562 kWh	d=a*b+a*c
Annual energy consumption of grinding process (e)	75,980.8 kWh	e=d*295
Annual energy cost (f)	€ 4,976.74	f=e*EUCR
Annual CO_2 emissions (g)	37,154.6 kg-CO_2	g=e*CO_2-EF

Hence, the annual electricity consumption of the grinding process in the subject plant is 75,980.8 kWh accounting for 2.6% of the overall plant electricity consumption. The associated annual energy cost, and annual CO_2 emissions are €4,976.74 and 37,154.6 kg-CO_2, respectively.

Having determined the overall energy consumption of the grinding systems, the identified ESPs within the grinding system are explained in the following subsections.

5.3.1.2 ESPS BY KEEPING THE IDLE MACHINES OFF

During the measurement of the energy consumption of Grinding Station 1 some observations have been made. The most obvious energy waste in the station was observed as running of the fans during idle hours. The function of air fans in the grinding station is to absorb the dust produced during grinding processes. These fans are to work during grinding processes and they are not needed during production downtime. Therefore, the operator is supposed to turn off the fans. However, it was observed that the operator did not bother to turn off the fans and even he sometimes forgot it and left it on. This can be observed in the power demand graph in Figure 5-17. On the graph, it can be seen that there is a constant background power demand which is around 3.4 kW. This value belongs to the air fans and it does not add value to the grinding process. Thus, it can be accepted as energy waste due to the non-value-added activity emanenating from the ignorance of the worker **(i.e. Human Factor).** Figure 5-18 has been prepared to best illustrate this waste energy.

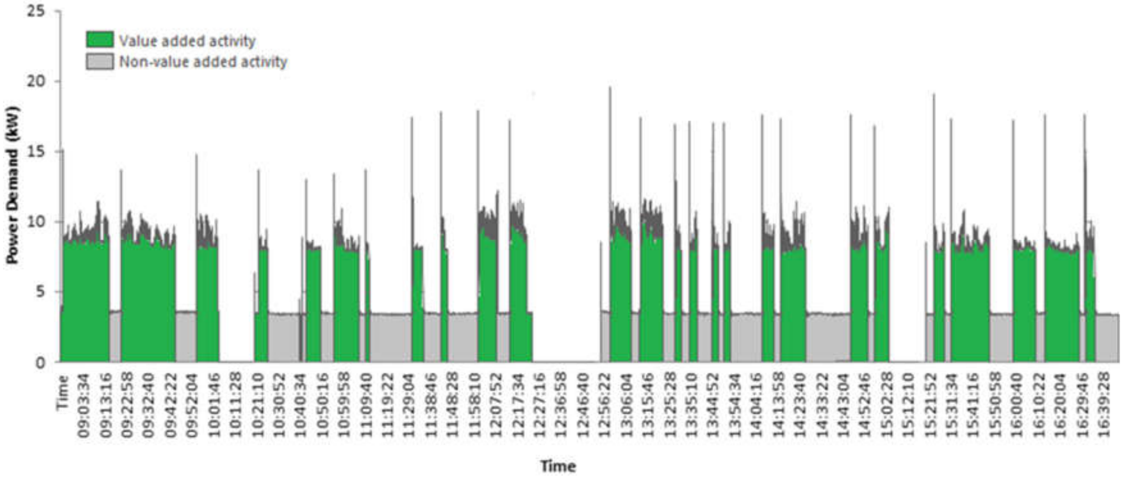


Figure 5-18 Value added and non-value-added power consumption during the grind process

However, it is not rational to expect the operator to turn off the fans each time when not necessary because there are sometimes when the operator has to set the product or change its position to grind different surfaces. In those periods, the fans continue to operate. Apart from those times, the fans should be turned off. For the purpose of this study, periods more than 5 minutes will be accepted as non-value-added times. Thus, 8 non-value-added times in total have been identified. Energy consumption during these periods has been calculated from the tabulated energy data and presented in Table 5-12. Total energy consumed in non-value-added times is 6.515 kWh which makes 15% of the total energy use of the grinding station. If the ventilation fans are turned off, 15% of energy use of the grinding station will be reduced and saved. Thus, there is an ESP% of 15%.

Table 5-12: Energy consumption in non-value-added time periods

Non-value-added time period No:	**Electricity use (kWh)**
1	0.556559
2	0.95286
3	1.092865
4	0.790829
5	0.786268
6	1.143601
7	0.589488
8	0.603279
Total	6.515

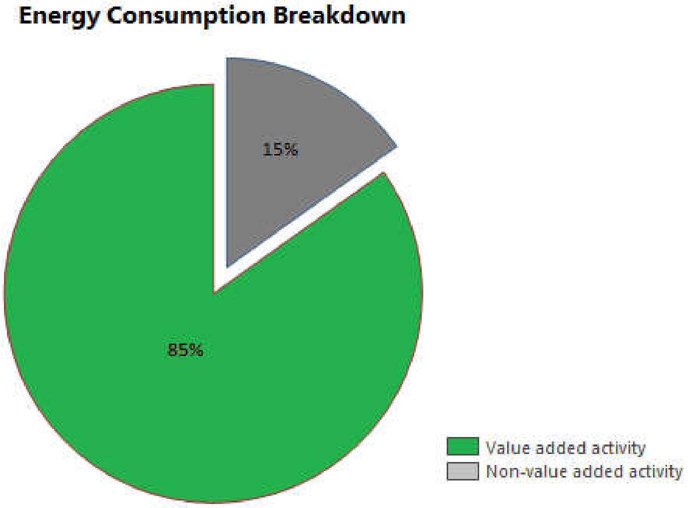


Figure 5-19: Share of non-value-added activity on overall energy consumption

Assuming that other 2 grinding stations have the same operational characteristics, annual ESP, primary ESP, ECSP, and CO_2 ERP in grinding process by keeping the idle machines off can be calculated as presented in Table 5-13. The associated ESP can be designated as **“ESP 5-3, ESP by Keeping the Idle Machines off”.**

Table 5-13: Calculations for ESP 5-3: Annual ESP, PESP, ESCP, and CO_2 ERP

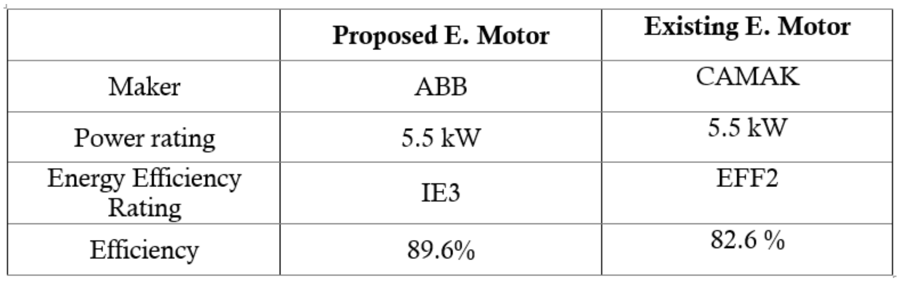
		Source/equation/calculation
ESP (a)	15%	Calculated above in the text
Annual energy consumption of grinding process (b)	75,980.8 kWh	Table 5-11
Annual ESP (c)	11,397 kWh	c=a*b
Annual PESP (d)	28,150.6 kWh	Equation 3-1
Annual ECSP (e)	€746.5	Equation 3-2
Annual CO_2 ERP (f)	37,154.61 kg-CO_2	Equation 3-3

As Table 5-13 summaries, annual ESP% in the grinding stations by keeping the idle fans off will be 15%. The associated annual ESP, PESP, ESCP, and CO_2 ERP will be 11,397 kWh, 28,150.6 kWh, €746.5, and 37,154.61 kg-CO_2, respectively.

5.3.1.3 ESPS BY USING MORE EFFICIENT ELECTRIC MOTOR

As given in Table 5-8, the energy efficiency class of the electric motor of the pendulum grinders is EFF2. EFF2 is an old efficiency class and it corresponds to the IE1 class which is the lowest efficiency class in the EU Regulation 640/2009 and IEC 60034-30 classification standard as explained in Appendix B. The impact of replacing the existing electric motor with a premium energy efficient electric motor will be analysed for the electric motor of the pendulum-grinders and ESP will be identified. The associated ESP is designated as “**ESP 5-4, ESP by Using Premium Efficiency Electric Motor”.** The specifications of the proposed electric motor are compared with the existing one in Table 5-14.

Table 5-14: Rated specifications of the proposed electric motor



	Proposed E. Motor	**Existing E. Motor**
Maker	ABB	CAMAK
Power rating	5.5 kW	5.5 kW
Energy Efficiency Rating	IE3	EFF2
Efficiency	89.6%	82.6 %

Following the equation B-8 and B-9 in Appendix B, energy, environmental and monetary benefits of using more efficient electric motor in ventilation system have been calculated and presented in Table 5-15 below.

Table 5-15: Calculations for ESP 5-4: annual ESP, PESP, ESCP, and CO_2 ERP

Hours of electric motors operate in a shift (a)	5.48 hours	From Figure 5-18 (value added times)
Energy Saving of an electric motor in one grinding station in a shift (b)	2.13 kWh/day	Equation B-8
Number of electric motors (c)	3	
Number of shifts (d)	2	
Number of working days (e)	295	
Annual ESP in all Grinding Stations (f)	3,770.1 kWh	f=b*c*d*e
Annual PESP (g)	9312.14 kWh	Equation 3-1
Annual ECSP (h)	€247.1	Equation 3-2
ESP % (i)	4.9%	Appendix B
Annual CO_2 ERP (j)	1,847.35 kg-CO_2/year	Equation 3-3

As Table 5-15 summaries, annual ESP% in grinding stations by using premium efficient electric motor instead of the existing electric motors is 4.9 % and corresponding annual ESP, PESP, ECSP, and CO_2 ERP will be 3,770.1kWh/year, €247.1, and 1,847.35 kg-CO_2/year, respectively.

5.3.1.4 ESP BY USING EFFICIENT TRANSMISSION BELT

As described earlier, the grinding rotating wheel in the pendulum-grinder is driven through an electric motor. Power transmission between electric motor and rotating grinding wheel is achieved through 2 standard V-type belts. Besides the energy lost due to the inefficiency of the motor as well as operating inefficiently, there is an additional energy waste while transmitting the power from electric motor to the rotating grinding wheel of the pendulum-grinder. This is because the power at the drive shaft of the electric motor cannot be transmitted to the rotating wheel with 100% efficiency due to the factors such as slippage, energy used to the flex the belt while it goes around pulleys, and stretching and compression of the belt (Muller and Papadaratsakis, 2003)

The maximum efficiency of standard V belts is about 94% (Muller and Papadaratsakis, 2003). An alternative of standard V belts is notched V belts as shown in Figure 5-20. “A notched belt has grooves or notches that run perpendicular to the belt’s length, which reduces the bending resistance of the belt. Notched belts can use the same pulleys as cross-section standard V-belts. They run cooler, last longer, and are about 2% more efficient than standard V-belts (DOE, 2012)”.

Figure 5-20: Notched belts (DOE, 2012)

Hence, energy saving potential by replacing the current standard V belts used in PBGM with notched V belts can be estimated as follows:

$$ESP = Annual\ energy\ consumption * (1/\eta 1 - 1/\eta 2) \qquad (Eq.\ 5\text{-}2)$$

Where, $\eta 1$ is the efficiency of current standard V belts is, $\eta 2$ is the efficiency of the proposed notched V belts. Assuming $\eta 1=94\%$ and $\eta 2=96\%$ (Muller and Papadaratsakis, 2003), the ESP by using the notched V belts instead of standard V belts has been calculated together with the corresponding annual PESP, ECSP and CO_2 ERP and presented in Table 5-16. The associated ESP is designated as "ESP 5-5 ESP by More Efficient Transmission Belt".

Table 5-16: Calculations for ESP 5-5: annual ESP, PESP, ESCP, and CO_2 ERP

		Source/equation/calculation
Efficiency of existing V belt, $\eta 1$ (a)	94%	(Muller and Papadaratsakis, 2003)
Efficiency of notched V belt, $\eta 2$ (b)	96%	(Muller and Papadaratsakis, 2003)
Annual Energy Consumption (c)	75,980.8 kWh /year	Table 5-11
Annual ESP (d)	1,582.9 kWh /year	Equation 5-2
ESP % (e)	2%	e=d/c%
Annual PESP (f)	3,909.76	Equation 3-1
Annual ECSP (g)	103.68	Equation 3-2
Annual CO_2 ERP (h)	774.04 kg -CO_2	Equation 3-3

As Table 5-16 summaries, annual ESP% in grinding stations by using notched V belts instead of the existing standard V type belts is 2%. The corresponding annual ESP, annual PESP, annual ECS, and annual CO_2 ERP will be 1,582.9 kWh, 3,909.76 kWh, €103.68, and 774.04 kg-CO_2/year, respectively. A simple investment is needed for this ESP and should be assessed in terms of cost effectiveness.

5.3.2 REVIEW OF THE ESPS IDENTIFIED IN THE GRINDING SYSTEM

In total, three ESPs have been identified:

- ESP 5-3, ESP by Keeping the Idle Machines off
- ESP 5-4, ESP by Using Premium Efficient Electric Motor
- ESP 5-5, ESP by Using More Efficient Transmission Belt

The total ESP in the grinding systems, ESPgrindingsystem will be the sum of the all ESP identified in the grinding systems. Thus,

$$\text{ESPgrindingsystem} = \text{ESP 5-3} + \text{ESP 5-4} + \text{ESP 5-5}$$

$$\text{ESPgrindingsystem} = 11{,}397 + 3{,}770.1 + 1{,}582.9 = 18{,}655.9 \text{ kWh}$$

If the all identified ESPs are materialized, an overall ESP of 18,665.9 kWh in the grinding systems can be realized. This is about 24.5% of the overall annual grinding system energy use (i.e. 76,187.3 kWh). The associated annual ESP, PESP, ECSP, and CO_2 ERP will be 18,665.9 kWh, 46,080 kWh, €1,221.9, and 9,122.6 kg-CO_2, respectively. These ESPs together with the total ESP in the overall grinding system are summarised and documented in Table 5-17.

Table 5-17: ESPs Summary of ESPs identified in Grinding System

ESP No:	Measure	EPS (%)	Annual ESP (kWh/year)	Annual PESP (kWh/year)	Annual ECSP (€)	Annual CO_2 ERP (kg-CO_2)
5-3	ESP by Keeping the Idle Machines Off	15%	11,397	28,150.6	746.5	5,573.13
5-4	ESP by Using Premium Efficient Electric Motor	4.9%	3,770.1	9,312.1	247.1	1,847.3
5-5	ESP by More Efficient Transmission Belt	2%	1,582.9	3,909.7	103.68	774.03
Overall $ESP_{grindingsystems}$		24.5%	18,655.9	46,080	1,221.9	9,122.6

5.4 ABRASIVE BLASTING SYSTEM

The abrasive blasting system used in the subject plant is a mechanical abrasive blasting machine (shown in Figure G5 – G8 in Appendix G) which is much more efficient than the other alternative, pneumatic abrasive blasting machine (Beeley, 2001) and energy is used more efficiently. The abrasive blasting system is one of the most complex energy using systems in the subject plant incorporating various elements. The abrasive blasting machine possesses 2 centrifugal impellers (as shown in Figure G-6) which are driven by two electric motors. In addition to the impellers, the blasting system incorporates a vibrator driven two electric motors (i.e. separator), a local dust collection system, an elevator and screw, a hook and hoist, and a dust grinder, all powered by electric motors. Table 5-18 shows the power ratings for each element.

The workpieces to be abrasive blasted are placed on a load tray hung to a hook (as shown in Figure G-5) and the tray is moved into the blasting cabinet by using a built-in hoist. The hook rotates around its own axis so that the abrasive will strike every surface of the workloads. This kind of blasting machines are called as Spinner Hanger Hook Blast and they are ideal for blasting the mixed loads of diverse size and irregularly shaped workpieces.

The abrasive material stored in the hopper (Figure G-7) flows down into a pneumatic nozzle which blows the abrasive into the centre of rapidly rotating blasting impeller. The rotating blades at high speed accelerates the abrasive media and throws the abrasive from the end of the blades with centrifugal forces towards the workpiece suspended to the rotating hook. Thus, the workpiece surfaces are blasted and cleaned. A dust collection system collects the dust ensuing from the blasting of the workpieces Figure G-8. A carrying system which consists of a rotating helicoid screw at the base of the blasting cabinet and an elevator carries the spent abrasive abrasives into the separator. The reusable part of the spent abrasive is separated by the vibrating separator and stored in a hopper whereas the remaining unusable part is stored in another hopper for discarding.

5.4.1 IDENTIFYING ESPs IN THE ABRASIVE BLASTING SYSTEM

The abrasive blasting system in the subject plant responsible for about 33,133.8 kWh of annual electricity consumption based on the power measurement. As seen in Table 5-18, the total installed power rating of the blasting system is 62.15 kW. As noticed, the most energy intensive elements of the abrasive blasting machine are the blast impellers and air fan. Power rating of each electric motor driving the impellers is 22 kW, which accounts of 71% of the overall system power rating. The mechanical energy produced by the electric motors are transferred to the blast impellers via V-belts.

On the other hand, the electric motor of the air fan is 11 kW accounting for %18 of the overall system power rating. The electric motor is directly connected to the fan.

As explained earlier, the major impact on overall energy consumption comes from the electric motors of the fan and blast impellers since these system components accounts for 89% of the overall power demand (as shown in Table 5-18). Therefore, focusing on their energy consumption with a systems approach to explore energy savings will be a proper action. Increase in their energy efficiency or reduction in their sizes will correspondingly contribute to the overall system energy efficiency. The name plates of the electric motors of the impellers and air fan indicate the following data in Table 5-19.

Table 5-18 Power rating of the abrasive blasting system components

Subsystem	**Driver**	**Power rating (kWh)**	**Quantity**	**Total installed power (kW)**	**Proportion (%)**
Blast impellers	Electric motor	22	2	44	71
Air fan		11	1	11	18
Vibrator		1.1	1	1.1	2
Elevator		4	1	4	6
Hook and Hoist		1.5	1	1.5	2
Dust grinder		0.5	1	0.55	1
Total				62.15	100

Table 5-19: Rated specifications of the electric motor of the impellers in the abrasive blasting system

	Fan electric motor	**Impellers e.motor**
Power rating	11 kW	22 kW
Energy Efficiency Class	EFF1	EFF1
Rated Efficiency	90%	92.50%

In order to analyse the energy consumption performance of the abrasive blasting system, power and energy measurement have been performed during a typical day and night production shift. For this purpose, PEL 103 has been used for the energy and power data logging at 1 second time intervals. As well as measuring the energy performance of the system and subsystems itself, the system operator`s impact on the energy consumption has been observed.

The power demand profile for the abrasive blasting process in a typical day and night production shift is shown in Figure 5-21 and Figure 5-22, respectively. Three distinct power demands can be observed as indicated in Figure 5-21. Instant large power peaks are belonged to the motor start-ups. After the start-up, the electric motors draw about their rated power demand during the blasting process is taking place. This can be defined as the entire system power demand as indicated in Figure 5-21.

When the electric motors of abrasive-blasting impellers are turned off, the bag house air fan can still run because of the system design. The air fan is supposed to operate during abrasive blasting process and should be turned off when not needed. However, the system operator many times left the air fan running after turning off the impellers. The background power demand after entire system power demand in Figure 5-21 belongs to the air fan although it should not operate when there is no need for ventilation. Energy consumed by the air fan is unnecessarily and wasted. Therefore, **there is an ESP by turning off the fan when not needed.**

As noticed in the data in Table 5-19, the energy efficiency rating of the motors is EFF1. Hence, **there is an ESP by replacing the existing electric motors with premium efficiency electric motors in IE3 class.** The efficiency of the electric motor itself is only one of the factors which have a bearing on the overall energy consumption. An energy efficient electric motor can be used inefficiently. From a systems approach perspective, the entire system and other factors which can affect the motor energy consumption should be taken into account.

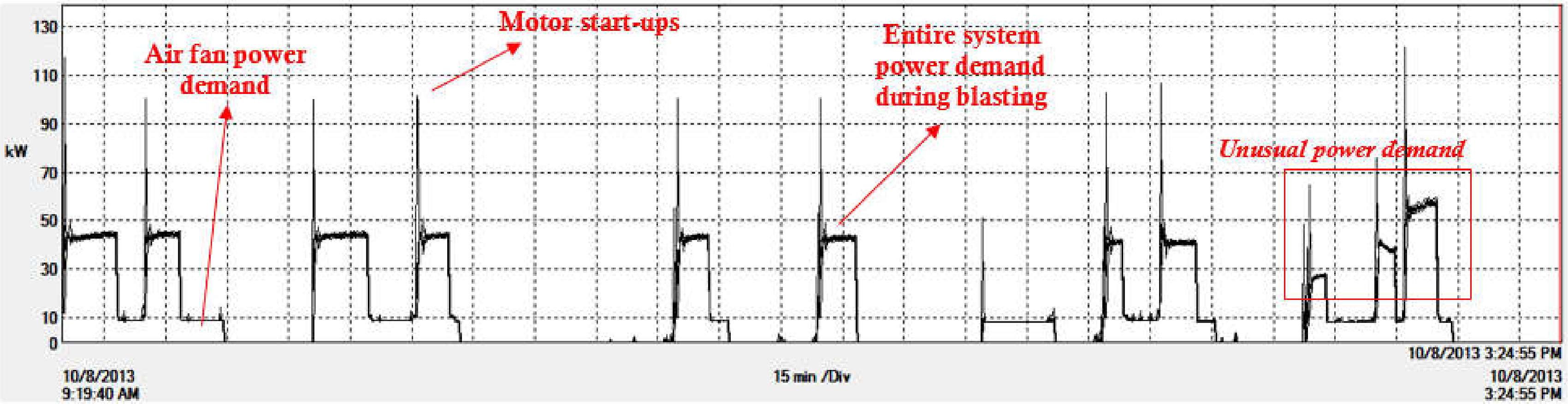


Figure 5-21**:** Power demand of the abrasive blasting process during a typical day time production shift

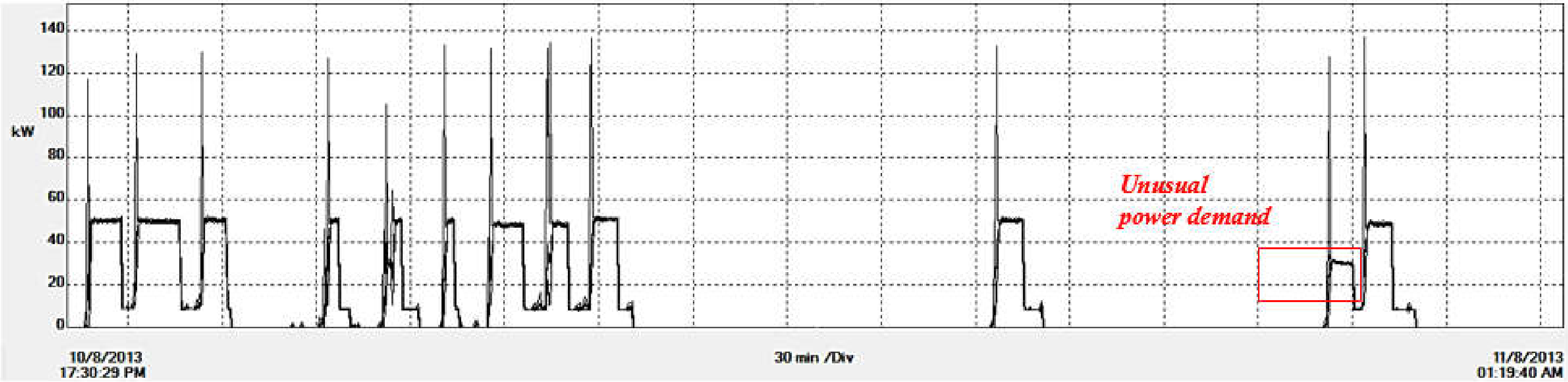


Figure 5-22: Power demand of the abrasive blasting process during a typical night time production shift

For example, the transmission efficiency between the electric motors and blast impellers can be increased by replacing the existing V-belts with a notched type V-belt, which is more efficient than the existing one. Thus, there is an additional energy saving potential by improving the transmission efficiency.

From the perspective of a systems approach, an important factor determining the energy efficiency of the blasting process is the optimum processing cycle. Optimum blasting cycle should be paid attention and over-blasting should be avoided. In this point, the machine operator has a vital role because the blasting system cannot determine when the workpiece surfaces are optimally blasted and the optimum blasting cycle is covered.

Duration of abrasive blasting time for each batch is important for energy saving purposes. When the required surface quality is obtained, the additional abrasive blasting will be energy waste. However, it is very difficult to define a reference surface quality and optimum blasting time in this case study to see whether the operator uses the machine energy inefficiently by performing over-blasting. This is due to the fact that product mix is extremely diverse and surface quality of the workpieces are not extremely important since they are casting (i.e. heavy duty work where surface quality is not a priority). Bearing this fact in mind, it will be assumed that the system operator abrasive-blasts the workpieces for an optimum blasting cycle and energy is not wasted.

As is understood from the preceding paragraph, the amount of the workpieces to be blasted and required surface quality determine the blasting process cycle, thus so does the energy consumption. Because the product mix of the subject plant is very diverse, diverse products of different hardness, size and dimensions are blasted in the abrasive blasting system. In fact, this is the nature of Spinner Hanger Hook Blasting systems. As a result, diverse products of different hardness, size and dimensions are arriving in the abrasive blasting station which means that each product to be blasted in the abrasive blasting system has different blasting times. To handle this complexity, the system operator in the subject plant loads the items to the abrasive blasting system in batches. He groups similar products with respect to their estimated blasting times based on his experiences. Thus, similar work pieces in terms of the required blasting time are blasted together and the maximum capacity of the blasting machine is utilized. This is an effective solution to handle such complexity and improve energy efficiency by increasing the system throughput.

Also, the distance between the workload and blasting impellers should be optimum; otherwise, the blasting energy will diminish until the accelerated abrasive reaches to the workpiece surface if this distance is too far. This will result in longer blasting cycles than normal which will cause the excessive energy consumption. This is particularly important for the blasting machines which are designed for blasting the flat surfaces because the distance between the flat surfaces and blast impellers can be optimised and kept constant. On the other hand, this is difficult for spinner-hanger blast systems, as is the case with the subject plant, because the distance will be changing owing to the irregular shape and volume of the workpieces to be blasted. In fact, optimum distance between the work load and blasting impellers is a factor which should be paid attention during the design and manufacture of an efficient blasting machine. Unfortunately, to the knowledge of the Author of this thesis, there is no criteria or standard such as energy labelling to evaluate the energy efficiency of an abrasive blasting machine. This can be recommended as a future work.

Other factors which will affect the blasting cycles are flow rate and pattern of the blast stream. The full flow rate of the abrasive which the blasting impellers are designed for should be maintained and kept constant during operation. A reduction from full flow rate will reduce the cleaning efficiency and increase the blasting cycle. Further, the electric motor of the impellers will draw less current compared to the rating current and will operate inefficiently. Therefore, insufficient, or excessive flow rate to the impellers should be avoided. Insufficient flow can be due to the low amount of abrasive material in the system. As mentioned earlier, some of the abrasive medium which cannot be reused will be discarded by the separator; therefore, amount of the abrasive medium in the system will be lessen by time. Therefore, new abrasive should be regularly added to the system for an efficient blasting operation.

On the other side, excessive flow can be due to the improperly working flow control valves. Excessive abrasive flow than normal can block the feed lines or the impeller can be chocked. Besides, any problems within the system components such as the blasting impellers, feed lines, separator, and so on can also result in system inefficiencies. For instances, wears on the blades and other parts of the impellers can preclude an optimum flow pattern reducing the cleaning efficiency. A malfunctioning separator, e.g. because of worn mesh filter, can change the composition of the abrasive medium which will again affect the cleaning efficiency negatively.

In this respect, regular maintenance of the components of the blasting system should be conducted as a preventative action. In addition to this, the current drawn by the electric motors of each impeller should be continuously monitored which can be carried out by means of an amperage monitoring system integrated to the blasting system. Thus, the operator can be aware whether the impeller motors are operating at full power or not.

The subject plant lacks such a monitoring system. Any abnormalities in the blasting system are only noticed in the event of any unusual blasted surface patterns which can be noticed by the operator. In such cases, the operator informs the person responsible for plant maintenance and corrective measures are conducted, as it is the case for most equipment and machine systems in the subject plant. Such a case has been encountered in the subject plant during the power and energy measurement of the abrasive blasting system. These can be noticed in Figure 5-21 and Figure 5-22, which are indicated as unusual power demand. The normal power demand throughout all blasting processes varies between 41-43 kW. However, the power demands during the first and second period indicated as unusual in Figure 5-21 are around 27 kW and 55 kW, respectively. This fault was discussed with the system operator and the maintenance personnel. They stated that the system operator noticed that the incomplete cleaning on the workpiece surface and reported the situation to the maintenance personnel who further investigated the system and found that this failure was due to a misalignment in the flow control valve of one of the blasting impellers. The abrasive flow rate was less than the normal so that the impeller motor was drawing less power. Although the maintenance personnel responded the failure, it reoccurred and the motor was overloaded this time so that the power demand rise to around 55 kW. The same failure occurred during the night production shift as can be noticed in Figure 5-22.

In the light of the above explanations, there are 3 ESPs in the abrasive blasting system of the subject plant:

1. ESP by Turning off the Unnecessarily Operating Air Fan
2. ESP by Using Premium Efficiency Electric Motor
3. ESP by Using More Efficient Transmission Belts

5.4.1.1 EXISTING PERFORMANCE OF THE ABRASIVE BLASTING SYSTEM

Normally, because it is the workpiece surface to be blasted, energy consumption can be linked to the work piece surface area, energy consumption per blasted surface area can be defined as energy performance indicator. This approach is useful for blasting the work pieces which have flat surfaces, e.g. sheet metals used in the shipyards. Concerning the subject plant, linking the energy consumption to blasted surface area is very laborious task owing to the fact that the product mix to be blasted consists of mixed workpieces of medium and large sized irregularly shaped components. Instead, energy consumption can be linked to the production volume or weight assuming that the surface area will be proportional to the casting weights. Based on this, the annual energy consumption of the abrasive blasting process can be approximated by two approaches.

SEC of the abrasive blasting system

23 batches of workpieces comprising of various intermediate and final products corresponding to 8980 kg were abrasive-blasted during the power and energy consumption logging period which are presented in Figure 5-21 and Figure 5-22. The total electricity consumption for blasting the 8980-kg-workpiece is 164.87 kWh. Thus, the SEC (kWh/kg) is calculated as follows:

$$SEC = \frac{power\ consumption}{weight\ of\ workpieces} = \frac{164.87\ kWh}{8980\ kg}$$

$$= 0.01835\ \mathrm{kWh/kg}$$

The process cycle time for abrasive-blasting the 8980-kg-workpiece is 2.38 hours. Thus, the specific cycle time can be found as 3773.1 kg/hour. Total duration of time in which the abrasive blasting system was on is 7.07 hours.

The annual casting output is 1,444,525 kg. This means that, taking the SEC (i.e. 0.01835 kWh/kg) into account, the energy consumed by the abrasive blasting system to blast 1,444,525 kg of casting in a year can be calculated as follows:

$$energy\ consumption\ = SEC * total\ casting\ output = 0.01835 \frac{kWh}{kg} * 1{,}444{,}535$$

$$= 26{,}507.03\ \mathrm{kWh}$$

However, as mentioned earlier, the product mix to be blasted in the abrasive blasting system comprises of intermediate and final products. The castings after being heat treated are abrasive blasted for short time to remove and clean the burnt surface on the castings and sent to the quality control. This initial blasting is a requisite for quality control processes and corrections. After quality control (and also correction processes if necessary), the casting product is re-blasted for final time which takes long time than that of the initial blasting. Due to the need of initial blasting process, the annual casting amount to be blasted in the abrasive blasting system is higher than the plant annual casting output (i.e. 1,444,525 kg/year). Thereupon, the annual electricity consumption will be higher than the above calculated 26,507.03 kWh in a year. The blasting operator stated that the initial abrasive blasting duration will be approximately one quarter of the final abrasive blasting duration based on his experiences. Based on this, the casting amount for initial blasting process can be assumed as one quarter of the final casting output, which makes 361,131.25 kg a year. The corresponding electricity consumption for initial blasting will be 6,626.75 kWh. Hence, the total energy consumption for initial and final blasting processes will be 33,133.78 kWh in a year. These calculations are summarised in Table 5-20 below.

Table 5-20: Operation and energy consumption characteristics for abrasive blasting system

		Source/ equation / calculation
SEC (a)	0.01835 kWh/kg	measurement
Annual casting amount to abrasive-blast (b)	1,805,656.25 kg/year	Subject plant
Annual electricity consumption (c)	33,133.8 kWh	c=a*b
Average specific cycle time (d)	3,773.1 kg/hour	measurement
Annual working hours (e)	478.56 hours	e=b/d
Average daily energy consumption (f)	112.31 kWh/day	f=b/295
Annual primary energy consumption (g)	4,460 MWh/year	g=c*pecf
Annual energy cost (h)	€ 2,170.26	h=c*unitcost
Annual CO_2 emissions (i)	64,904.21 kg-CO_2	i=c* CO_2 EF

5.4.1.2 ESP BY TURNING THE UNNECESSARILY WORKING VENTILATION FAN OFF

The bag house air fans are supposed to operate during abrasive blasting process and should be turned off when not needed. It was observed during the audit that the baghouse air fan of the abrasiveblasting machine is frequently forgotten to be turned off by the machine operator after the abrasive blasting ends. The power measurement results validated this observation. The unnecessary operation and resulting power demand is shown in grey colour and numerated Figure 5-23 and Figure 5-24. The corresponding energy consumption in these periods are presented in Table 5-21. There are 10 non-value-added activities in daytime shift and night shift.

As seen in Table 5-21, total duration of non-value-added fan operation in a production day is 2.20 hour and the corresponding electricity consumption in this period is 19.82 kWh. As mentioned earlier, the total energy consumption was 164.87 kWh in 7.06 hours of system operation time. Thus, the unnecessary energy consumptions due to the unnecessary operation of air fan accounts for 12% of overall energy consumption to blast 8980-kg workpiece is 2.38 hours. Therefore, if the unnecessarily working ventilation fan is turned off, the associated ESP will be 12%. This ESP is designated as **"ESP 5-6, ESP by Keeping off the Idle Fans".** The calculations for ESP 5-6 are presented in Table 5-22.

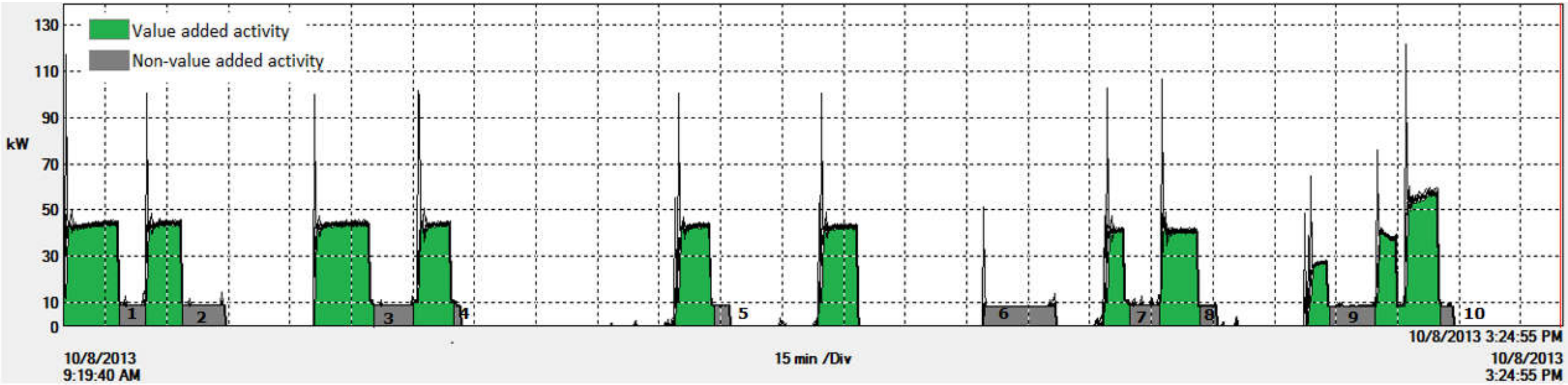


Figure 5-23: Value-added and non-value added power consumption during the abrasive-blasting process in day shift

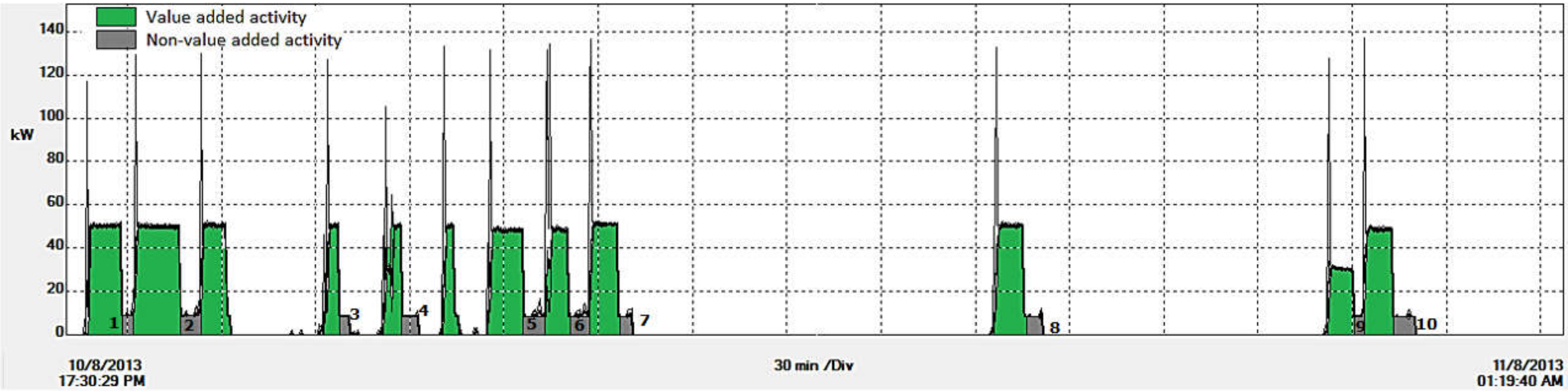


Figure 5-24: Value added and non-value-added power consumption during the abrasive-blasting process in night shifT

Table 5-21: Energy consumption in non-value-added operation of airbag fan in abrasive blasting system in daytime shift

Period	**Avg. Power Demand (kW)**	**Duration (mins)**	**Energy Consumption (kWh)**
Daytime Shift			
1	9.17	5.9	0.902
2	9.02	9.71	1.4606
3	9	10.93	1.6404
4	8.98	3.81	0.5714
5	8.9	2.1	0.3115
6	8.77	17	2.4862
7	9.04	8.31	1.2534
8	8.96	4.5	0.6723
9	8.91	11.8	1.7534
10	8.78	3.13	0.4582
Total		75.1 mins	11.5 kWh
Night time Shift			
1	9	4.25	0.6375
2	8.8	6.8	0.9973
3	8.79	3.53	0.5171
4	8.75	5.31	0.7743
5	8.93	8.45	1.2576
6	8.77	7.18	1.0494
7	8.65	4.66	0.6718
8	8.65	6.06	0.8736
9	8.75	3.56	0.5191
10	8.68	7.11	1.0285
total		56.91 mins	8.32kWh
TOTAL day		2.20 hours	19.82 kWh

Table 5-22: Calculations of ESP 5-6: annual ESP, PESP, ESCP, and CO_2 ERP

		Source/ equation / calculation
ESP (a)	12%	
Annual energy consumption of abrasive blasting process (b)	33,133.8 kWh	From Table 5-20
Annual ESP (c)	3,976.05 kWh	c=a*b
Annual PESP (d)	9,820.84 kWh	Equation 3-1
Annual ESCP (e)	€260.43	Equation 3-2
Annual CO_2 ERP (f)	1,944.3 kg-CO_2	Equation 3-3

5.4.1.3 ESP BY USING MORE EFFICIENT ELECTRIC MOTOR

As given in Table 5-23, the energy efficiency class of the electric motors of impellers is EFF2. Therefore, there are ESPs by replacing the existing electric motor with premium efficiency electric motor in IE3 class. The specifications of the proposed energy efficient electric motor are compared with the existing ones in Table 5-23.

Table 5-23: Rated specifications of the proposed electric motor for (source: product datasheets)

	Proposed E. Motor for Impellers	**Existing E Motor of Impellers**
Maker	ABB	Motorsan Abana
Power rating	22 kW	22 kW
Energy efficiency rating	IE3	EFF2
Efficiency	93.5	88.4

Following Equation B-8 and B-9 in Appendix B, energy, environmental and monetary benefits of using more efficient electric motor in the impellers of abrasive-blasting system have been calculated and presented in Table 5-24 below. The associated ESP is designated as **"ESP 5-7, ESP by Using Premium Efficiency Electric Motor".**

Table 5-24: Calculations for ESP 5-7: annual ESP, PESP, ESCP, and CO_2 ERP

		Source/equation/calculation
Hours of electric motors operate in a year (a)	478.56 hours	From Table 5-19
Energy saving of an electric motor in one impeller (b)	519.7 kWh	Equation B-7-8
Number of electric motors (c)	2	
Annual ESP (d)	1,039.4 kWh	d=b*c
Annual energy consumption (d)	33,133.8 kWh	Table 5- 3
Annual PESP (e)	2,567.3 kWh	Equation 3-1
Annual ECSP (f)	€ 67.50	Equation 3-2
ESP %	3%	
Annual CO_2 ERP (g)	508.6 kg-CO_2/year	Equation 3-3

As Table 5-24 summaries, annual ESP% in abrasive-blasting system by using premium efficient electric motors for the impellers instead of the existing electric motors is 3% and the associated annual ESP, annual ECSP, and annual CO_2 ERP will be 1039.4 kWh/year, €67.5, and 508.6 kg-CO_2/year, respectively.

5.4.1.4 ESP BY USING MORE EFFICIENT TRANSMISSION BELT

As described earlier, the impellers of the abrasive-blasting system are driven through two electric motors. The power transmission between the electric motors and impellers is achieved through standard V-type belts. Therefore, an ESP can be realised by replacing the current standard V belts with notched V belts. The associated ESP is estimated as presented in Table 5-25. This ESP is designated as "**ESP 5-8, ESP by Using Efficient Transmission Belt".**

As Table 5-25 summaries, annual ESP% in by using more efficient notched V belts instead of the existing standard V type belts is 2%. The corresponding annual ESP, PESP, ECSP, and CO_2 ERP will be 662.67 kWh, 1636.8 kWh, €43.4, and 324 kg-CO_2, respectively. A simple investment is required for this ESP and should be assessed in terms of cost effectiveness.

Table 5-25: Calculations for ESP 5-8: annual ESP, PESP, ESCP, and CO_2 ERP

		Source/equation/calculation
Efficiency of existing V belt, $\eta 1$ (a)	94%	(Muller and Papadaratsakis, 2003)
Efficiency of notched V belt, $\eta 2$ (b)	96%	(Muller and Papadaratsakis, 2003)
Annual energy consumption (c)	33,133.8 kWh/year	From Table 5-20
Annual ESP (d)	662.67 kWh/year	Equation 5-2
ESP % (e)	2%	e=d/c%
Annual PESP (f)	1636.8 kWh/year	Equation 3-1
Annual ECSP (g)	€43.4	Equation 3-2
Annual CO_2 ERP (h)	324 kg-CO_2/kWh	Equation 3-3

5.4.2 REVIEW OF THE IDENTIFIED ESPS IN ABRASIVE BLASTING SYSTEM

In total, three ESPs have been identified:

- ESP 5-6, ESP by Keeping the Idle Fans off
- ESP 5-7, ESP by Using Premium Efficient Electric Motor
- ESP 5-8, ESP by Using More Efficient Transmission Belts

The total ESP in the abrasive blasting system, $ESP_{abrasiveblasting}$ will be the sum of the identified ESPs. Thus;

$$ESP_{abrasiveblasting} = ESP\ 5\text{-}6 + ESP\ 5\text{-}7 + ESP\ 5\text{-}8$$

$$ESP_{sandreclamation} = 3{,}976.05 + 1{,}039.4 + 662.67 = 5{,}678.12\ kWh$$

The % ESP will be:

$$ESP\ \% = \frac{ESP_{abrasiveblasting}}{annual\ energy\ consumption}\% = \frac{5{,}678.12}{33{,}133.8} = 17.1\%$$

Therefore, if all the ESPs are applied in real life, the overall annual ESP in the abrasive blasting system will 5,678.12 kWh. This is about 17.13 % of the overall annual abrasive blasting energy consumption as calculated above. The associated annual PESP, ECSP, and CO_2 ERP will be

14,025 kWh, €372, and 2,776.6 kg-CO_2, respectively. The ESPs identified in the abrasive blasting system of the subject plant together with the overall ESP are documented in Table 5-26.

Table 5-26: ESPs identified in the abrasive blasting system of the subject plant

ESP No:	Measure	EPS (%)	Annual ESP (kWh/year)	Annual PESP (kWh/year)	Annual ECSP (€)	Annual CO_2 ERP (kg-CO_2)
5-6	ESP by turning the unnessarily working fan off	12%	3,976.05	9,820.84	260.43	1,944.3
5-7	ESP by Using Premium Efficient Electric Motor	3%	1039.4	2,567.3	67.5	508.6
5-8	ESP by More Efficient Transmission Belt	2%	662.67	1650.04	43.43	324.7
Overall $ESP_{abrasiveblasting\ system}$		17.1%	5,678.12	14,038	371.36	2,777.60

5.5 MACHINE SHOP

The subject plant is supported by 4 vertical lathes in a major machine shop section. Before commencing the energy audit it is essential to understand the energy consumption behavior of machine tools so that it can facilitate to create appropriate means to exploit for energy saving.

Machine tools are complex energy consuming systems as they are made of various functional components. Energy consumption of a typical machine tool may be expressed as proposed by Jeffrey B. Dahmus and Timoty G. Gutowski (2004):

$$E = \textit{Fixed Energy Consumption} + \textit{Variable Energy Consumption}$$

"Fixed Energy Consumption" is constant during the machining process and independent from machining process. It stems from the machine tool auxiliary equipment e.g.: cutting chip handling equipment, lubrication pump, cutting zone lighting, and computer or control panel, which keep the machine tool ready for machining operation and support the cutting (or machining process). When the machine tool is powered on, these auxiliary elements operate constantly and have a fixed energy consumption rate. The magnitude of the fixed energy consumption is related to the specifications of each machine tool and can partly determine the energy efficiency level of that machine tool. These elements should be efficient in terms of energy, equipped with energy saving devices such as frequency drivers, and not oversized.

On the other hand, "variable energy consumption" is due to the elements such as main drive units for main motions (e.g. spindle), feed drive units, positioning drive units, work piece - tool fixing and changing units. Some of these do not consume energy in conventional or universal machine tools because they are manually handled. For instance, work piece and tool fixing and changing is carried out manually in old universal lathes whereas this can be done by machine tools itself in modern CNC machine tools. However, this can be a disadvantage as it will increase the production cycle as manual fixing and changing would take more time. Also, ageing of the machine tool can contribute to the energy consumption because drive units for main motions, feed, and positioning would deteriorate by time and also, they would be outsourced by new technology.

In addition to the above said elements, work piece material specifications, machining parameters (feed rate, cutting speed, cutting depth, dry or wet cutting, etc.), cutting insert material, cutting insert sharpness, etc. have an impact on the variable energy consumption. Work piece material specification, or the machinability, determine the specific energy requirement for material removal of the work piece. The material with high strength means higher specific energy requirements and higher resistance between work piece and cutting insert. Specific cutting energy for different materials can be found in (Kalpakjian and Schmid, 2013). Thus, more power is drawn to overcome higher forces while machining. However, the work piece material specifications cannot be changed for energy saving purposes because it determines the functional requirements of the product to be produced.

5.5.1 IDENTIFYING ESPS IN THE MACHINE SHOP

5.5.1.1 ESP BY REPLACING OLD LATHE WITH A NEW ONE

One of the lathes employed by the subject plant is a very obsolete one as Figure 5-25 shows. The impact of machine tool age on the energy consumption was studied by several authors before (Deshpande et al., 2011; Kordonowy, David N., 2002). The same factor has been also considered by the Author for the subject plant in the energy audit. For this purpose, 2 identical work pieces from daily operations the plant have been chosen. These 2 identical work pieces (Figure 5-26) were subjected to various machining operations (Figure 5-27) on 2 different aged vertical lathes. One is a 33-years-old vertical lathe shown Figure 5-25 and the other one is a 4-years-old Tongtai TVL-8DC vertical lathe shown in Figure 5-28. The maker of oldest one is not known by the plant management. Its construction year is estimated to be as 1980s. While it was initially a universal vertical lathe, it was then converted to a CNC one by some additional technical upgrades. These vertical lathes are of the same size and can handle work pieces up to Ø600 mm. Therefore, they can be accepted as the same capacity.

As seen in Figure 5-27, 5 different parts of the work pieces have been machined in order to cover the impact of various cutting processes. The raw work piece weight was approximately 72.3 kg. After machining, the work piece weight was measured to be 67.1 kg. Thus, about 5.2 kg of material was removed by machining. All the CNC programmes have been made by the same CNC operator. Power & energy measurement was conducted by using PEL 103 at 1 second intervals.

Figure 5-25: Old CNC Vertical Lathe (1980)

Figure 5-26: The product for case study: before (left) and after machining (right)

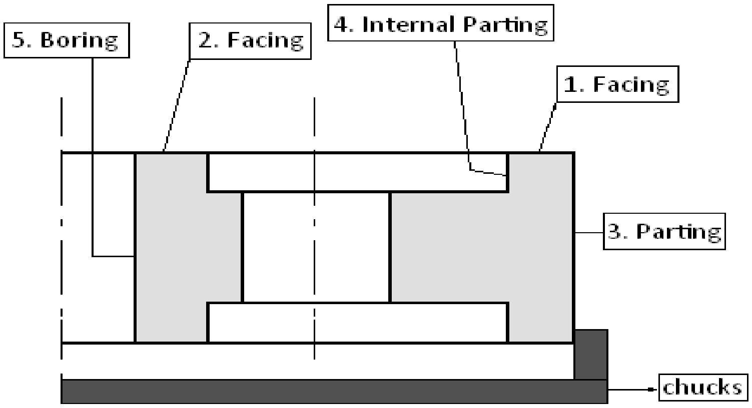


Figure 5-27: Machining operations applied to the product

Figure 5-28: New Vertical CNC Lathe, Tongtai (2009)

Figure 5-29 and Figure 5-30 shows the power demand profiles for two different age and type of the vertical lathes during the machining of two identical work pieces. Figure 5-29 shows the power demand of the old lathe while Figure 5-30 shows that of the newer lathe. As seen in these figures the power signatures for the lathes are quite different. This is because the CNC programme made for the old lathe is different from the one that was made for the other two new lathes. Due to technical limitations of the old lathe, the CNC operator chose smaller spindle revolutions (N) for machining operations conducted by the old lathe.

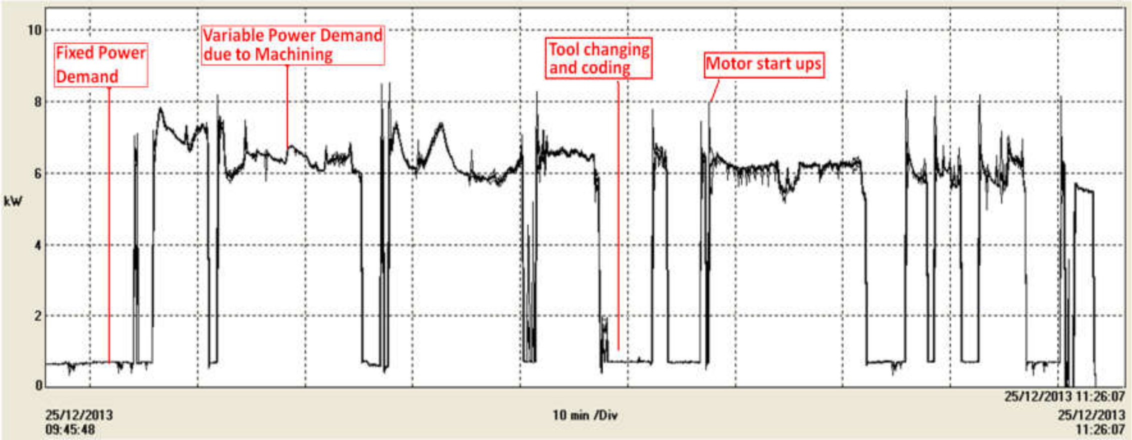


Figure 5-29: Power Demand Graph for machining with Old Vertical Lathe

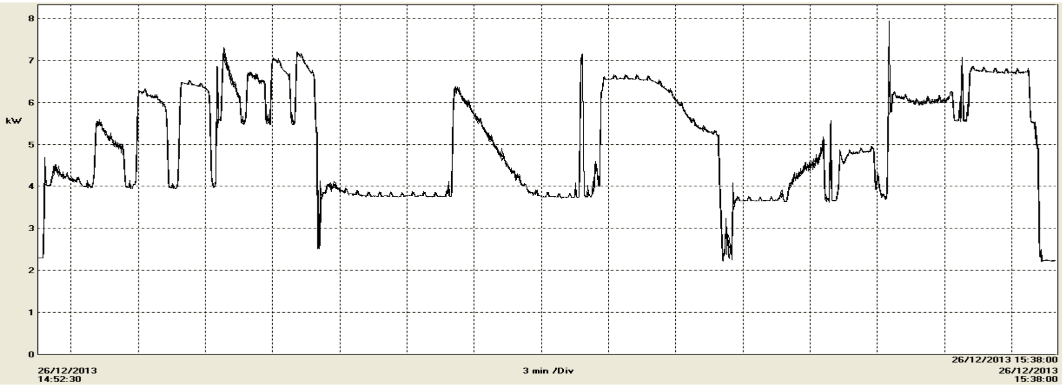


Figure 5-30: Power Demand Graph for machining with 2009 – Tongtai Vertical Lathe

The energy consumption results for the two vertical lathes are presented in Table 5-27. As seen, the lowest energy consumption for the machining of the work piece has been achieved with the Tongtai Vertical Lathe, which is a modern CNC, while the old vertical lathe presented the much higher consumption as expected. Moreover, in terms of the productivity, Tongtai vertical lathe also presented much favourable figure over the old vertical lathe.

As seen in Figure 5-29, there is a background power demand of around 0.72 kW. This is the fixed power demand regardless of machining processes. When the machine tool is started, it is drawn constantly. The fixed power demand is due to auxiliary (peripheral) elements of the machine tool such as oil pump, cutting fluid pump, control panel, cutting chip handling equipment as explained before. The subject vertical lathe does not possess any cutting fluid pump and cutting chip handling equipment. The CNC control panel and oil pump are the only elements contributing to the fixed power demand which is around 0.72 kW as mentioned earlier. The average power demand for the old lathe is 4.334 kW. This covers the whole operation. On the other hand, average power demand while only machining, which is made of both variable and fixed power consumption, is calculated to be 6.254 kW from PEL 103 output. In Figure 5-29, it can be seen that the power demand sometimes goes down to the fixed power demand level and remains there for some time. This is because the operator was changing tools and coding the CNC programme for the next operation. Normally, in a modern CNC machine tool, all the programming can be done at the first set up. Furthermore, the machine tool can change the cutting tool holders during operation with no need to operator help because it is also programmable at the beginning and the machine tool would have a turret on which multiple tools are mounted. The impact of this can be seen in Figure 5-30; there is almost no energy consumption due to the factors such as tool changing, work piece position, and programming. All these were programmed at the initial set up by the operator and the machine tool machined the work piece from the start to the end without any interruption.

From the power demand profile graph and PEL 103 output, average time consumed for tool change and coding is about 14.76 minutes. The corresponding energy consumption in those periods is 0.1652 kWh, which is 2% of the overall energy consumption, 7.249 kWh. This is one of the reasons why the old lathe consumed more energy compared to other the new lathe. In total, the old lathe consumed 7.249 kWh whereas the new one consumed 3.822 kWh. The new lathe consumed around 47% less energy from the old lathe for machining the same work piece. One of the reasons beyond this consumption difference has been explained in previous paragraph. Other reasons can be due to more powerful transmission system of the new lathe. As explained, smaller cutting speeds were chosen due to technical limitations of old lathe. Moreover, ageing impact on machine tool components, transmission systems, and electric motors can affect the energy consumption negatively. In addition to the energy saving, there is also a productivity gain through the new lathe: the production cycle time was 1.471 hours for old lathe. However, the new lathe achieved the same production output in 0.75 hours; thereby providing 0.721 hours (i.e. 49%) timesaving. The annual operation hours for the old lathe is 3,600 hours as given by the plant management. The equivalent working for the new lathe will be 1906 hours. The old lathe will consume 17,748 kWh in 3600 hours (in a year) whereas the new one will consume 9,723.1 kWh in 1,906 hours (in a year) for performing the same work as calculated and presented in Table 5-27. This means that there is an ESP of 45%. The annual ESP, associated annual ECSP, and CO_2 ERP are 8,025 kWh, €525.6, and 3,924.22 kg, respectively. This ESP is designated as **"ESP 5-9, ESP by Replacing Old Lathe with a New One".**

Table 5-27: Estimation of ESP 5-9: Annual ESP, PESP, ESCP, and CO_2 ERP

	Old CNC Vertical Lathe	**2009- Tongtai Vertical Lathe**	**Source/equation/calculation**
Energy Consumption for the case machining process (a)	7.249 kWh	3.822 kWh	Measured
Production Cycle Time (b)	1.471 hours	0.75 hours	measured
Hourly energy use for the same work output (c)	4.93 kWh/hour	5.096 kWh/hour	c=a/b
Annual operation hours for old lathe (d)	3600 hours	-	Plant management
Annual operation hours for new lathe (e)	-	1908 hours	
Annual energy use (f)	f1=17,748 kWh	f2=9,723.17 kWh	f1=c*d, f2=c*e
Annual ESP(g)	8,025 kWh		g=f1-f2
Annual PESP (h)	19,420.5 kWh		Equation 3-1
Annual ECSP (i)	€525.6		Equation 3-2
%ESP (j)	45%		i=g/f1 %
Annual CO_2 ERP (k)	3,924.22 kg		Equation 3-3

5.5.1.2 ESP BY AVOIDING UNNECESSARY MACHINE OPERATION

Based on the Author's observations and discussions with the plant management, it has been found out that the machine tools are started when the respective production shift begins in the morning and kept "on" unnecessarily until the production shift ends in the evening. This was no matter if there is machining required or not. There was a belief that they keep the machine tools ready in case it might be needed. However, as in the case of this study, the plant managers are unaware of the importance of this energy consumption and it is widely unknown that the energy consumed by a machine tool in standby is insignificant. When the energy is consumed without adding value to the production it will be categorised as a waste unless there is a good cause that seems not to be the case. In order to show the impact of this waiting waste a vertical lathe has Figure 5-31 been considered in a case study and, its energy and power consumption has been logged for a typical production shift.

Figure 5-31: Vertical Lathe measured for energy and power consumption for a typical production shift

The power demand profile of the subject machine tool is shown in Figure 5-32 during a typical production shift. The power and energy logging was performed from 08:55:00 to 17:08:00 hrs so as to cover a typical production shift. As seen in Figure 5-32, the power demand profile is not constant. The variable and fixed power demands can be discerned easily as such the fixed power demand was always drawn as a background power during the measurement. This means that the machine tool was powered on in the morning and kept "on" unnecessarily until the production shift was ended. Therefore, it consumed energy although there was no production output.

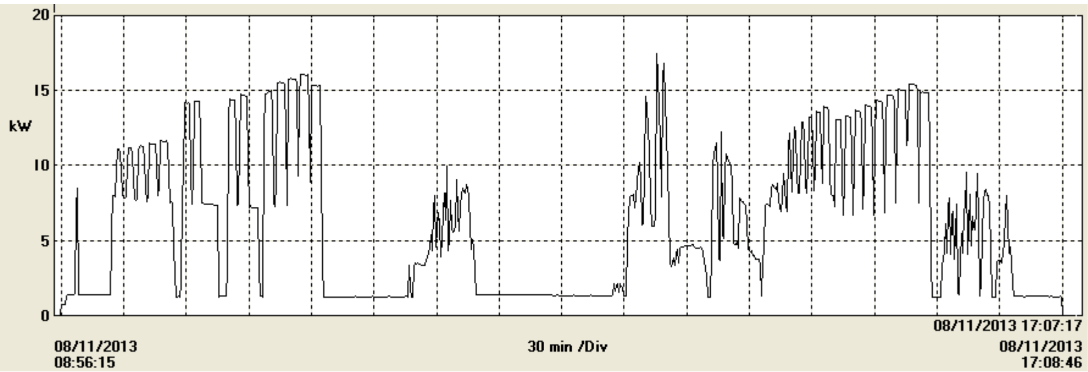


Figure 5-32: Power demand graph of a vertical machine tool during a typical production shift

The idle time periods that machine tool operates can be defined as "non-value-added time" and the energy consumption during non-production hours can be defined as "non-value-added energy consumption". Likewise, the production hours can be defined as "value added time", and corresponding energy consumption as "value-added energy consumption".

Based on the above definitions, Figure 5-33 is included to show the power demand during the value-added times by green colour and in the non-value-added times by grey colour. During the audit, it was observed that the non-value-added times were due to "tool changing, programming, part set-up" or "idle hours". Non-value-added times due to idle hours are the focus of this case study. The non-value-added times due to the tool changing, programming, part set-up depends on the operator speed and technical specifications of the machine tool.

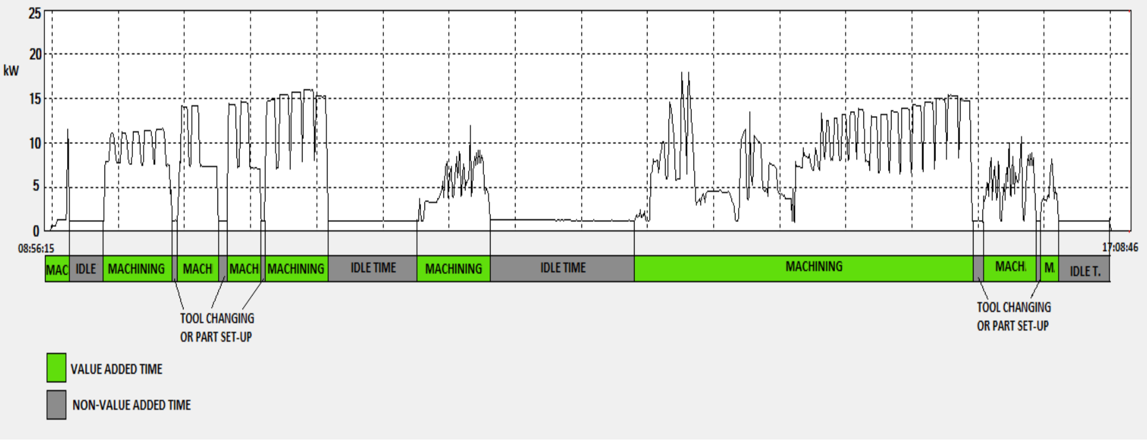


Figure 5-33: Value added and non-value-added time and corresponding power demand

Therefore the non-value added times due to idle hours, when no production is performed, have been identified from the power demand profile and PEL 103 output and corresponding energy and power values have been estimated. The results have been shown in Table 5-28 below.

Table 5-28: Average power demands and energy consumption periods in non-value- added time periods

Non-Value Added Time no	**(hours)**	**Avg. Power Demand (kW)**	**Energy Consumption (kWh)**
1	0.26	1.26	0.327
2	0.69	1.28	0.883
3	1.12	1.38	1.54
4	0.4	1.3	0.52
Total	2.47		3.27

As seen in Table 5-28 and Figure 5-33, there are 4 idle time periods which can be defined as the non-value-added time due to the idle hours. In these periods of the machine tool operations, which are not productive, the operator left the lathe powered-on. As such, the machine tool consumed energy, but did not produce any production output. The total of non-value-added hours is 2.47 hours whereas the total time the lathe was on is 8.13 hours. Thus, the non-value-added hours account for 30% of the overall machine tool operation. In total, the non-value-added energy consumption due to idle hours is 3.27 kWh whereas the total energy consumption (i.e. non-value added + value-added energy consumption) is 50.2 kWh. Thus, the non-value-added energy consumption accounts for 6.5% of the overall machine tool energy consumption in a production shift. Hence, assuming energy saving would be 3.27 kWh per typical production day, annual ESP. annual PESP, associated ECSP, and CO_2 ERP can be estimated as presented in Table 5-29. This ESP is designated as **"ESP 5-10, ESP by Turning the Unnecessarily Working Machine off".**

Table 5-29: Estimation of ESP 5-10: annual ESP, PESP, ESCP, and CO_2 ERP

		Source/calculation/ equation
Daily energy use (a)	50.2 kWh	measured
Annual energy use (b)	14,809 kWh	b=a*295
ESP (c)	6.5%	calculated in the text
Annual ESP (d)	964.7 kWh	d=c*b
Annual PESP (e)	2,383.8 kWh	Equation 3-1
Annual ESCP (f)	€63.2	Equation 3-2
Annual CO_2 ERP (g)	472.7 kg-CO_2	Equation 3-3

5.5.2 REVIEW OF THE IDENTIFIED ESPS IN THE MACHINE SHOP

Two major ESPs have been identified:

- ESP 5-9, ESP by Replacing the Old Lathe with a New One,
- ESP 5-10, ESP by Turning off the Unnecessarily Working Machine.

The total ESP in the audited machine tools, $ESP_{Machineshop}$ will be the sum of the identified ESPs in the machine shop. Thus,

$$ESP_{machineshop\,=}\ \text{ESP 5-9} + \text{ESP 5-10}$$

$$ESP_{machneshop} = 8{,}025\ + 964.7\ \text{kWh} = 8989.7\ \text{kWh}$$

Thus, the overall annual ESP in the energy audited machine tools will be 8,989.7 kWh if the identified ESPs are materialised. The associated annual total PESP, ESCP, and CO_2 ERP are 22,204.5 kWh, €588.8, and 4,396.92 kg-CO_2, respectively. These ESPs and the overall ESP in the machine shop of the subject plant are summarised and documented in Table 5-30 below.

Table 5-30: Summary of ESPs identified in the Machine Shop

ESP No:	ESP Measure	EPS (%)	Annual ESP (kWh/year)	Annual PESP (kWh/year)	Annual ECSP (€)	Annual CO_2 ERP (kg-CO_2)
5-9	ESP by replacing old lathe with a new one	45%	8,025 kWh	19821.75	€525.6	3924.22
5-10	ESP by turning the unnecessary working machine off	6.5%	964.7 kWh	2382.8	€63.2	472.7
Overall $ESP_{Machineshop}$			8,989.7 kWh	22,204.5	€588.8	4396.92

5.6 SAND RECLAMATION SYSTEM

The subject plant uses a mechanical sand reclamation system powered by electricity (Figure 5-34). The sand reclamation system is operated by 2 vibration electric motors and 1 air fan. Each vibrator motor has a power rating of 6.2 kW. The air fan absorbs the dust generated by the reclamation process and send it to a baghouse. The power rating of the fan electric motor is 30 kW.

The annual electricity consumption of the vibrators is 67,260 kWh whereas the annual electricity consumption of the air fan is 12,2573 kWh. The calculations are presented in Table 5-31 for the vibrators and Table 5-32 for the air fan. Thus, the overall sand reclamation system annual energy consumption is 189,833 kWh. This is about 6% of the overall plant energy consumption. The associated overall annual energy cost and CO_2 emissions are €12,434 and 93,004.4 kg-CO_2, respectively.

Table 5-31: The sand reclamation system vibrators power consumption values

		Source/calculation/equation
Daily operation hours (a)	15 hours (7.5 hrs per shift)	measured
Average power demand (b)	15.2 kW	measured
Annual working hours (c)	4,425 hours	c=a*295
Annual energy consumption (d)	67,620 kW	d=a*b*c
Annual energy cost (e)	€4,405.5	e=d*EUCR
Annual CO_2 emissions (f)	33,066.2 kg-CO_2	f=d*CO_2 -EF

Table 5-32: The sand reclamation system air fan power consumption values

		Source/calculation/equation
Daily operation hours (a)	15 hours (7.5 hrs per shift)	measured
Average power demand (b)	27.7kW	Calculated based on Appendix B
Annual working hours (c)	4,425 hours	c=a*295
Annual energy use (d)	122,573 kWh	d=a*b*c
Annual energy cost (e)	€8,029	e=d*EUCR
Annual CO_2 emissions (f)	59,938.2 kg-CO_2	f=d* CO_2 EF

Figure 5-34: Sand Reclamation System in the subject plant

5.6.1 ESP BY AVOIDING UNNECESSARY SYSTEM OPERATION

When the sand reclamation system is powered on, the vibrator electric motors operate at a constant rate with no regard to whether the system is loaded or not. This is how the system was designed and built. Therefore, the sand reclamation system should not run when it is unload. Despite this, the Author observed that the operator of the sand reclamation system did not use it efficiently. While the power logging was conducted, the Author observed the behaviour of the system operator. When the moulds to be reclaimed finished, the operator went to the fettling station to bring more moulds to load to the system. While doing this, unfortunately, he left the sand reclamation system powered-on. The system worked unloaded for approximately 42 minutes (i.e. 0.7 hours) which is about 9.3% of the total operation hours (i.e. 7.5 hours) in a production shift. This is indicated on the power demand profile of the system in Figure 5-35.

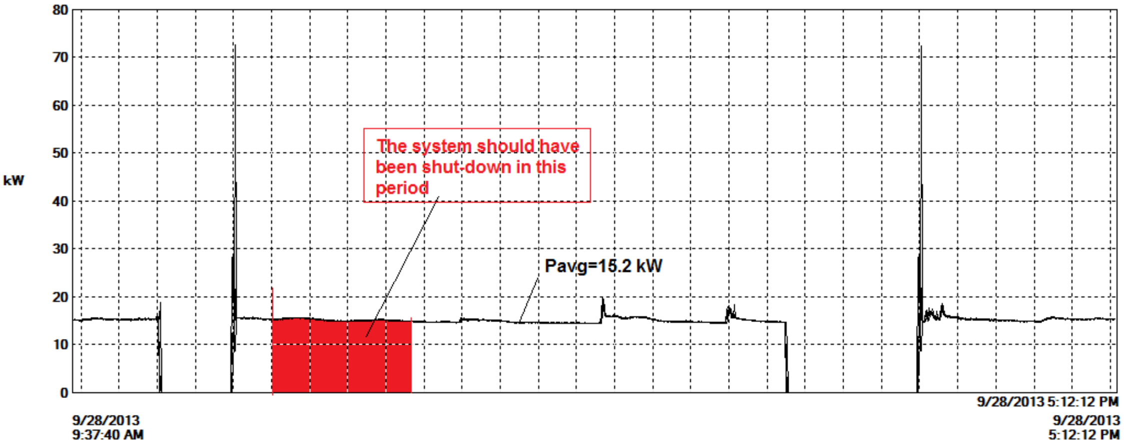


Figure 5-35 Power demand profile of the sand reclamation vibrators in a typical day time production shift

Assuming that the operator acts in the same way in each shift, the annual energy consumption due to the unnecessary operation will be 6,188 kWh. This can be regarded as an annual ESP if the unnecessary operation is avoided. The calculations of this ESP are presented in Table 5-33. This ESP is designated as **"ESP 5-11, ESP by avoiding the unnecessary operation of sand reclamation system".** As seen in Table 5-33, %ESP, annual ESP, annual PESP, annual ECSP, annual CO_2 ERP are 9%, 6,188 kWh, 15,284.36 kWh, €405.3, and 3,026 kg-CO_2, respectively.

Table 5-33: Calculations for ESP 5-11, ESP by avoiding the unnecessary operation of sand reclamation system

		Source/calculation/equation
Annual unnecessary system operation hours (a)	411.5	9.2% of annual operation hours
Average power demand (b)	15.2 kW	Table 5-31
Annual ESP (c)	6,188 kWh	c=a*b
Annual PESP (d)	15,284.36 kWh	Equation 3-1
Annual ECSP (e)	€405.3	Equation 3-2
ESP % (f)	9%	f=c/annual energy consumption% (annual energy consumption = 67,620 kWh from Table 5-30)
Annual CO_2 ERP (g)	3,026 kg-CO_2	Equation 3-3

5.6.2 ESP BY USING MORE EFFICIENT ELECTRIC MOTOR FOR THE AIR FAN OF SAND RECLAMATION SYSTEM

The energy efficiency of the electric motor of the sand reclamation system air fan is 86.4% and its power rating is EFF2 as given in Table 5-34. There is an ESP by using more efficient electric motor. The specifications of the existing and proposed electric motor are given in Table 5-34.

Table 5-34: Specifications of the sand reclamation system fan electric motor (source: manufacturers` data)

	Existing E. Motor	**Proposed E. Motor**
Maker	CAMAK -GM 200 L 4	ABB
Power rating	30 kW	30 kW
Energy Efficiency Rating	EFF2	IE3
Efficiency	84.5%	93.6%

Following Equation B-7 and B-8 in Appendix B, energy, environmental and monetary benefits of using more efficient electric motor have been calculated and presented in Table 5-35 below. This ESP is designated as **“ESP 5-12, ESP by Using Premium Efficiency Electric Motor for Sand Reclamation System Air Fan.”**

Table 5-35: Calculation of annual ESP, primary ESP, ESCP, and CO_2 ERP in ESP 5-12

		Source/calculation/equation
Annual ESP (a)	12,219 kWh	Equation B-8
Annual PESP (b)	30,181.1 kWh	Equation 3-1
Annual ECSP (c)	€800	Equation 3-2
ESP %	10%	Equation B-8
Annual CO_2 ERP (d)	5,975.1 kg-CO_2	Equation 3-3

As presented in Table 5-35, ESP%, annual ESP, annual PESP, annual ECS, and annual CO_2 ERP are 10%, 12,219 kWh, 30,191.1 kWh, €800, and 5,975.1 kg-CO_2, respectively.

5.6.3 REVIEW OF THE ESPS IDENTIFIED IN THE SAND RECLAMATION SYSTEM

The total ESP in the sand reclamation system, ESPsandreclamation will be the sum of the identified ESP in the sand reclamation system. Thus,

$$\text{ESP}_{\text{sandreclamation}} = \text{ESP } 5\text{-}11 + \text{ESP } 5\text{-}12$$

$$\text{ESP}_{\text{sandreclamation}} = 6{,}188 + 12{,}219 = 18{,}407 \text{ kWh}$$

If ESP 5-11 and ESP 5-12 are materialized, the overall annual ESP in the sand reclamation system will 18,407 kWh. This is about 9.7% of the overall annual sand reclamation energy use (i.e. 189,833 kWh). The associated annual PESP, ECSP, and CO_2 ERP will be 45,465.3 kWh, €1,206.2, and 9,001 kg-CO_2, respectively.

5.7 SAND MIXING SYSTEM

Figure 5-36 shows the power demand profile of the sand mixing system in a typical production day. Based on the power measurement, average energy consumption per day is 13.18 kWh. Thus, the annual energy use is 5,888 kWh. The corresponding annual energy cost and CO_2 emissions are €386 and 2,885.12 kg-CO_2, respectively. Its contribution to overall plant use is insignificant. No ESP is identified in this energy using system.

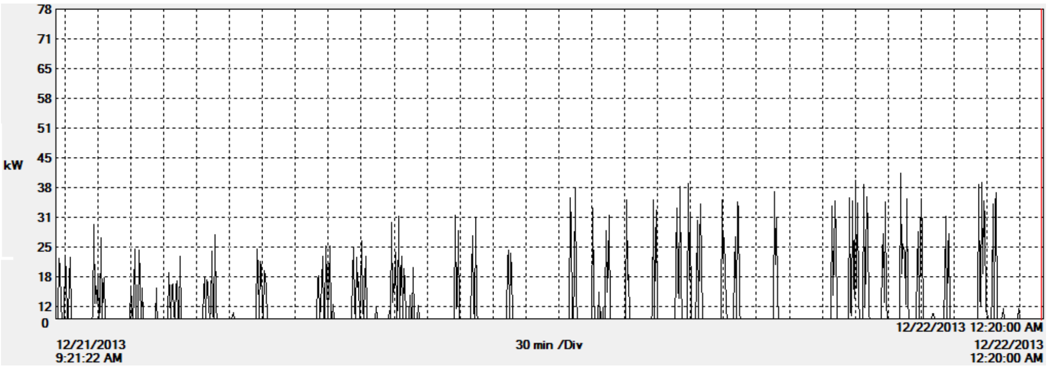


Figure 5-36 Power demand profile of the sand mixing system in a typical production day

5.8 HEAT TREATMENT PROCESS

The heat treatment is one of the fundamental manufacturing processes in the subject plant. It is a highly energy intensive process both using significant amounts of natural gas and electricity. The process flow for the heat treatment process performed in the plant can be seen in Figure 5-37. Heating and soaking cycles of the heat treatment process is performed in a heat treatment furnace in the subject plant which is shown in Figure 5-38. The cycles of heating and soaking are followed by the quenching process which is either liquid quenching performed in quenching pool or air-quenching performed by air fans.

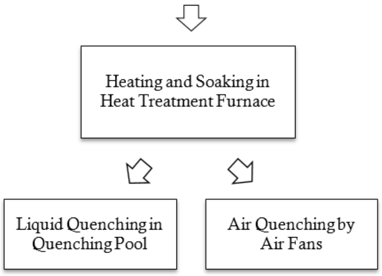


Figure 5-37 Heat Treatment Process in the Subject Plant

5.8.1 IDENTIFYING ESPS IN THE HEAT TREATMENT FURNACE

5.8.1.1 ESP BY USING PREMIMUM EFFICIENCY ELECTRIC MOTOR

The subject plant uses a direct heating batch mode furnace powered by natural gas combustion for performing various heat treatment processes. The heat treatment furnace of the plant can be seen in Figure 5-38. The power rating of the furnace is 1.8 MW. It is equipped with 4 burners and an air supply fan. The burners mix the natural gas and the combustion air supplied by the air fan at an appropriate rate and combust the fuel mix to generate heat energy, which is then is blown into inside the furnace to expose the workpieces to the generated heated. The furnace operates on a batch mode basis, that is, workpieces are loaded into the furnace in batch and heated at a time, not continuously.

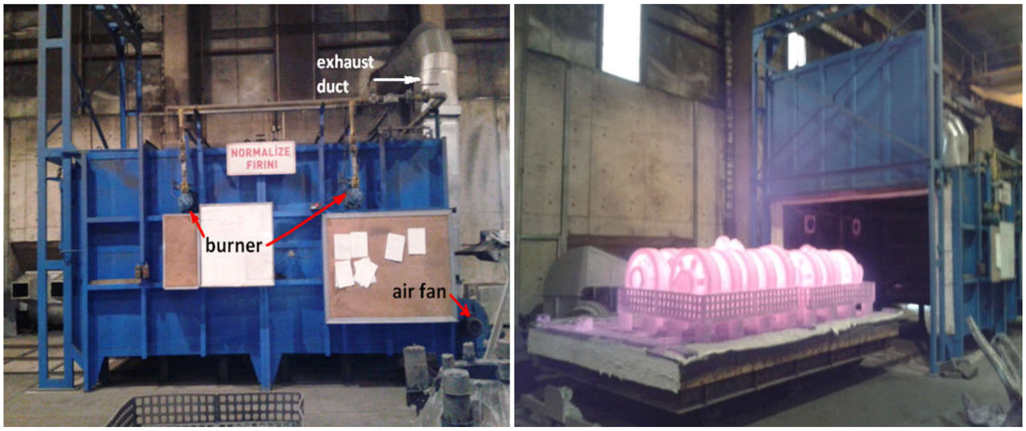


Figure 5-38: The heat treatment furnace in the plant and an example of a batch of steel workpieces right after heating

As noted before, the identifying ESPs in natural gas users is beyond the scope of this thesis. The furnace is equipped with an air fan driven by a 5.5-kW-electric motor (Its specifications are given in Table 5-36). This fan works for about 14 hours per day which makes 4,130 hours per year (i.e. 12hours*295days) and its annual electricity use is 13,629 kWh. The fan speed is controlled by a VFD with regards to the desired furnace inside temperature. When more oxygen is needed, the fan speed increases and more air is blown inside the furnace. It is estimated by the plant electrician that the electric motor operates about 60% loaded.

Table 5-36: Specifications of the electric motor of the air fan of normalisation furnace (source: manufacturers` data)

Maker	Watt Arcelik
Power Rating	5.5kW
Efficiency Class	EFF2 (IE1)
Efficiency	85.5%

As seen in Table 5-36, the electric motor efficiency class is EFF2. It can be replaced with a premium efficient one and energy can be saved. The specification of the proposed motor is given in Table 5-37.

Table 5-37: Specifications of the electric motor of the air fan of normalisation furnace (source: manufacturers` data)

Maker	ABB
Power Rating	5.5kW
Efficiency Class	IE3
Efficiency	89.7%

Following the equation B-7 and B-9 in Appendix B, energy, environmental and monetary benefits of using premium efficiency electric motor have been calculated and presented in Table 5-38. As presented in Table 5-38, ESP%, annual ESP, PESP, ECSP, and CO_2 ERP are 5.4%, 746.6 kWh, 1,844.1 kWh, €49, and 374.5 kg-CO_2, respectively. This ESP is designated as **"ESP 5-13, ESP by Using Premium Efficient Electric Motor".**

Table 5-38: Annual ESP, PESP, ESCP, and CO_2 ERP for ESP 5-13, ESP by Using premium efficient electric motor for the heat treatment furnace air fan

		Source/calculation/ equation
Annual ESP (a)	746.4 kWh	Equation B-8
Annual PESP (b)	1,844.1 kWh	Equation 3-1
Annual ECSP (b)	€ 49	Equation 3-2
ESP %	5.40%	Equation B-8
Annual CO_2 ERP	374.5 kg-CO_2	Equation 3-3

5.8.2 IDENTIFYING ESPS IN AIR-QUENCHING SYSTEM

The subject plant uses air fans for air-quenching of castings. Figure 5-39 shows the air-quenching arrangement set-up in this facility where the blast air is blown by using air fans to high temperature castings right after the heat treatment process that is carried out in the normalisation furnace next to the air-quenching station. There are two air fans both driven by electric motors. The power ratings of the fan electric motors are 30 kW and 22 kW. Figure 5-40 shows the collective power demands of the air fans. As seen, the total power demand is about 50 kW. Based on the information given by the plant management, the daily operation of air-quenching fans 1.5 hours on average. Thus, the annual running hours of the air fans is 442.5 hours. The corresponding annual electricity use, energy cost, and CO_2 emissions are 22,125 kWh, €1,449.2, and 10,820 kg-CO_2, respectively. The quenching air fans account for less than 1% of the overall plant electricity use.

Figure 5-39: Air-quenching Facility in the Subject Plant: air-quenching fans in the plant and a batch of workpieces while being air quenched

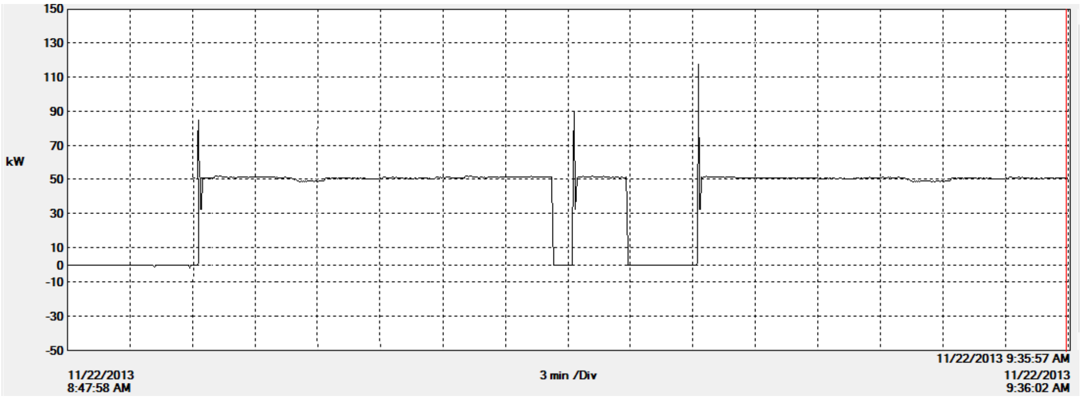


Figure 5-40: Air-quenching fans power demand for air-quenching a batch of workpieces

During the energy audit, it has been observed that the air fans are absorbing the air which is being heated up by the high temperature castings. Since the castings are quenched right after their heat treatment the temperatures can be up to 1,000°C. The inlets of the air fans are very close to the quenching station and the air fans absorb and blow the ambient air with rising temperature. Obviously, the purpose of air-quenching is to cool down the high temperature castings to a certain lower temperature. Blowing hotter air would delay the actual cooling time, and the air fan would work for extra time to cool the castings and thus consume more energy. Therefore, there is an ESP by relocating the air fans outside the plant and blowing in cooler environment.

To show this inefficiency, the air inlet temperatures of an air fan have been recorded by using a temperature data logger in a typical quenching process. The measurement was done for the air-quenching of cooling from 1050 °C to 250 °C of 2,700 kg steel castings. Figure 5-41 shows the temperature profile of the ambient air temperature absorbed by the air fan during this typical process.

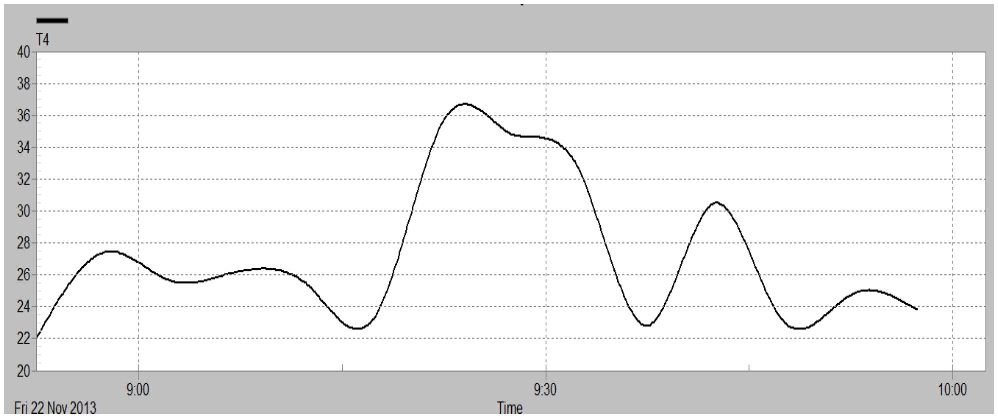


Figure 5-41: Temperature profile of the air fan inlet (°C)

As seen in Figure 5-41, while the ambient temperature was around 22°C before the steel castings at 1,050°C were brought to quenching station. Once the castings were arrived, the ambient temperature rose to around 26°C. This is because the high temperature castings radiated heat to the ambient. When the air blowing started, the ambient temperature boomed to 36°C. This can be explained by the heat transfer by convection in addition to the radiation. When the air fans started to blow air on the casting, this increased the convectional heat transfer between high temperature casting surfaces and the ambient.

As highlighted above, blowing hotter air would delay the actual cooling time, and the air fan would work for extra time to cool the castings and thus consume more energy. To avoid this and blow cooler air to the casting, the solution is to locate the air fans outside of the plant and doing so the quenching air can be blown through air ducts inside. While recording the ambient temperature, the outside temperature was measured to be around 15.4°C. The outside air will provide a steady cooling rate and reduce the air fan working time. Hence, energy will be saved.

Although the above result does not give a quantitative ESP, it gives a clear idea regarding the energy efficiency awareness of the plant. Furthermore, it indicates the importance of consideration for the location of air fans outside the plant in the design stage of the plant because relocation of them will disrupt the production and require additional construction work and space outside the plant.

5.8.3 IDENTIFYING ESPS IN THE LIQUID-QUENCHING SYSTEM

The subject plant has a quenching pool designed for liquid-quenching of castings from high temperatures. The quenching pool is located next to the normalisation furnace, where the normalisation heat treatment of castings is performed before quenching. Water or oil is used as quenching fluid. This depends on the specifications of the casting to be quenched. This quenching fluid is circulated by a pumping system and cooled through a cooling tower. The simplified diagram of the quenching pool and cooling tower is shown in Figure 5-42. To provide a uniform cooling during the quenching process, an agitator is used. This is a small simple propeller driven by an electric motor. It mixes the quenching fluid while quenching. Figure 5-43 shows a liquid quenching process in the subject plant.

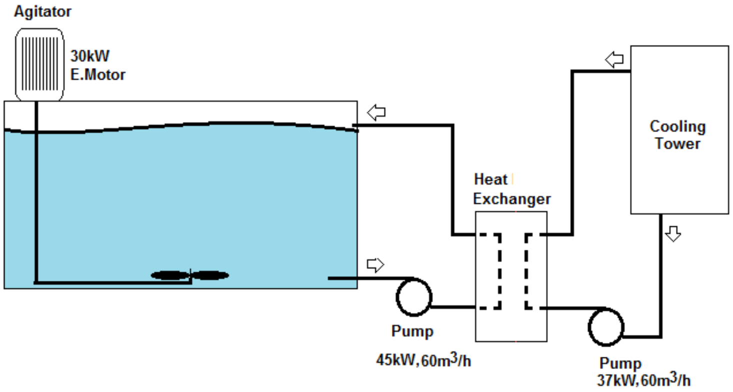


Figure 5-42: Simplified diagram of the quenching system, quenching pool, agitator, heat exchanger, cooling tower, and pumps

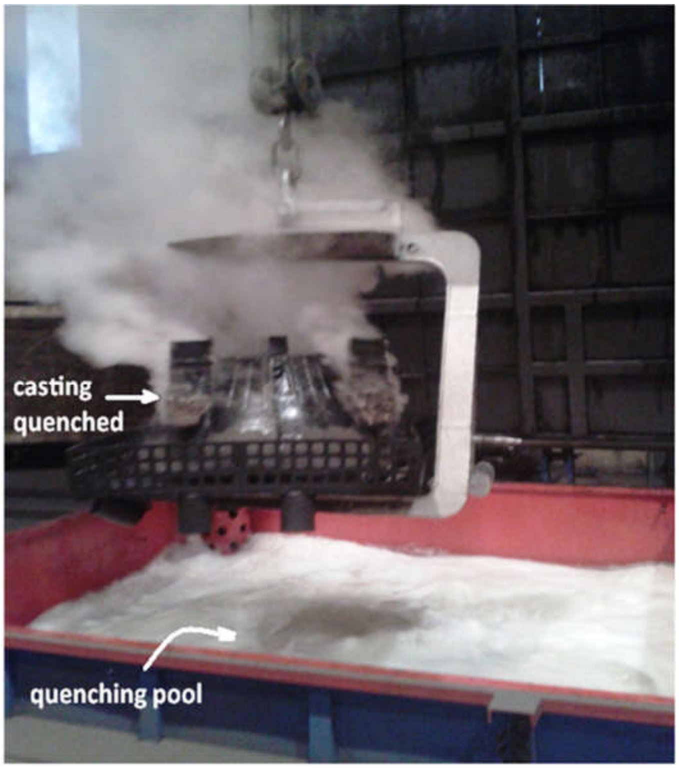


Figure 5-43: Liquid Quenching Pool in the Subject Plant: a batch of workpieces while being liquid quenched

As described above, the quenching pool consists of various power consuming elements. The duration for liquid quenching process differs from day to day depending on the casting specifications and amount. Based on the information given by the plant management, the agitator works for about 2 hours per day while the pool liquid circulation pump works for about 4 hours per day. This is because the agitator is stopped by the operator when the quenching is finished. But, the cooling of the hot quenching liquid needs more time; therefore, the circulation of it through the heat exchanger continues. This can be seen in Figure 5-44 which shows the power demand profile of the quenching pool power consuming components. As seen quenching pool circulation pump draws about 35 kW which means that the load factor for this pump is 77% (i.e. 35/45%). The collective power demand of the circulation pump and agitator is about 65 kW. Thus, the power demand of the agitator is about 30 kW (i.e. 65kW -30kW). Considering the daily working hours of the agitator and circulation pumps (i.e. 2 hours and 4 hours, respectively), the annual power consumption for them are 17,700 kWh for the agitator and 41,300 kWh for the circulation pump. Thus, the total annual electricity consumption and the associated energy cost and CO_2 emissions are 59,000 kWh, €3,865, and 28,851 kg-CO_2, respectively. They account for about 2% of the annual plant electricity use.

Because the technical specifications for the circulation pump and its electric motor is not available, it was not possible to conduct a detailed analysis for their energy performance. Therefore, the ESP identification was only focused to the agitator.

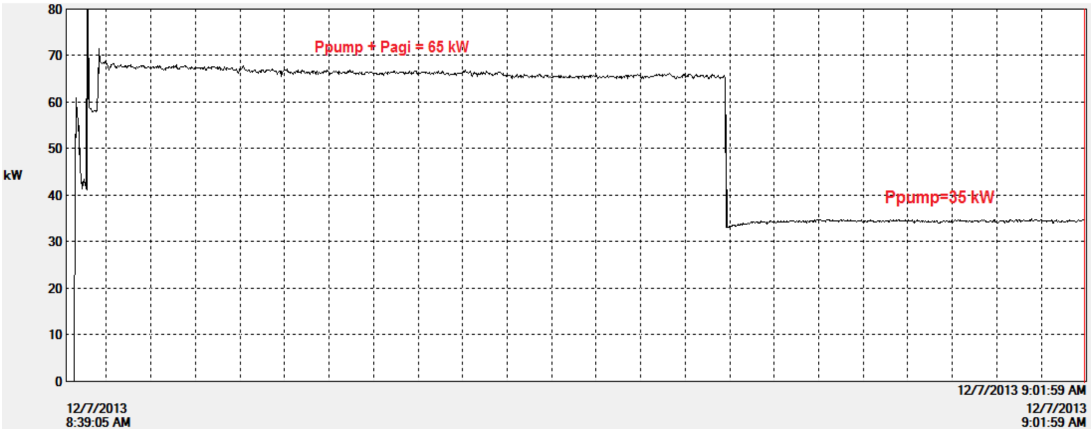


Figure 5-44: Power demand profile quenching pool circulation pump and agitator

5.8.3.1 ESP BY USING MORE EFFICIENT ELECTRIC MOTOR FOR THE AGITATOR

The energy efficiency of the electric motor of the agitator is 89% as given in Table 5-39. There is an ESP by using more efficient electric motor. The agitator works approximately 2 hours per day which makes annual working hours of 590 hours. The efficiency of the proposed motor is 93.6%.

Table 5-39: Rated specifications of the proposed electric motor and existing motor

	Proposed E. Motor	**Existing E. Motor**
Maker	ABB	Siemens 1 LA 21 56 - 4AA B3 P33
Power rating	30 kW	30 kW
Energy Efficiency	IE3	N/A
Efficiency	93.6%	89%

Following the equation B-7 and B-8 in Appendix B, energy, environmental and monetary benefits of using more efficient electric motor have been calculated and presented in Table 5-40 below. As presented in Table 5-40, ESP%, annual ESP, annual PESP, annual ECSP, and annual CO_2 ERP are 4.4%, 782 kWh, 1,931.54 kWh, €52, and 382.3 kg-CO_2, respectively. This ESP is designated as **"ESP 5-14, ESP by Using Premium Efficient Electric Motor for the Quenching Pool Agitator".**

Table 5-40: Annual ESP, Primary ESP, ECSP, and CO_2 ERP for ESP 5-14, ESP by using premium efficient electric motor for the quenching pool agitator

		Source/calculation/equation
Annual ESP (a)	782 kWh	Equation B-8
Annual PESP (b)	1931.54 kWh	Equation 3-1
Annual ECSP (c)	€52	Equation 3-2
ESP %	4.4%	Equation B-8
Annual CO_2 ERP	382.3 kg-CO_2	Equation 3-3

5.9 CHAPTER SUMMARY AND CONCLUSIONS

The steps 1 and 2 of PHASE-2 of the Energy Auditing Methodology of the developed holistic framework in the thesis requires the detailed study and analysis of the collected data on the target energy consuming systems in order to identify ESPs which will reduce energy consumption and improve the energy efficiency of the plant. As a requirement of the energy auditing methodology, the objective of this chapter was to present the energy auditing analyses conducted on the target energy consuming systems of the production process systems which included Melting System, Grinding System, Abrasive Blasting System, Machine Shop, Sand Reclamation System, Sand Mixing System, and Heat Treatment System of the subject plant. This was done through detailly studying and analysing the data collected through the energy audit conducted in the subject plant.

The following major conclusions can be drawn from this chapter:

- The energy consumption of Melting System, which is the most significant energy consumer in the subject plant accounting about 35% of the overall plant energy consumption, can be reduced by 15%. To achieve this, the subject plant has to reduce its specific melting energy consumption by 50% of the specific improvement potential identified in the analysis through benchmarking against the European Best Level. This requires the subject plant to improve its meltings skills (ESP 5-1). In addition to this, the subject plant should reduce its annual casting defect rates by 50% (ESP 5-2).

- The Grinding System energy consumption can be reduced by 24.5%. A major contribution to 24.5% comes from behaviour change which requires the subject plant to keep the idle machines off (ESP 5-3) which would yield an attractive 15% energy saving in the grinding system. In addition to behaviour change, the subject plant should do energy efficiency retroffiting for further savings; one is replacing the existing electric motors of the pendulum-grinders with premium efficient ones (ESP 5-4), and the other one is using more efficient transmission belts for the pendulum grinders (ESP 5-5).

- The Abrasive Blasting System energy consumption can be reduced by 17.1% given that the unnuessary working of the ventilation fan of the blasting system is avoided (ESP 5-6); the existing electric motors of the vibrators are replaced with premium efficient ones (ESP 5-7); and more efficient transmission belts are used (ESP 5-8).The effect of human factor to overall saving is considerable by about 12% (ESP 5-6).

- The total energy consumption of the audited machine tool in the Machine Shop can be reduced by 45% through replacing it with a new one (ESP 5-9). In addition to this, the subject plant can reduce the energy consumption of machine tools by about 6.5% by simply turning the unnecessarily working machine tools off (ESP 5-10).

- The annual energy consumption of the Sand Reclamation System can be reduced by 9.7%. In order to achieve this, the subject plant should avoid the unneccessary operation of the sand reclamation system which accounts for 9% of the total energy consumption (ESP 5-11). Besides, further energy consumption reduction can be achieved by replacing the existing electric motor of the air fan of the sand reclamation system with a premium efficieny electricity motor (ESP 5-12).

- The electricity consumption of the Heat Treatment Furnace of the subject plant due to its air fan can be reduced by 5.4% by replacing the existing electric motor with a premium efficiency electric motor (ESP 5-13). Similarly, the electricity consumption of the quenching pool of the heat treatment process can be reduced by 4.4% by by replacing the existing electric motor of the agitator with a premium efficiency electric motor (ESP 5-14)

- In total, the production process systems included in the energy audit accounts for about 48.6% of the total plant energy consumption. The materialisation of the ESPs identified in the production process systems can yield an annual ESP of 206,216 kWh which is 14.3% of the overall production process energy consumption and about 7% of the total plant annual energy consumption. These reduction potentials are technically feasible. Their economic feasiblities are evaluated in Chapter 7.

- Human factors such as behavior changes for energy saving. In most cases, behavior change for energy efficiency can provide more savings than technical factors in an energy consuming system as it is the case for the Grinding System (ESP 5-3), the Abrasive Blasting System (ESP 5-6), and the Sand Reclamation Sysetm (ESP 5-12) of the subject plant. This clearly shows the importance of the human element for improved energy performance.

- The results of the energy audit conducted on the production process systems presented in this chapter clearly presents that there exist considerable energy efficiency gaps in each system. The energy efficiency can be improved focusing on technicalities and human factors through the following measures:

  - energy efficiency retrofits/replacement
  - using right sized equipment/system
  - avoiding/eliminating non-value added equipment/system operations
  - changing behavior for energy efficiency and increased awareness
  - process improvement and resource efficiency
  - preventative maintenance

6

Energy Saving Potentials in Production Support Systems

6.1 INTRODUCTION

The objective of this chapter is to present the energy auditing analyses conducted on the target energy consuming systems of the production support systems of the subject plant to identify the appropriate ESPs using alternative methods and their application. To meet this objective, this chapter is structured in five sections:

- Ventilation System (Section 6.2)
- Compressed Air System (Section 6.3)
- Cooling Tower Systems (Section 6.4)
- Lighting Systems (Section 6.5)
- Plant Offices (Section 6.6)

Finally, a brief summary of the chapter and concluding remarks of the overall chapter are given in Section 6.7.

6.2 VENTILATION SYSTEM

The subject plant has a ventilation system in the foundry unit. It is an exhaust ventilation system and used to remove the low quality indoor air arising from dust and fumes generated by various processes performed in the plant. The ventilation system of the plant consists of a central exhaust ventilation system and several local exhaust ventilation systems such as the one in Figure 6-1.

The central ventilation system is used for capturing and removing dust and fumes which the local ventilation systems cannot cope with. Furthermore, there are other pollution sources in the plant in addition to the above-said dust and fumes. For example, large amounts of emissions such as particular matter, oxides of carbon, and VOCs including formaldehyde, etc. (EPA, 2016) are intensely released while carrying and pouring the molten metal into the moulds. An example of this can be seen in Figure 6-2 which was taken as the molten metal was being poured to a ladle from the furnace. Figure 6-3 also shows another emission releasing while the castings are waiting for cooling down right after the pouring.

The local exhaust ventilation systems are equipped with small size electric motors such as 0.75 kW whereas the central exhaust ventilation system has a power rating of 45 kW. The central ventilation system is one of the major energy consumers in the subject plant. Based on the power consumption measurement, it was found to be responsible for energy consumption of approximately 250,071.5 kWh/year. This accounts for 8.4% of the overall annual electricity consumption of the plant. The associated annual primary energy consumption, energy costs, and CO_2 emission generation values are 617,739 kWh, €16,391.34, and 122,297.3 kg-CO_2. The local ventilation systems were not taken into account in this study. This chapter is devoted only to the central exhaust ventilation system and will be called as "ventilation system" hereafter. The calculations for energy consumption characteristics of the central exhaust ventilation system are summarised in Table 6-1.

Table 6-1: Operation and energy consumption characteristics for ventilation system

		/Source
Daily Operation Hours (a)	17.5 hours	Plant data
Annual Operation Hours (b)	5,162.5 hours	Plant data
Average Power Demand (c)	48.44 kW	Power measurement
Energy Consumption in a typical shift (d)	847.7 kWh	Power measurement
Annual Energy Consumption (e)	250,071.5 kWh	e=b*c
Annual Primary Energy Consumption (f)	617,739 kWh	f=e*PECF
Annual Energy Cost (g)	€16,391.34	g=e*EUCR
Annual CO_2 Emissions (h)	122,297.3 kg-CO_2	h=e*CO_2 EF

Figure 6-1 An example of local exhaust ventilation at one of the grinding stations in the subject plant (Photo taken by the Author)

Figure 6-2: Large amounts of dusts and fumes are produced while the furnace load (i.e. molten metal) is poured to the ladles (Photo taken by the Author)

Figure 6-3: Large amounts of dusts and fumes are produced while the castings are cooling down (Photo taken by the Author)

The ventilation system of the subject plant comprises of four main components: an air fan, an electric motor, a system of ducts, and a baghouse (dust collector). They can be seen in Figure 6-4. A simplified diagram of the ventilation system of the plant can be seen in Figure 6-5. Also, the plant utilises a VFD (variable frequency driver) which is attached to the electric motor to control the speed of the air fan. It is shown in Figure 6-6. The technical specifications of the electric motor of air fan is given in Table 6-2.

The air fan, which is driven by the electric motor, creates a negative pressure which causes to an air flow from plant indoor to the baghouse through the ductworks. Thus, the low quality indoor air is conveyed to the baghouse where the dust and fumes are captured and separated from the air flow (Kleinman and Marley, 2005). The type of dust collector used in the ventilation system of the plant is a pulse-jet dust collector, which is a type of fabric filters representing the most efficient dust removal technology available (Abu-Shaqra, 2005). Fabric filters are also called as baghouses.

The dust laden air inside the plant is pulled through the fabric filter by means of the negative pressure produced by the air fan. The air passes from the outside to the inside of the filter bags. At this point, the particulate matters such as dust and fumes in the air stream are trapped and captured by the filters and accumulated on the outside surface of the bags. Thereafter, the filtered air leaves the baghouse and released to the atmosphere (EPA, n.d.). The filters should be regularly cleaned for an efficient filtering operation. Otherwise, the dust accumulation on the outer surface of the filter will improve the filtering act as a barrier to the incoming air flow and increase the pressure drop which will impose additional load on the fan. The impact of these factors on ventilation system energy consumption in the case plant were technically impossible to measure and assess during the energy audit period; therefore, the efficiency of filters in the subject plant are beyond the focus of this study.

Table 6-2: Specifications of the electric motor of the fan in the ventilation system (Source: product datasheet)

Power rating	45 kW
Energy Efficiency Rating	EFF2
Efficiency	92.4%

Figure 6-4: The ventilation system of the plant: air fan, filter unit, and ducting system

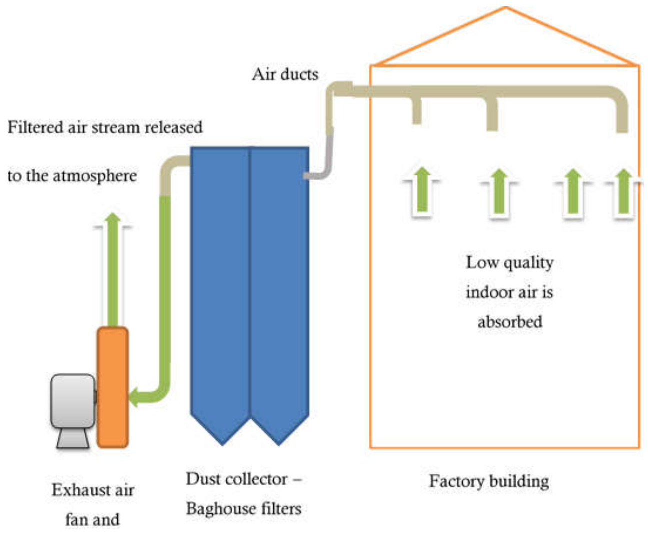


Figure 6-5: A simplified diagram of the ventilation system in the subject plant

6.2.1 IDENTIFYING ESPS IN THE VENTILATION SYSTEM

If there is no pollution generated in the plant, there will be no need for a ventilation system and no energy will be consumed. However, preventing the dust emissions in a foundry is unrealistic because the foundry production is very polluting by its nature. But, this does not mean the dust is continuously generated at a constant rate. The indoor air quality is not constant, it is rather variable depending on the production conditions.

This is also the case for the subject plant. The ventilation need of the plant is varying in time because of the varying level of impurities in the plant indoor air depending on the production conditions. For example, while the indoor air quality of the plant is lowest during pouring of the molten metal, it is relatively in better condition in other production periods. Therefore, the ventilation system does not always have to run continuously at full capacity. Rather, it should match the load actually required by the plant conditions.

For such cases where the ventilation need is varying over time, using a variable air volume flow ventilation system will be advantageous from the point of energy savings. The flow rate of a variable volume ventilation system can be modified according to the desired patterns. This concept is called as “Demand Controlled Ventilation (DCV)” and it can work automatically using appropriate automatic control systems (Fahlén, 2008; Litomisky, 2007; Maripuu, 2009). A DCV system adapts the airflow rate continuously to the actual pollutant emission levels from activities and processes in a production medium. For this purpose, a VFD is attached to the air fan electric motor.

Regarding the subject plant, the ventilation system is a variable air volume ventilation system. A VFD to vary the fan speed was integrated to the system during the initial set up. However, the speed regulation is carried out manually, so the system can be regarded as a manually controlled system. The manual controlling knob of the VFD can be seen in Figure 6-6.

The plant somehow made an investment in a VFD during the initial set up of the ventilation system.. However, during the discussions with the plant personnel and observations throughout the energy audit, it has been seen that the plant does not use the VFD and unaware of the ESP that VFD will provide. The VFD board is located at the furnaces bay and the furnace operator is just responsible for just turning on the VFD in the morning and off at the end of production shift. Therefore, the ventilation system operates at full capacity like a constant volume flow system without regards to the actual ventilation demand. More efficient VFD control can be achieved through automatic control systems (i.e. Demand controlled ventilation system), which adjust the VFD speed based on the real-time measurements of indoor air quality of the plant. This can yield to energy savings.

Figure 6-6: VFD used in the ventilation system (Photo taken by the Author)

In addition to the above, as seen in Table 6-2, the energy efficiency rating for the existing electric motor is EFF2. Thus, energy can be saved by replacing the existing electric motor with an energy efficient one.

The above preliminary analysis suggests two ESPs. These are:

1. ESP by Using Demand-Controlled Ventilation System (DCVS).
2. ESP by Using Premium Efficiency Efficient Electric Motor.

These will be investigated and explained in the following sections.

6.2.1.1 ESP BY USING DEMAND CONTROLLED VENTILATION SYSTEM

In this thesis, a generic DCV system proposed by (Litomisky, 2007) will be considered as an energy saving measure for the ventilation system of the case manufacturing plant. An overview of the system can be seen in Figure 6-7.

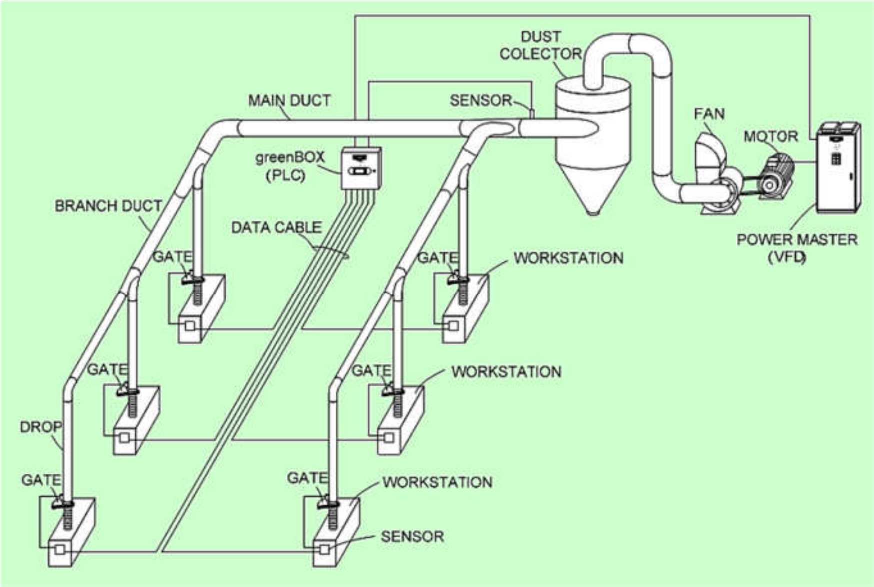


Figure 6-7: Demand-controlled ventilation system (Litomisky, 2007)

In this demand-controlled ventilation system, a sensor is located at each workstation as well as a gate to close each ventilation duct as seen in Figure 6-7. A central controller continuously receives data from the dust sensors, which measures the dust levels. The controller calculates the required speed of the air fan which will create adequate air flow based on the data received from dust measuring sensors (Litomisky, 2007) rather than running the fan at a constant rate with no regard to the actual dust levels inside the plant. (Litomisky, 2007) estimated the energy savings by using on-demand ventilation system in various industrial and commercial fields. These include a battery producer, a dental lab, a wood working factory, and a car manufacturing plant. An average energy saving of 68% in ventilations systems of these plants were estimated by using demand controlled ventilation systems over unregulated systems by (Litomisky, 2007).

In this study, ESP by using such a system has been estimated for the subject plant on the basis of the above explained reasons which lead to energy inefficiencies. A detailed DCV system design tailored to the subject plant and determining technical specifications of each system components are beyond the scope of this thesis. Instead, a case study has been performed to demonstrate energy saving effect of DCVS on the subject plant. However, it should be borne in mind that system size and specifications are of important in terms of cost-effectiveness of the system. Therefore, the Author consulted a company which undertakes similar works in Turkey to learn the required system size for the subject plant and latest relevant cost figures. A simplified DCV system diagram for the subject plant is presented in Figure 6-8. The air duct and branches, baghouse filters, air fan and electric motor, and VFD already exist in the plant. The existing ventilation system requires the following components to be converted to a DCVS as specified by the company consulted by the Author:

- 5 dust sensors which will be located at each duct branches and measure dust concentrations and send data to a controller.
- 1 controller which receives information from dust sensors and adjusts the speed of the air fan by means of the VFD and opens/closes the motorised blast gates based on the ventilation need.
- 10 blast gates: which provide automatic opening and closure of the dust extraction ports on the duct branches. These are electrically driven and wired remote controlled by the controller.

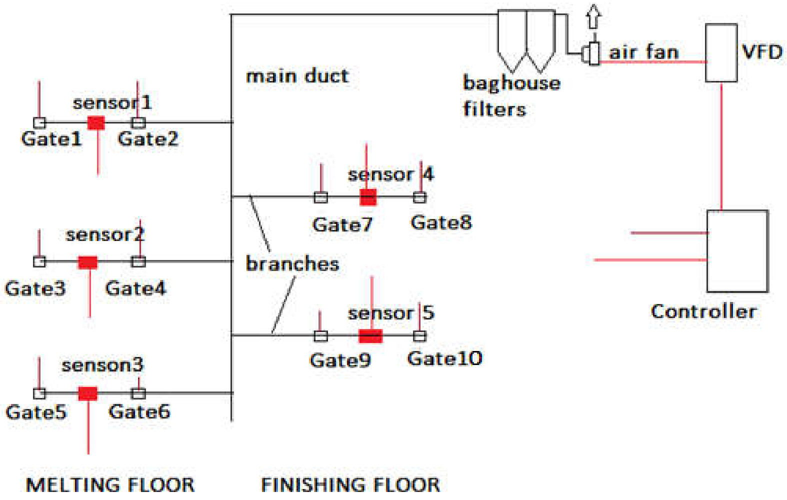


Figure 6-8: Simplified diagram of the DCV system for the subject plant

As described earlier, the controller in a DCV system receives information from dust sensors installed onsite the plant and adjusts the speed of the air fan by means of the VFD. Because a VFD is already employed by the subject plant, it is possible to manually vary the speed of the air fan with regards to the inside air conditions. Exploiting this opportunity, energy consumption of the fan was recorded in two cases:

- Case 1 (Operation Without VFD)**:** At full load of the fan in one shift, assuming it as an example for existing plant utilisation of the VFD.

- Case 2 (Operation With VFD): At partial load by manually changing the revolution of the electric motor through the VFD based on the observations made on the indoor air quality, presenting the more efficient use of the VFD and energy.

Case 1: Operation without VFD

This case reflects the plant`s attitude about using ventilation fan: operation at full load without using VFD. Current (A) profiles can be seen in Figure 6-9. Right hand side of the graphs belongs to Case 1, operation without VFD as noted on the Figure. As expected, there is no change in both in current and the graph is steady. This is because the prime mover of the ventilation system, the electric motor, operates at full load speed (about 1618 rpm) and draws constant power. The calculations in Table 6-3 are made so as to find the energy consumption in Case 1.

Table 6-3: Energy consumption and cost in Case 1

Case 1: operation without VFD		
		Source/Calculations/Equation
Total measurement time (a)	7.6 hours	(measured)
Total active energy use (b)	368.41 kWh	(measured)
Average power demand (c)	48.44 kW	c=b/a
Daily operation hours (d)	17.5 hours	(plant)
Annual operation days (e)	295	(plant)
Annual operation hours (f)	5,162.5 hours	f=d*e
Estimated annual energy use (g)	250,096.79 kWh/year	g=e*c
Estimated annual energy cost (h)	€1,6381.34	h=g*EUCR

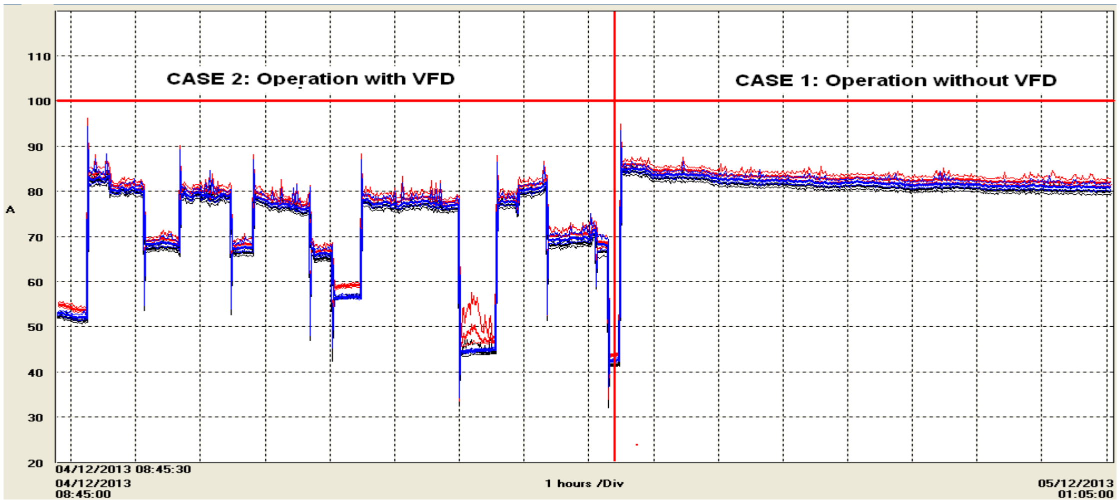


Figure 6-9: Power demands of the ventilation system for two cases

Case 2: Operation with VFD

This case reflects how the ventilation system should be used for energy saving and better utilisation of the VFD which was already invested and installed in the plant. The varying rpm of the air fan is assumed to be achieved by means of the control system and dust sensors. To imitate this operation, the speed of the electric motor was changed manually using the VFD based on the observations made on the indoor air quality. Hence, this case presents the more efficient use of the VFD and energy: operation at partial load using VFD. Current (A) profile of Case 2 can be seen on the left-hand side of Figure 6-9. As seen, the graphs are not constant for current values. As the speed of the electric motor was changed through VFD, the frequency and the current values correspondingly changed. The calculations in Table 6-4 are performed so as to find the energy consumption in Case 1.

Table 6-4 : Energy consumption and cost in Case 2

Case 2: operation with VFD		
		/Source/Equation
Total measurement time (a)	8.17 hours	(measured)
Total active energy use (b)	363.01 kWh	(measured)
Average power demand (c)	41.64 kW	c=b/a
Daily operation hours (d)	17.6 hours	(plant)
Annual operation days (e)	195	(plant)
Annual operation hours (f)	5,162.5 hours	f=e*d
Estimated annual energy use (g)	214,987.15 kWh	g=c*f
Estimated annual energy cost (h)	€14,081.65	f=e * EUCR

The power consumption difference between Case 1 and Case 2 corresponds with the ESP that will be realised owing to the better utilisation of the VFD as part of a DCVS. This ESP is designated as **"ESP 6-1, ESP by Using DCVS".** The calculations for ESP 6-1 are presented in Table 6-5. As the calculations in Table 6-5 show, the ESP by Using a DCVS will be 214,987.15 kWh/year; and the associated ESP%, annual PESP, ECSP, and CO_2 ERP are 14.38%, 35,109.64 kWh, 86,720.8 kWh, €2,299.66, and 17,168.6 kg-CO_2, respectively. This analysis has been done based on the assumption that the controller will change the speed of the air fan at a rate as in the above presented case study. Depending on the plant indoor air conditions, ventilation need, energy consumption, and ESP will vary. In this study, an ESP of 14.38% will be used as a representative in ventilation system by converting the existing ventilation system into a DCVS.

Table 6-5: Calclations for ESP 6-1: Annual ESP, PESP, ECSP, CO_2 ERP

		/Source/Equation
Annual Energy Use in Case 1 (a)	250,096.79 kWh	Table 6-3
Annual Energy Use in Case 2 (b)	214,987.15 kWh	Table 6-4
Annual ESP (c)	35,109.64 kWh	c=a-b
Annual PESP (d)	86,720.8 kWh	Equation 3-1
Annual ESCP (e)	€2,299.66	Equation 3-2
ESP % (f)	14.38%	f=c/a %
Annual CO_2 ERP (g)	17,168.6 kg-CO_2	Equation 3-3

The above analysis has been conducted to represent the case which assumes that the subject plant uses a DCVS system. There are various costs associated with the application of the DCVS. For that reason, a detailed investment analysis based on NPV and B/C ratio methods is presented in Appendix E. Their cost effectiveness are evaluated in Chapter 7.

6.2.1.2 ESP BY USING PREMIUM EFFICIENCY ELECTRIC MOTOR

As given in Table 6-6 below, the energy efficiency class of the electric motor of the air fan is EFF2. The impact of replacing the existing electric motor with a premium energy efficient electric motor will be analysed for the electric motor of the plant. The specifications of the proposed electric motor are compared with the existing one in Table 6-6.

Table 6-6: Rated specifications of the proposed electric motor (source: manufacturer`s data)

	Existing E. Motor	**Proposed E. Motor**
Maker	CAMAK	ABB IE3 cast iron motor
Power rating	45 kW	45 kW
Energy Efficiency Rating	EFF2	IE3
Efficiency	92.4%	94.2%

Following Equation B-8 and B-9 in Appendix B, energy, environmental and monetary benefits of using more efficient electric motor in ventilation system have been calculated and presented in Table 6-7 below.

Table 6-7: Calculations for ESP 6-2: Annual ESP, %ESP, PESP, ESCP, and CO2 ERP

		/Source/Equation
Annual ESP (a)	3,843.3kWh	Equation B-8
Annual PESP (b)	9,491.95 kWh	Equation 3-1
Annual ESCP (c)	€251.7	Equation B-9
ESP % (d)	2.23%	Equation B-8
Annual CO_2 ERP (e)	17,168.6 kg-CO_2	Equation 3-3

As presented in Table 6-7, the associated ESP%, annual ESP, annual PESP, annual ESCP, and CO_2 ERP are 2.23%, 3,843.3 kWh, 9491.95 kWh, €251.7, and 17,168.6 kg-CO_2, respectively. Because replacing the existing electric motor in the ventilation system with an energy efficient one involves additional investment cost, a detailed investment analysis based on NPV and B/C ratio methods is presented in Appendix E and evaluated in Chapter 7. This ESP is designated as **ESP 6-2, ESP by Using Premium Efficiency Electric Motor.**

6.2.2 REVIEW OF THE ESPS IDENTIFIED IN THE VENTILATION SYSTEM

As a result of the energy audit analyses focusing on the ventilation system of the subject plant, two ESPs have been identified:

- ESP 6-1, ESP by Using DSV System
- ESP 6-2, ESP by Premium Efficiency Electric Motor

The identified ESPs in the ventilation system are summarised and documented in Table 6-8.

Table 6-8 Summary of ESPs identified in ventilation system of the subject plant

ESP No	**Measure**	**EPS (%)**	**Annual ESP (kWh/year)**	**Annual PESP (kWh/year)**	**Annual ECSP (€)**	**Annual CO_2 ERP (kg-CO_2)**
6-1	ESP by using DCV system	14.48.5%	35,109.64	86,720.89	2,299.66	17,168.6
6-2	ESP by Using Premium Efficiency Electric Motor	2.23 %	3,843.3	9,492.95	251.7	1,879.37
Overall $ESP_{ventilation}$		15.5 %	38,952.94	96,213.8	2,551.36	19,047.97

Overall, the total ESP in the ventilation system, $ESP_{ventilation}$ is the sum of all the identified ESP in the ventilation systems Thus,

$$ESP_{ventilation} = ESP\ 6\text{-}1 + ESP\ 6\text{-}2$$

$$ESP_{ventilation} = 35{,}109.64 + 3{,}843.3 = 38{,}952.94\ \text{kWh}$$

If all the identified ESPs materialized, the overall annual ESP in the ventilation system of the subject manufacturing plant will be 38,952.94 kWh which about 15% of the overall annual ventilation systems energy consumption. Using Equations 3-1, 3-2, and 3-3, the associated annual PESP, ECSP, and CO_2 ERP will be 96,213.8 kWh, €2,551.36, and 19,047.9 kg-CO_2, respectively.

6.3 COMPRESSED AIR SYSTEM

As many manufacturing plants, compressed air is an essential and most expensive source of energy for the case plant. Compressed air is required in almost all stages of manufacturing processes in the plant, from moulding, casting, dismantling to machining stages, either directly used by air guns or used to power pneumatic systems as in the machine tools. Based on the power measuremments and calculations conducted by the author, annual energy consumption for the CAS of the subject plant is approximately 132,728.46 kWh which is about 4.5 % of the overall plant consumption. The corresponding annual primary energy consumption, energy cost, and CO_2 emissions generation are 327,839.3 kWh, €8,693.71, and 64,904.21 kg- CO_2, respectively.

There are two air compressors in the subject plant. One (Compressor 1) is bigger in capacity and size and other one (Compressor 2) is smaller. The plant uses the smaller one in night shift because they think that compresed air demand (CAD) will be lower so that the smaller compressor can meet the night demand. Specifications for both compressors and energy consumption figures are given in Table 6-9 and Table 6-10, respectively. As seen, Compressor 1 has a power rating of 55 kW and Compressor 2 has a power rating of 18 kW. Their specific capacities (SC) are 10.154 m^3/min and 3.25 m^3/min for Compressor 1 and Compressor 2, respectively. Their specific power consumption (SPC) are 0.1595 m^{3}kW/min for Compressor 1 and . The type of both compressors is Fixed Speed Drive (FSD) rotary screw controlled with load/unload controlling. The volume of the storage tank in the CAS of the subject plant is 2 m^3. The pictures of the compressed air system are provided in Appendix G.

Table 6-9**:** Technical Specifications for Compressor 1 and Compressor 2

	Compressor 1	**Compressor 2**	**Source**
Maker	Dalgakiran	Atlas Copco	Compressor nameplate and manuals
Type	Screw	Screw	
Control	FSD Load/Unload	FSD Load/Unload +	
Rated Power	55 kW	18 kW	
SC	10.153 m^3/min	3.25 m^3/min	
SPC	0.1595 m^{3}kW/min	0.1756 m^{3}kW/min	
Employment	Day shift	Night Shift	
Storage tank	2 m^3		

Table 6-10: Operation and Energy Consumption Characteristics for Compressor 1 and Compressor 2

	Compressor 1	**Compressor 2**	**Source**
Daily Operation Hours	8.75 hours	8.30 hours	Audit power and energy measurements/ Collected data
Annual Operation Hours	2,581.25 hours	2,448.5 hours	
Average Power Demand	41.47 kWh	10.49 kWh	
Energy Consumption in a typical shift	338.8 kWh	94.93 kWh	
Annual Energy Consumption	107,043.7 kWh	25,684.76 kWh	
Annual Energy Cost	€7,011.36	€1,682.35	
Total Annual Energy Consumption (a)	132,728.46 kWh		
Total Annual Primary Energy Consumption (b)	327,839.3 kWh		b=a*PECF
Total Annual Energy Cost (c)	€8,693.71		c=a*EUCR
Annual CO_2 Emissions (d)	64,904.21 kg-CO_2		d=a* CO_2 -EF

6.3.1 IDENTIFYING ESPS IN COMPRESSOR 1

So as to identify the appropriate ESPs in the CAS, the existing performance of the compressors are needed to be analysed. Their performances have been analysed based on the power measurement data obtained through the energy auditing, and the results are presented in the following sections.

6.3.1.1 EXISTING PERFORMANCE OF COMPRESSOR 1

The power demand of Compressor 1 was recorded in a typical production shift. The overall power profile has been broken down into consecutive periods of 1 hour through the software of PEL 103, and the corresponding power demand profiles for each period have been produced as one can see in Appendix C. Figure 6-10 is presented as an example.

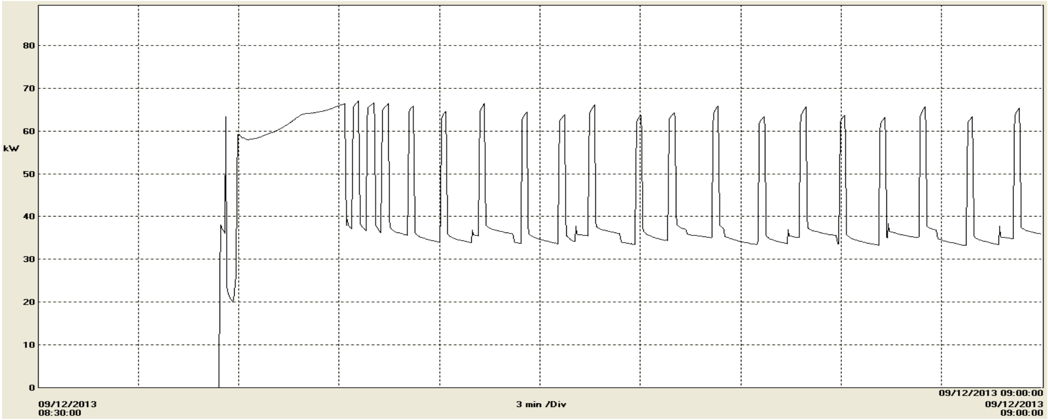


Figure 6-10: Compressor1 power demand profile between 08:30-09:00

As seen in Figures in Appendix, the power demand of Compressor 1 has a cycling nature. This is due to the **load/unload control** type of Compressor 1. Rotary-screw FSD air compressors with this type of control system cycles between periods of compressed air generation and idling (Abels and Kissock, 2011). Thus, a compressor operates in two modes: load-mode and unload-mode; compressed air generation takes place in load-mode whereas idling in unload-mode; and these are determined by upper and lower activation system pressures settings. The compressor operates in load-mode and produce compressed air to the air storage tank until the system pressure reaches to a certain point, which is defined as **upper activation pressure**. When the system pressure reaches to the upper activation point, the compressor goes into unload-mode and the compressor air discharge valve is closed to stop the air flow to the system (Beals, 2009).

Meanwhile, the lubricant sump/separator vessel (which is an air/lubricant separator and sump assembly in lubricated rotary-screw compressors that filters and collects the compressor lubricant that was injected into the main compression elements during compressor operation (Beals, 2009)) starts to be relieved gradually. This is called as **blow-down** and continues until the sump/separator vessel pressure is fully relieved. In parallel to this, power consumption of the compressor begins to decrease and the **unload-mode power** is realized when the lubricant sump/separator is fully relieved (Sullair, 2004).

During the unload mode period, because the compressed air in the system is still consumed by the compressed air end-users in the subject plant, the volume of compressed air in the storage tank decreases and the system pressure continuously goes down. The system pressure goes down until it reaches to a certain point, which is defined as **lower activation pressure.** When the system pressure reaches to the lower activation pressure, the control system activates the compressor; the unload-mode ends. For load-mode period to begin, air/lubricant sump/separator is re-pressurised which takes about 3 seconds. This is called as **sump-up** (Beals, 2009). The compressor operates fully loaded and produces compressed air. The sum of unload mode and load mode period constitutes a **cycle**. Length of a cycle period is important for efficient operation of an FSD compressor with load/unload control and its electric motor driver. Cycle, load-mode, unload-mode, sump pressurisation, and blow-down sections over the power demand profile of Compressor 1 are demonstrated in Figure 6-11 based on 4-minutes snapshot of power demand.

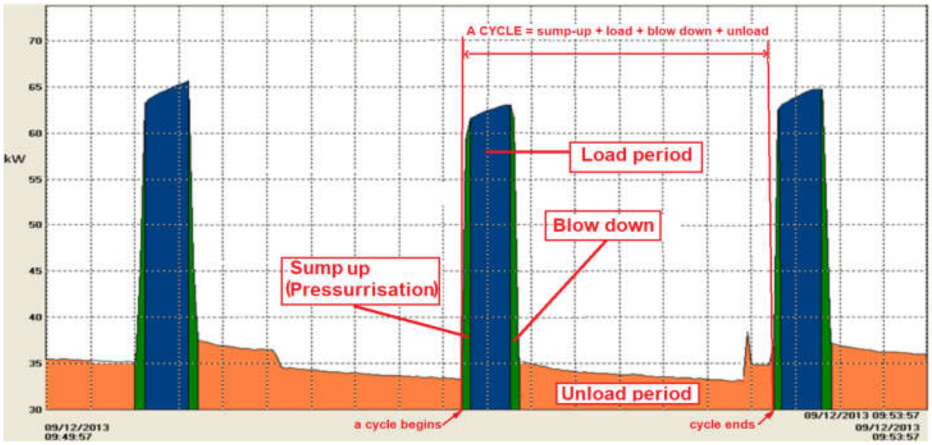
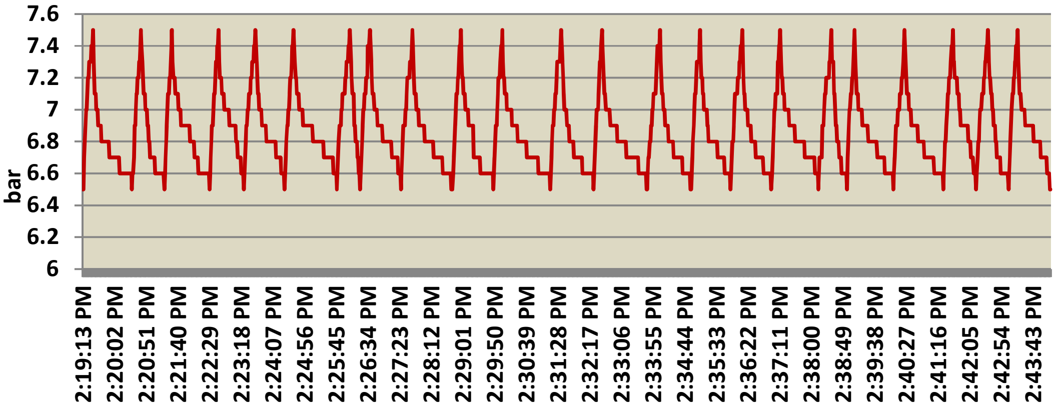
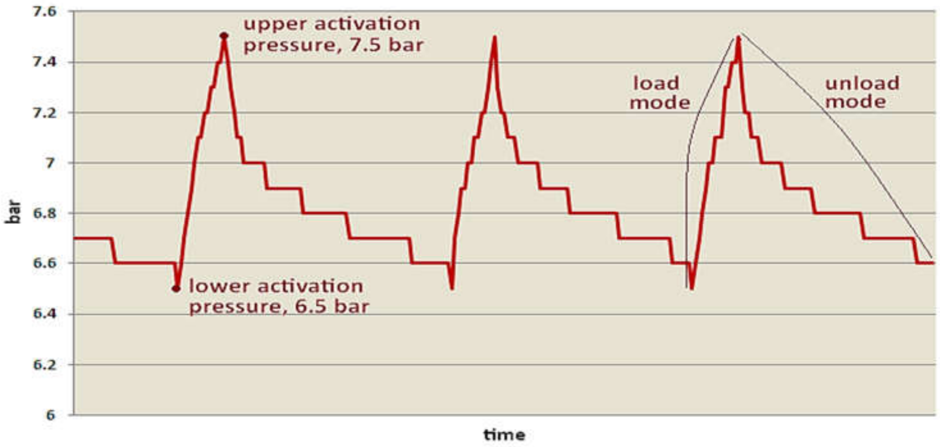


Figure 6-11: Load-mode, unload-mode, sump-pressurisation and blow-down sections over the power demand profile

The cycling of Compressor 1 between upper activation pressure and lower activation point can be seen in Figure 6-12a, which shows the pressure profile of Compressor 1 logged at one second intervals from the front panel of the air compressor for about 20 minutes. Figure 6-12b further shows the upper and lower pressure points and load and unload-modes. The upper and lower activation pressures for Compressor 1 is 7.5 bar and 6.5 bar, respectively. Thus, Compressor 1 operates on a pressure band of 1 bar.



a) pressure profile of Compressor 1 for 20 minutes



b) magnified view of pressure profile within a very short period

Figure 6-12: Compressor 1 pressure profile

As a result of cycling between upper and lower activation pressure (i.e. operating between load-mode and unload-mod), the power demand of Compressor 1 has a cycling profile, as well. This can be clearly seen on from in Appendix CCC, the power demand goes up and down frequently between around 60-65 kW and around 35 kW. This means that the fully loaded power demand in load-mode is between 60-65 kW and the partially loaded power demand in idling unload-mode is around 35 kW for Compressor 1. As seen, load-mode power demand is quite higher than unload-mode power demand. This is as expected because the compressor is fully loaded in load-mode and should draw higher power than in idling unload-mode. Although power rating of the compressor is 55 kW, it draws about 60-65 kW, which is about 110% of its power rating (i.e. 55kW). This is a characteristic for compressors with load-unload controlling; a compressor with this control type draws about 105-115% of its power rating in load-mode and about 20-60% in unload-mode (Schmidt and Kissock, 2005).

As seen in Figure 6-11, which shows a snapshot of power demands in load and unload modes for Compressor 1, there is a constant background power demand around 35 kW due to unload-mode. Unload-mode does not produce and add compressed air to the system. Therefore, it is a **non-value-added** operation of the compressor and thus non-value-added energy consumption, which does not produce work.

In fact, the non-value-added operation in unload-mode can be avoided by shutting off the compressor during unload-modes. Normally, shutting off the compressor in unload mode is achieved by **"automatic-shutoff control type"** in load/unload mode operating compressors as an additional specification. With auto-shutoff control, the compressor will enter auto--shutoff if it runs unloaded for an adjustable time delay for example 5 to 10 minutes (Schmidt and Kissock, 2005), and start to run again when the system pressure reaches the lower activation setting, reducing the non-value added energy consumption of unload-mode.

But the auto-shutoff control of Compressor 1 is not activated, and it consumes energy during unload-mode periods. **In fact, even if it was activated, it is obvious that it would not function under the above analysed conditions. The compressor would have not found time to shut off itself because it is too frequently cycling, and the unload mode periods are very short,** as explained above.

In addition to the above, from Figure 6-11, it is obvious that the time Compressor 1 spends in the load-modes is very short compared to the time it spends in unload-mode. This means that the compressor begins to produce compressed air and add to the system; as a result, **the system pressure quickly reaches the upper activation setting and the compressor begins to run in unload-mode.** The loaded running takes about 10 to 15 seconds whereas unload time takes more. This situation can be also observed in Figure 6-12; while it takes less time to reach the upper activation pressure of 7.5 bar, it takes more time to go down to the lower activation pressure of 6.5 bar.

In light of the above observations, it is obvious that Compressor 1 too frequently cycles between load-mode and unload-mode throughout the entire operating period. In other words, it is loading and unloading in an unending manner.

6.3.1.2 SHORT CYCLING

The above type of operation manner is called as **short-cycling** (Bierbaum and Hütter, 2004) and is not a desired manner of working for a compressor. First of all, unload mode periods are too short; as a result, auto-shutoff mechanism, which turns off the compressor if it works in unload mode for a certain time, cannot function and energy consumption in unload times cannot be prevented. What is more, short-cycling poses a strain on the compressor electric motor and too often cycling can damage it. The allowed Number of Cycles (NC) for an electric motor per hour depending on the power rating of the motor are provided in Table 6-11. The NC per hour for a compressor should not exceed these values for an efficient, safe, and reliable electric motor operation. Therefore, the values presented in Table 6-11 can be referred as the maximum NC a compressor can do in an hour. Also, these values can be used to decide whether a compressor is short cycling or not. To do this, the NC in an hour a compressor does must be estimated first and then can be checked against the values in Table 6-11. **While doing this, a high LF for the compressor should be also ensured so that the compressor capacity is utilised. If a high LF is not possible, then unload times should**

be long enough so that the auto shutoff control can turn of the compressor preventing unnecessary power consumption.

Table 6-11: Allowed number of cycles for an electric motor depending on the power rating of the motor (Bierbaum and Hütter, 2004)

Motor power rating (kW)	Allowed cycles/h Al(1/h)
4-7.5	30
11-22	25
30-55	20
65-90	15
110-160	10
200-250	5

The NC done by a compressor in a reference time can be estimated as follows:

$$NC = \frac{reference\ time}{cycle\ time} \qquad \text{Eq.}\,6-1$$

where;

reference time : measurement time (min)
cycle time : the sum of load and unload times (min)

A cycle is comprised of load and mode periods, as explained before. Therefore, cycle time can be estimated as follows:

$$cycle\ time = load\ time + unload\ time\ (min) \quad Eq.6-2$$

If NC is calculated for an hour`s period, this can be considered as Cycle Speed (CS) and be used for comparison purpose. Alternatively, CS in a given period can be calculated as follows (Bierbaum and Hütter, 2004):

$$CS = \frac{60}{average\ cycle\ time\ within\ given\ period} \quad (1/h) \qquad Eq.6-3$$

Then, CS calculated for a compressor can be compared with the allowed values given in Table 6-11 to decide whether the compressor is doing short cycling or not.

Both load mode and unload mode of a cycle should be long enough for an efficient compressor operation. By this means, a compressor can operate continuously in long load-modes doing value-added work which means that the compressor capacity is utilised and that it consumes energy to create added value. Similarly, it can stay unload-mode long enough so that the auto-shut-off system turns off the compressor to save energy. Taking these into account, for a given period of compressor operation time, a compressor should do long-cycling. In other words, NC of a compressor does in a given operating period should be small. This will result in longer load and unload modes and small CS.

Regarding the reasons for short-cycling, there can be various reasons. On the one hand, the pressure band width, the difference between the upper and lower activation pressure points, can be very narrow so that the compressor can quickly reaches the upper pressure setting. The pressure range can be changed and adjusted, and a broader pressure range can be set on the compressor so that the CS will decrease. For example, if the pressure range is doubled, the CS will drop by half. However, the pressure range is very important for functioning of various compressed air users in the subject plant and decreasing or increasing the pressure range can fail the operation of the compressor air users or cause a damage on them. On the other hand, the amount of the compressed air generated by the compressor in load-mode periods can easily fill the **air storage tank** and consequently the system pressure quickly reaches to the upper activation pressure; thus, the load mode ends, and the unload mode starts. This can be due to either an oversized compressor, or an undersized air storage tank, or a combination of both factors. Indeed, the primary reason behind using an adequate storage tank in CASs is to prevent **short-cycling** (Beals, 2009). Similar to the pressure band example given above, if the storage volume is increased, it will take longer time to be filled and reach the upper activation point; thus, the compressor will operate longer in load-mode and a compressor cycle will last long with longer load time.

The above initial analysis suggests that Compressor 1 does too-frequent-short-cycling. There are two possible reasons behind this:

- The SC of Compressor 1 can be oversize in comparison to the compressed air demand by the subject plant in a daytime production shift.
- The volume of the air storage tank can be undersize so that it is quickly filled and emptied causing fluctuating pressure changes which cause the compressor to do short cycling.

In order to identify the root cause of the short cycling for Compressor 1`s case and quantitatively ensure that the cause is an oversized compressor or an undersized storage or both of them, further analysis is required. **The SC of the compressor can be compared with the CAD of the subject plant and also the effect of the air storage volume can be assessed.**

To do these, Load Factor (LF) for Compressor 1, which is a useful parameter that shows how often a compressor runs loaded or unloaded as well as length of their load-unload mode times and gives useful information to determine the compressed air production (CAP) by the compressor, should be put under the scope.

Overall, more detailed analysis is required to quantify the load/unload times and LF of the compressor. This will be done in the following subsections.

6.3.1.3 DETERMINING LF FOR COMPRESSOR 1

LF shows the percentage a compressor runs loaded in one cycle and can be expressed as follows:

$$Load\ Factor, LF\ (\%) = \frac{load\ time}{load\ time + unload\ time}\ (\%) \qquad Eq.(6-4)$$

LF therefore provides useful information about operational characteristics of a compressor; demonstrates **how often the compressor is running loaded or unloaded**. This can be also used to determine the actual CAD of the subject plant.

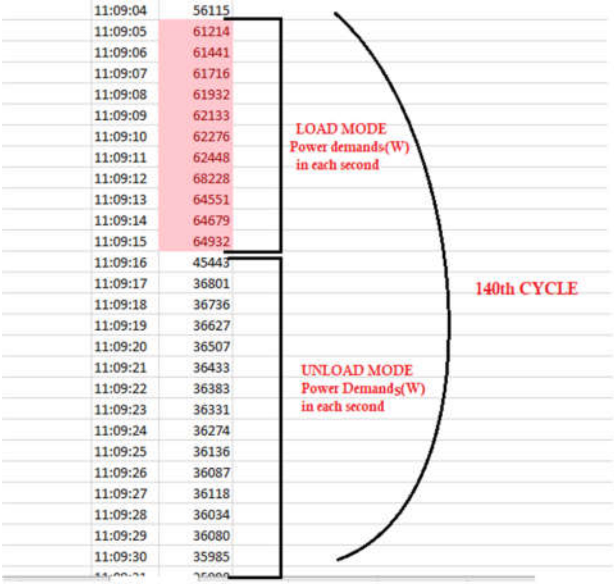
As explained before, an air compressor with load/unload control system cycles between load mode and unload mode; and the sum of a load mode and unload mode periods constitutes a cycle. The operation of a load/unload-controlled compressor is comprised of a number of consecutive cycles of different durations. Therefore, one can say that some operational characteristics of a load/unload-controlled compressor within a period can be modelled by means of the cycles. For example, the total operation time of the compressor will be the sum of the lengths of all cycles. Similarly, the compressed air production (CAP) by the compressor within a period will be the sum of the CAPs in load modes of each cycles. In the same vein, the LF of each cycle will determine the overall LF of the compressor within the operation period.

Bearing the above paragraph in mind, the operation of Compressor 1 has been broken down to its cycles. To do this, the overall power consumption data obtained through the power measurement at 1 second intervals were exported to Excel spreadsheet and seconds in each consecutive load and unload modes have been counted. The lengths of load and unload modes have been found as described as follows:

- Load mode period of a cycle: this value has been determined by counting the time seconds in which the power demand of Compressor 1 is equal to or greater than 60 kW on the Excel spreadsheet. The values with 60 kW or greater are counted because Compressor 1 draws 60 kW or greater when it operates in loaded mode as explained before. When the load mode of the cycle ends, the power demand drops below 60 kW and unload mode begins.

- Unload mode period of cycle: This value has been determined by counting the time seconds in which the power demand of Compressor 1 is less than 60 kW. The values less than 60 kW are counted because Compressor 1 draws about 35 kW (i.e. less than 60 kW) when it operates in unloaded mode as explained before. When the unload mode of the cycle ends, the power demand rises above 60 kW and the load mode of next cycle begins.

Figure 6-13 shows an example about how the length of load and unload modes of a cycle are counted and determined.



11:09:04	56115
11:09:05	61214
11:09:06	61441
11:09:07	61716
11:09:08	61932
11:09:09	62133
11:09:10	62276
11:09:11	62448
11:09:12	68228
11:09:13	64551
11:09:14	64679
11:09:15	64932
11:09:16	45443
11:09:17	36801
11:09:18	36736
11:09:19	36627
11:09:20	36507
11:09:21	36433
11:09:22	36383
11:09:23	36331
11:09:24	36274
11:09:25	36136
11:09:26	36087
11:09:27	36118
11:09:28	36034
11:09:29	36080
11:09:30	35985

Figure 6-13: Determining the load and unload modes durations of cycles based on the power demands

In total, 467 cycles for Compressor 1 throughout the operation period have been identified. The length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles have been determined and presented in tables in Appendix C. As an example, the cycles and the values for various associated parameters between in 08:35and09:00am are presented in Table 6-12 (associated parameters in Table 6-12 will have been explained in the forthcoming paragraphs and subsections).

Table 6-12: Load time, unload time, cycle time, power demands in load and unload mode in cycles in 08:35-09:00

Interval	Cycle No	Load time (sec)	Avg. Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	Cycle time (min)	LF (%)
8:35-09:00	1	12	63.91	13	35.47	25	0.42	48.00%
	2	15	63.91	12	35.47	27	0.45	55.56%
	3	13	63.91	35	35.47	48	0.80	27.08%
	4	10	63.91	49	35.47	59	0.98	16.95%
	5	9	63.91	59	35.47	68	1.13	13.24%
	6	11	63.91	65	35.47	76	1.27	14.47%
	7	11	63.91	56	35.47	67	1.12	16.42%
	8	12	63.91	42	35.47	54	0.90	22.22%
	9	11	63.91	74	35.47	85	1.42	12.94%
	10	10	63.91	48	35.47	58	0.97	17.24%
	11	13	63.91	66	35.47	79	1.32	16.46%
	12	11	63.91	72	35.47	83	1.38	13.25%
	13	12	63.91	62	35.47	74	1.23	16.22%
	14	12	63.91	59	35.47	71	1.18	16.90%
	15	11	63.91	61	35.47	72	1.20	15.28%
	16	11	63.91	61	35.47	72	1.20	15.28%
	17	12	63.91	73	35.47	85	1.42	14.12%
	18	11	63.91	73	35.47	84	1.40	13.10%
	19	12	63.91	38	35.47	50	0.83	24.00%

Based on the duration of load and unload modes, the LF for each cycle have been calculated using Equation 6-4. For example, the LF for 1st Cycle can be calculated as follows:

Load mode time=12 sec;

Unload mode time=13 sec;

Using Equation 6-4;

$$Load\ Factor, LF\ (\%) = \frac{12}{12+13} = 48\ \%$$

Thus, the LF for 1st cycle of Compressor 1 is 48%. Similarly, the LFs for all other cycles have been calculated. Figure 6-14 shows the LF of all compressor cycles throughout the entire compressor operation between 08:35am and 16:45pm. As seen, the LF for Compressor 1 varies between round 10% and 60%. But, the spots on Figure 6-14 are very intense between 10% and 20%. Table 6-13 shows the descriptive statistics for LF% of the cycles of Compressor 1. As seen, the maximum, minimum, and average LF values are 61%, 8%, and 18%, respectively.

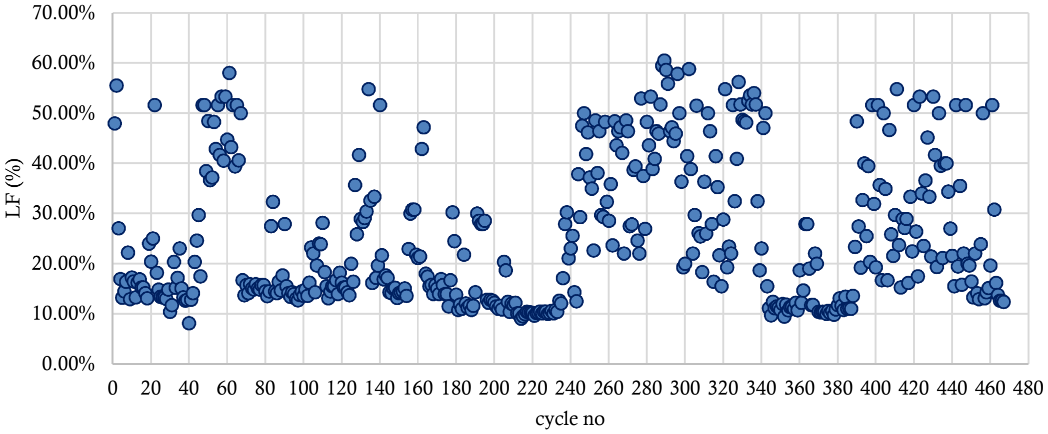


Figure 6-14: LF (%) for compressor cycles

Table 6-13**:** Descriptive statistics for LF% of cycles for Compressor 1

Mean	0.18
Standard Deviation	0.14
Range	0.52
Minimum	0.08
Maximum	0.61
Count (number of cycles)	467

Having determined the LF profile of Compressor 1, the next step is to ensure that the compressor does "short-cycling" or not. For this purpose, the NC done by the compressor must be determined. The NC in a period can be calculated by using Equation 6-1 or just simply counting the cycles within an associated period on the tables in Appendix C (As stated earlier, all cycles for Compressor 1 have been identified together with the various parameters such as LF, cycle time, etc and presented in tables in Appendix C). The Author has used the latter. For example, as one can see in Table C-2 and C-3 in Appendix C, there are 65 cycles between 09:00am and 10:00am.

For convenience, the operation period between 08:35am and 16:45pm have been divided into consecutive periods of 30-minutes, and the average values for load mode time, unload mode time, cycle time, load mode and unload mode power demands, NC, and CS parameters in these periods have been calculated and presented in Table 6-14.

Table 6-14: Average load and unload time, average power demand and load factor values in 30 minutes intervals

nterval	Average Load time (sec)	Average Unload time (sec)	Average Cycle time (sec)	NC in interval	CS (1/h)	Average LF %
08:35 - 09:00	12	54	65	19	55	20.4
09:00 - 09:30	12	63	74	25	48	17.8
09:30 - 10:00	13	37	50	40	72	27
10:00 - 10:30	11	58	70	27	51	17.15
10:30 - 11:00	12	52	64	28	56	19
11:00 - 11:30	12	47	59	31	61	23.5
11:30 - 12:00	11	67	78	23	46	15.42
12:00 - 12:30	11	67	78	23	46	16.21
12:30 - 13:00	11	96	107	17	33	10.21
13:00-13:30	13	48	61	13	59	26.61
13:30 - 14:00	15	23	39	46	92	36.05
14:00 - 14:30	11	30	44	42	83	33
14:30 - 15:00	11	77	88	21	41	13.7
15:00 - 15:30	11	84	95	19	38	12.08
15:30 - 16:00	13	40	54	34	66	28.9
16:00 - 16:45	13	43	56	49	64	28

Discussion on LF, NC, and CS

As stated above, the average LF of Compressor 1 in a typical production shift is 18%. This means that compressor operates partially loaded (i.e. 82 % of the operation time) and consumes electricity although it does not produce useful output. As stated earlier, it is possible to turn off the compressor during the unload-mode by means of the auto-shut off system, which is 82% of the overall running time in this case and save energy. However, this requires the unload time to be long enough. In Compressor 1`s case, the unload times in each cycle are too short since the compressor is too frequently cycling due to the short cycling. While it is obvious from the power demand graphs from Figure C1-C9 that Compressor 1 cycles between load and unload mode too frequently, short cycling can be also diagnosed by studying the NC or CS (i.e. cycling frequency).

As shown in Table 6-14, the NC and CS values for Compressor 1 are very high. While the allowed NC of cycles in an hour is 20 for the 55-kW electric motor of Compressor, the minimum and maximum CS values, which shows the minimum and maximum NC in an hour, are 38 and 92, respectively. From this, it is evident that Compressor 1 is doing short-cycling at an extreme rate.

If the load and unload times are long enough, that is cycles are long enough rather than being distributed with short intervals over the entire operation, the auto-shutoff system could work, and the strain put on the compressor electric motor due to the short cycling could be avoided providing more efficient, reliable, and safe motor operation. Therefore, the short cycling of Compressor 1 must be avoided.

As mentioned previously, there might be two main reasons behind the short cycling: the capacity of Compressor 1 is oversize for what is demanded by the subject plant; or the air storage tank volume used with Compressor 1 is too small. LF also gives an idea regarding if Compressor 1 is oversized or not for the application. As stated above, the LF for Compressor 1 is too small. The CAP capacity of Compressor 1 is so big so that it can easily make the pressure in the air tank reach to the upper activation point (i.e.7.5 bar) and the load time in a cycle lasts short. Similarly, the compressed air in the storage tank is quickly consumed by the subject plant so that the pressure in the air tank quickly falls to the lower activation point (6.5 bar) and the compressor is activated to run in load-mode and produce compressed air. These short periods of load and unload modes cause the compressor to do short cycling.

As one can see from Table 6-14, even the maximum average LF, which is 36.05%, is still too low. Despite the LF of 36.05% between 13:30pm and 14:00pm is relatively higher than those LFs in other intervals, which implies that the utilisation of Compressor 1 increases, the NC between 13:30pm and 14:00pm is 47, which is higher than other measurement intervals. Similarly, the LF between 14:00pm and 14:30pm is 33%, relatively higher compared to the other measurement intervals; but, the corresponding NC for 33% LF is 42. The relation between LF and NC for Compressor 1 can be seen in Figure 6-15. Increase in LF results in increase in NC. This implies that Compressor 1 cycles too frequently between 13:30pm-14:00pm and between 14:00pm-14:30pm to meet the increasing CAD and this resulted in a relatively higher LF than those LFs in other periods. In other words, Compressor 1 has to do short-cycling to meet the increasing CAD. Rather than doing short-cycling, the associated LFs of 33% and 39% can also be obtained doing less cycles with longer load and unload modes.

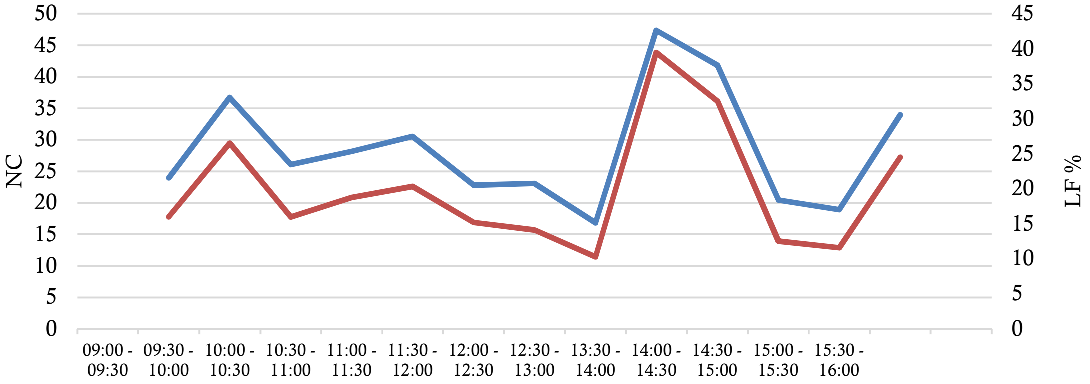


Figure 6-15: Change in LF and NC for Compressor 1

To better explain this, Figure 6-16 and Figure 6-17 have been prepared. Both Figure 6-16 and Figure 6-17 show the power demands of a hypothetical compressor for **producing the same amount of compressed air in the same operation period with the same average LFs consuming the same amount of electricity.** The only difference is the air storage tank capacity. As seen in Figure 6-16, there are only 3 cycles of which average LF is 39%. As for Figure 6-17, there are 10 cycles of which average LF is 39%; therefore, the compressor is working doing short cycling. This means that a compressor can operate efficiently (i.e. doing long cycling) or inefficiently (i.e. doing short-cycling) for producing the same work depending on the air storage tank capacity.

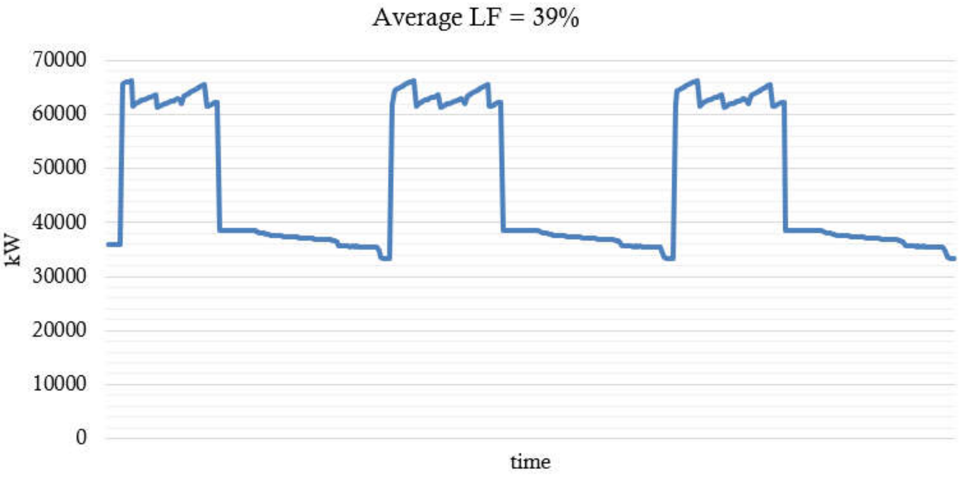


Figure 6-16: Normal cycling with average LF of 39%

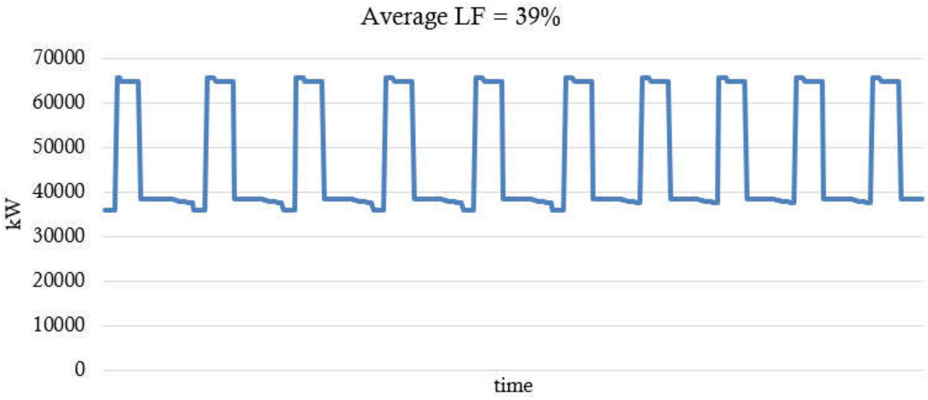


Figure 6-17**:** Short cycling with average LF of 39%

Overall, two main conclusions can be deduced from the above analysis:

- Low LF and short load-modes are the evidence for the fact that the SC Compressor 1 is oversize.
- Short load-modes are the evidence for the fact that the volume of the air storage tank is very small for Compressor 1`s SC.

Having determined the LF of Compressor 1, the CAD throughout the power consumption measurement period (i.e. 08:35-16:45) will be estimated in the following subsection to make a comparison with the SC of the existing Compressor 1 and determine the optimum compressor SC as well as the volume of air storage tank.

6.3.1.4 ANALYSIS OF CAD OF THE SUBJECT PLANT IN DAYTIME PRODUCTION SHIFT

In order to determine the optimum air compressor capacity for the subject plant and the associated optimum storage tank volume, it is required to find out the amount of the compressed air consumed by the plant. The present compressors output can give an accurate idea regarding the amount of the compressed air that the plant consumes. To measure the compressor output, inline or non-intrusive flow meters can be used. However, there was no flow measurement device had been installed on the air compressors and it was not possible during the auditing period as it would require some time and cause a disruption on the production process. Alternative to the inline flow meter is a non-intrusive flow meter such as an ultrasonic type. However, these kinds of devices are somewhat expensive, and their accuracy depends on various factors. Therefore, if an air flow measurement device was not installed to the compressor during the first setup of the plant (which is usually the case for SMEs), then, using a non-intrusive flow meter to measure the compressed air output becomes impractical (Schmidt and Kissock, 2003). Instead, compressed air output can be estimated based on the compressor power demand profile and the CAD of the subject plant can be approximated based on this estimated compressor output.

As explained in the above section, the operation of a load/unload-controlled compressor is comprised of a number of consecutive cycles of different durations, the operation of a load/unload-controlled compressor within a period can be modelled by means of the cycles. It is known that the compressor produces compressed air in load-mode and draws full power. From the compressor manual, the specific power consumption (SPC) of the compressor is 0.1595 $m^3/min*kW$. Also, the average power demands in the load-modes of each cycle are provided in tables in Appendix C based on the data obtained through the power measurements. Hence, the average CAP in load-mode of a cycle (CAP_{cycle}) by the compressor can be calculated as follows:

$$CAP_{cycle}\ (m^3) = SPC\ *\ P_{average_{load}}\ *\ t_{load}$$

Eq. (6-5)

where;

SPC : specific power consumption (m^3. kW/min),
$P_{average\_load}$: average power demand in a load mode (kW),
t_{load} : load-mode time.

The total CAP in total compressor operation period or in a plant production shift can be expressed as the sum of each CAP in all load modes (i.e. all cycles).

$$CAP_{total}\ (m^3) = SPC\ *\ \sum_{1}^{i} P_{average_{load}i} * t_{load\ i}$$

Eq. (6-6)

For instance, the CAP in load mode period of 1st cycle is calculated by using Equation 6-6 and the following data:

SPC = 0.1595 $m^3/min/kW$;

$P_{average\_load}$ = 63.91 kW;

t_{load} = 12 sec.

Substituting these values into Equation 6-5;

$$CAP_1 = 0.1595 \text{ m}^3\text{. kW/min} * 63.91 \text{ kW} * 12 \text{ sec} = 2.04 \text{ m}^3$$

Thus, CAP in <u>load mode</u> period of 1st cycle between 08:35-09:00 has been found to be 2.04 m^3. Therefore, one can say that the compressed air consumption by the subject plant in the <u>1st cycling period</u> is 2.04 m^3. If the CAP by the compressor in a load mode period of a cycle is divided by the overall cycling length, the instantaneous CAD by the subject plant throughout that cycling period can be estimated. Hence,

$$CAD_{cycle}\ (m^3/min) = \frac{CAP_{cycle}}{cycle\ length}$$

Eq. (6-7)

For example, the CAD throughout the 1st cycle, which takes 25 seconds (0.416 minutes), can be calculated by using Equation 6-7 as follows:

$$CAD_1 = \frac{2.04}{25} = 0.0816\frac{m^3}{sec} = 4.896\frac{m^3}{min}$$

Therefore, the subject plant demands 4.896 m^3/min (0.0816 m^3/sec) of compressed air throughout the 1st cycle of 25 seconds. In the same vein, the CAP (m^3) and CAD (m^3/min) for other cycles from 2 to 455 in the daytime production shift (i.e. 08:35am-16:30pm) have been calculated and presented in Appendix C. As an example, CAP (m^3) and CAD (m^3/min) for each cycle between 08:35-09:00am together with the associated load time (sec), unload time (sec), cycle time (min), load mode power demand (kW), unload mode power demand (kW), LF (%) values are presented in Table 6-15.

Based on these CAD values, a CAD profile for the subject plant between 08:35-09:00am has been produced and shown in Figure 6-18. Similarly, overall distribution of the CAD profile throughout the entire measurement period (i.e. the daytime production shift) have been produced as shown in Figure 6-19. Table 6-16 gives the descriptive statistics for the CAD of the subject plant in the daytime production shift.

Table 6-15: CAP and CAD values for each cycle during 16:30-18:30

Interval	Cycle No	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
8:35-09:00	1	2.04	4.90	0.0816
	2	2.55	5.67	0.0944
	3	2.21	2.76	0.0460
	4	1.70	1.73	0.0288
	5	1.53	1.35	0.0225
	6	1.87	1.48	0.0246
	7	1.87	1.67	0.0279
	8	2.04	2.27	0.0378
	9	1.87	1.32	0.0220
	10	1.70	1.76	0.0293
	11	2.21	1.68	0.0280
	12	1.87	1.35	0.0225
	13	2.04	1.65	0.0276
	14	2.04	1.72	0.0287
	15	1.87	1.56	0.0260
	16	1.87	1.56	0.0260
	17	2.04	1.44	0.0240
	18	1.87	1.34	0.0223
	19	2.04	2.45	0.0408

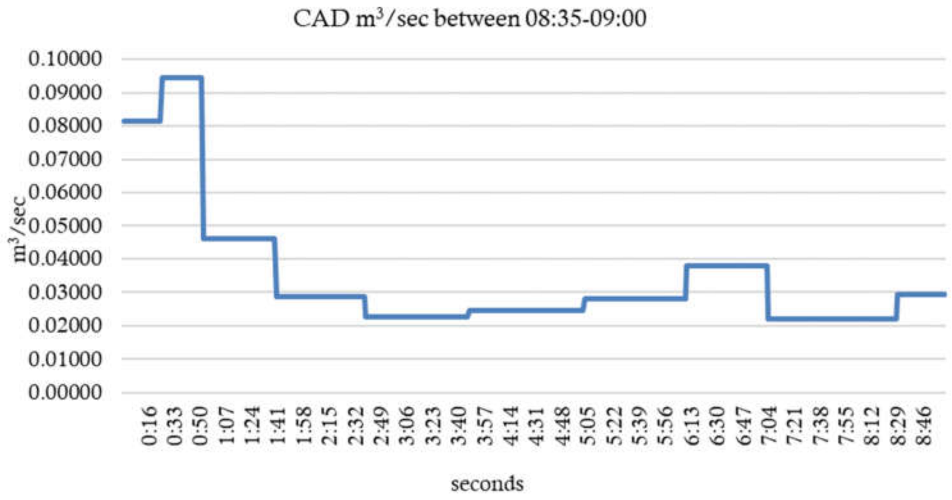


Figure 6-18: CAD profile of the subject plant between 08:35-09:00

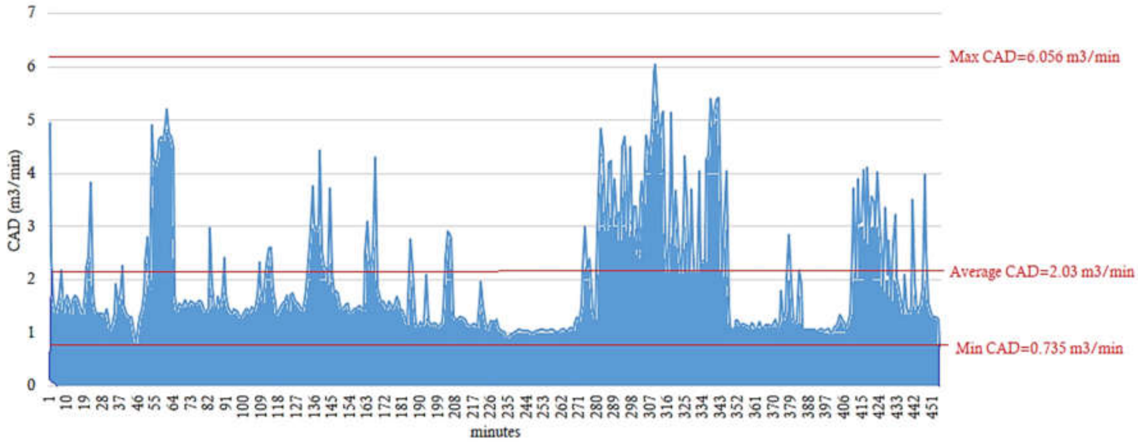


Figure 6-19: CAD by the subject plant between 08:35-16:45

Table 6-16: Descriptive statistics for CAD (m^3/min) of the subject plant in the day-time production shift

Mean	2.03
Standard Deviation	1.15
Mode	1.06
Range	5.32
Minimum	0.735
Maximum	6.056
Sum (total compressed air demand)	922.7
Count (Total duration in minutes)	455

In addition to the above, the CAD values (m^3/min) have been binned into 6 different groups as seen in Table 6-17. The aim of this is to see the behavior of Compressor 1 in terms of NC and LF when it is subjected to these different CAD groups. The average values of each bin have been calculated, as well. Figure 6-20 shows the distribution of the CADs binned into groups whereas the average value of each bin group and their frequencies (i.e. how many CAD in the bin which is also equal to the minutes in each bin because the CAD is on a minute basis) are given in Table 6-17.

Table 6-17: Distribution of CADs binned into different groups

Bin	***Average of Bin***	***Frequency***	***Cumulative %***
0.5<=CAD<1	0.93	10	2.20%
1<=CAD<1.5	1.23	203	46.81%
1.5<=CAD<2	1.66	91	66.81%
2<=CAD<2.5	2.23	37	74.95%
2.5<=CAD<3	2.75	30	81.54%
3<=CAD<3.5	3.23	22	86.37%
3.5<=CAD<4	3.74	15	89.67%
4<=CAD<4.5	4.27	21	94.29%
4.5<=CAD<5	4.77	15	97.58%
5<=CAD<5.5	5.24	9	99.56%
5.5<=CAD<6	5.91	1	99.78%
6<=CAD<6.5	6.06	1	100.00%
		Total=455	100.00%

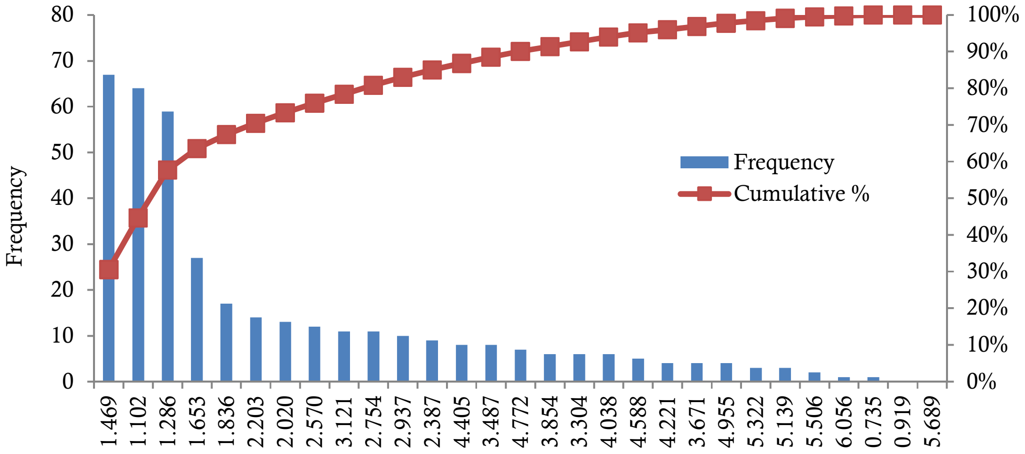


Figure 6-20: The distribution of CAD of the subject plant

As seen, the CAD of the subject plant is very fluctuating. As can be seen from Figure 6-19, the CAD fluctuates significantly in a relatively wide range of air flow rate from 0.735 m^3/min to 6.056 m^3/min. The maximum, minimum, average, and standard deviation of CAD values for a typical day time production shift are equal to 6.056 m^3/min, 0.735 m^3/min, 2.03 m^3/min, and 1.15 m^3/min, respectively, as presented in Table 6-17. While the maximum and average daytime CAD of the subject plant are 6.056 m^3/min and 2.03 m^3/min, respectively, the SC of Compressor 1 is 10.153 m^3/min. Thus, the analysis done here to determine the CAD of the subject plant is also an evidence for the fact that Compressor 1 is oversized. As a result of this and because of the undersized air storage tank as mentioned in the preceding section, Compressor 1 is experiencing short-cycling.

Having analysed and identified the CAD of the subject plant, the next subsection will investigate the possible solutions to avoid the short cycling and save energy.

6.3.1.5 DETERMINING OPTIMUM VS AND SC

As the preceding sections demonstrated that Compressor 1 is experiencing short-cycling because Compressor 1 is oversized and because the air storage tank used with it is undersized. Therefore, the SC of Compressor 1 and the air storage tank volume should be optimised. In the following sections, the impact of air storage tank volume Vs and SC will be investigated, and the optimal values of them will be sought for the subject plant.

As is the case for almost all production plants, the CAD of the subject plant is very discontinuous due to the discrete operation of the compressed air consumers. Discontinuous consumption of compressed air by the consumers can cause to air compressors to work on and off in a fluctuating manner. In contrast to this, air compressors, particularly the FSD compressors, are preferred to run continuously (Boehm and Franke, 2017) because frequently fluctuating operation and short-cycling are not desired forms of operation as explain before.

The purpose of using an air storage tank with an appropriate volume in a CAS is to adjust the supply of compressed air to its demand and to enable a reasonable system design concerning the characteristics of demand as well as continuation of its operational behavior (Boehm and Franke, 2017). By using a central air storage tank which functions as a buffer between air compressor and compressed air consumers, long-term compressed supply of the end-consumers can be achieved with minimal number of necessary compressor cycles. What is more, it prohibits imbalanced pressure fluctuations within the CAS (Boehm and Franke, 2017). Therefore, the optimum capacity of an air storage tank is very important for efficient operation of not only the air compressors but also the compressed air consumers in the plant.

The optimum air storage tank capacity be determined by using Equation 6-8 as follows (Agricola et al., 2003):

$$\mathrm{V}_S = \frac{SC * 60 * [x - x^2]}{NC_{max} * \Delta P} \qquad (m^3)$$

Eq. (6-8)

where;

Vs is required air storage tank volume (m^3).
ΔP is pressure difference (bar).
SC is specific capacity of the compressor (m^3/min).
x is utilization factor.

x is calculated as follows:

$$x = \frac{CAD_{max} - CAD_{avg}}{SC}$$

Eq. (6-9)

where;

$\mathrm{CAD}_{\mathrm{max}}$ is maximum CAD (m^3/min).
$\mathrm{CAD}_{\mathrm{min}}$ is minimum CAD (m^3/min).

ΔP is calculated as follows:

$$\Delta \mathrm{P} = \mathrm{P}_U - \mathrm{P}_L$$

(Eq. 6-10)

where;

$\mathrm{P_U}$ issupper activation pressure (bar) (7.5 bar for the subject plant).

$\mathrm{P_L}$ is lower activation pressure (bar) (6.5 bar for the subject plant).

Thus, ΔP is found to be 1 as calculated as follows:

$$\Delta \mathrm{P}=7.5-6.5=1 \text{ bar}$$

As seen Equation 6-8, the required air storage tank volume, Vs, is calculated based on SC, NCmax, $\mathrm{P_U}$, $\mathrm{P_L}$, $\mathrm{CAD_{max}}$, and $\mathrm{CAD_{max}}$. $\mathrm{P_U}$, $\mathrm{P_L}$, $\mathrm{CAD_{max}}$, and $\mathrm{CAD_{max}}$ are dictated by the subject plant compressed air consumption and cannot be modified (excluding the avoiding unnecessary compressed air consumption and losses). But, compressor SC and associated NC value can be varied to find out optimum Vs.

For the existing capacity of Compressor 1 (i.e. 10.153 $\mathrm{m^3}$/min), the optimum air storage tank volume, Vs, for allowed $\mathrm{NC_{MAX}}$=20 can be calculated by using Equation 6-8. The maximum and average CAD are 6.05 and 2.03 $\mathrm{m^3}$/min, respectively, as given in Table 6-16. Thus, the required air storage tank volume, Vs, can be calculated for the existing SC of Compressor 1 and associated NCmax as follows.

x is calculated by using Equation 6-9:

$$x = \frac{6.05 - 2.03}{10.153} = 0.39$$

Thus,

x =0.39
SC = 10.153 $\mathrm{m^3}$/min
NC max = 20 (from Table 8-3 for 55 kW)

Substituting these values into Equation 6-8:

$$\mathrm{V}_S = \frac{10.153 * 60 * [0.39 - 0.39^2]}{20 * \ 1} = 7.25\, m^3$$

Similarly, the Vs values have been calculated for other NC values of 16, 12, 8, and 4 and found to be 9.06 m^3, 12.08 m^3, 14.49 m^3, 18.12 m^3, and 36.23 m^3, respectively. This relation between Vs and NC is also shown in Figure 6-21. As seen, there is an inverse proportion between NC and Vs. To ensure that the existing 55kW-10.153 m^3/min-Compressor 1 has small NC and does less cycling, very big air storage tanks are needed; however, locating such big tanks in the subject plant compressor room is not materializable.

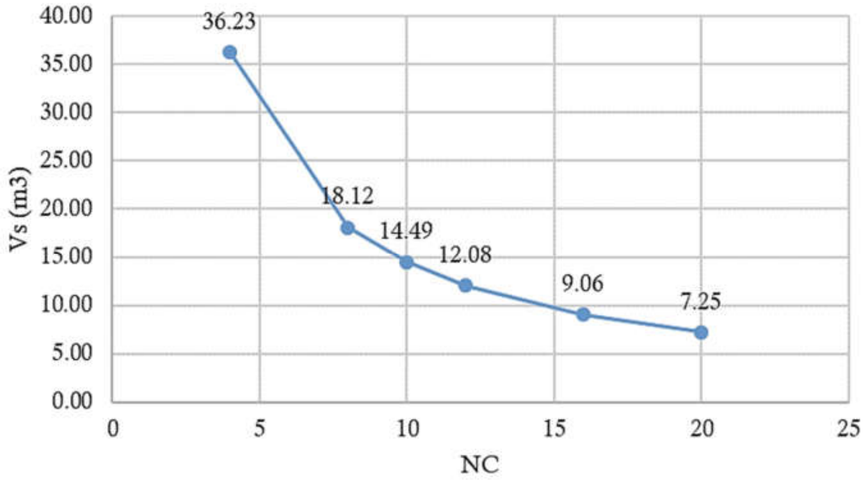


Figure 6-21**:** NC-Vs relation for the existing 55kW Compressor 1

As seen from the above calculations, while the optimum air storage tank size for the allowed NC_{MAX} of Compressor 1 not to exceed 20 is found to be 7.24 m^3, the volume of the existing air storage tank installed in the subject plant is 2 m^3. The optimum air storage tank volume for the subject plant is almost 4 times the existing volume. Thus, it is obvious that the existing air storage tank is undersized in terms of the subject plant compressed air consumption characteristics. Therefore, if a storage tank of 7.25 m^3 is used, the NC of Compressor 1 will not exceed 20.

As mentioned before, as well as NC for a compressor, LF should also be assessed to check the compressor operating efficiency. Therefore, the LF of Compressor 1 in each Vs and NC values should be assessed. Because the compressor will be subject to varying CADs, the LF for it will vary depending on the varying CAD. Bearing this in mind, the LF for Compressor 1 can be assessed for different CADs. For this purpose, the average CAD value of each CAD group and the associated frequencies presented in Table 8-8 can be used to see how the LF of Compressor 1 will be.

For example, the LF of Compressor 1 when an air storage tank of Vs=7.24 m^3 is used and it is subjected to the average CAD between 6-6.5 m^3/min (i.e. 6.05 m^3/min) can be estimated substituting the following values in:

Vs =7.24 m^3

SC =10.153 m^3/min

CAD =6.05 m^3/min

t_u, unload mode period can be calculated as follows (Agricola et al., 2003):

$$t_u = \frac{Vs \text{ x } \Delta P}{CAD}$$

(Eq. 6-11)

$$t_u = \frac{7.24\text{x}(7.5 - 6.5)}{6.05} = 1.2\ min$$

t_a, load mode period (Agricola et al., 2003):

$$t_l = \frac{Vs \text{ x } \Delta P}{SC - CAD}$$

(Eq. 6-12)

$$t_l = \frac{7.24\text{x}(7.5 - 6.5)}{10.153 - 6.05} = 1.76\ min$$

Using Equation 6-4 LF will be:

$$\text{LF} = \frac{1.76}{1.2 + 1.76} = 0.59$$

Like the above which estimated the LF for CAD=6.05 m^3/min, the LF for other CAD intervals have been calculated and presented in Table 6-18. Figure 6-22 shows the LF of Compressor 1 for different CAD intervals. It can be seen that increase in CAD results in higher LFs. However, as explained previously, the CADs are not equally distributed throughout the production shift; their frequency is different as shown in Figure 6-20 and their contribution to the overall average LF will be therefore different.

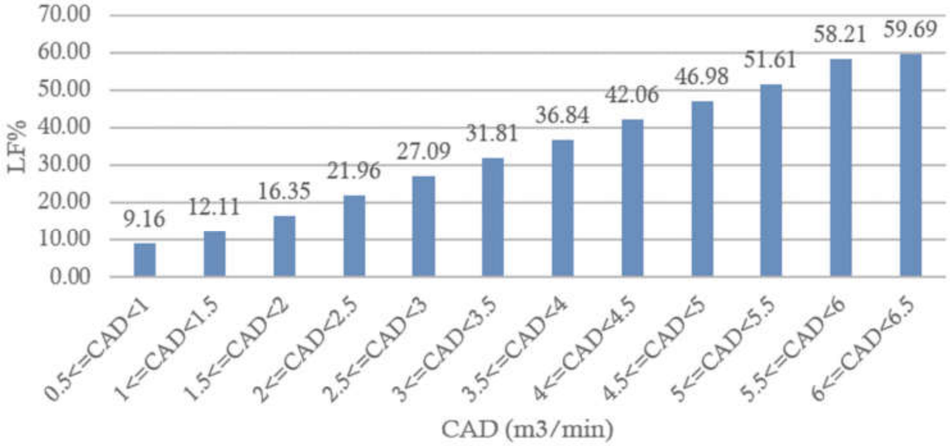


Figure 6-22 LF% of Compressor 1 for different CAD intervals when Vs=7.24 m^3

The overall average LF for Compressor 1 can be expressed as the sum of the LF in each CAD interval multiplied by the frequency of the CAD in each interval (i) as follows:

$$overall\ average\ Lf = \sum_{i=1}^{n} \frac{LF_i\ x\ frequency_i}{n} \qquad Eq. 6-13$$

By using Equation 6-13, the overall average LF of Compressor 1 for Vs=7.24 m^3 and SC=10.153 m^3/min has been found to be about 20% whereas it was 18% when Vs is 2 m^3 and SC=10.153, as presented in Table 6-18. It is obvious that there is just 2% reduction in the overall LF, which can be considered as insignificant. Thus, one can say that increasing the storage volume reduces the NC whereby improving the operating efficiency of the compressor, however; its contribution to the overall average LF is nonsignificant. Bearing these in mind, the SC of the compressor should be reduced in addition to the increased air storage volume. In other words, a smaller compressor should be employed; and the associated optimal air storage tank volume for the new compressor SC should be determined.

Table 6-18: LF of Compressor 1 for SC=10.153 m^3/min, Vs=7.24 m^3,

CAD interval	***Average CAD (m3/min) (a)***	***Frequency (b)***	***Frequency % (c)***	***Total CAD m3 (d=a*b)***	***SC (m3/min)***	***Vs (m3)***	***tu (min)***	***tl (min)***	***Average CT (min)***	***LF%***	***weighted LF (LF*c)***
0.5<=CAD<1	0.93	10	2.20	9.30	10.153	7.24	0.78	0.08	0.86	9.16	20.1
1<=CAD<1.5	1.23	203	44.62	249.69	10.153	7.24	0.03	0.00	0.03	12.11	540.5
1.5<=CAD<2	1.66	91	20.00	151.06	10.153	7.24	0.05	0.01	0.06	16.35	327.0
2<=CAD<2.5	2.23	37	8.13	82.51	10.153	7.24	0.09	0.02	0.11	21.96	178.6
2.5<=CAD<3	2.75	30	6.59	82.50	10.153	7.24	0.09	0.03	0.12	27.09	178.6
3<=CAD<3.5	3.23	22	4.84	71.06	10.153	7.24	0.10	0.05	0.15	31.81	153.8
3.5<=CAD<4	3.74	15	3.30	56.10	10.153	7.24	0.13	0.08	0.20	36.84	121.4
4<=CAD<4.5	4.27	21	4.62	89.67	10.153	7.24	0.08	0.06	0.14	42.06	194.1
4.5<=CAD<5	4.77	15	3.30	71.55	10.153	7.24	0.10	0.09	0.19	46.98	154.9
5<=CAD<5.5	5.24	9	1.98	47.16	10.153	7.24	0.15	0.16	0.32	51.61	102.1
5.5<=CAD<6	5.91	1	0.22	5.91	10.153	7.24	1.23	1.71	2.93	58.21	12.8
6<=CAD<6.5	6.06	1	0.22	6.06	10.153	7.24	1.19	1.77	2.96	59.69	13.1
total		**455**	**100.00**	**922.57**						**AVG LF=**	**19.97**

To find the optimum Vs and SC combination, using Equation 6-8, Vs can be calculated for different compressor SC values (obtained from a vendor`s catalogue) between 10 m^3/min and 1 m^3/min as presented in Table 6-19. In addition to these, the performance of the existing 3.25 m^3/min-18.5 kW Compressor (i.e. Compressor 2) of the subject plant will be assessed for the daytime production shift. The maximum allowed NC values depend on the SC of a compressor because the power rating of the compressor will increase or decrease depending on its SC. Compressor power ratings and SC values based on the vendor (Copco, 2018) and the associated maximum NC are presented in Table 6-19.

Table 6-19: Compressor power ratings and SC (the data for SC for power ratings from 15 kW to 55 kW is taken from (Copco, 2018) and extrapolated for 11 kW)

SC (m^3/h)	Power rating (kW)	NCmax (From table 6-11)
1.77	11	25
2.3	15	25
2.9	18	25
3.6	22	20
4.7	30	20
5.8	37	20
6.9	45	20
8.9	55	20
10.154**	55**	20**
3.25*	18*	25*

**existing Compressor 2   **existing Compressor 1*

Based on these values in Table 6-19, Vs (m^3) values for different SC (m^3/min) values have been calculated and presented in Table 6-20. In addition, LFs, which is an important indicator showing the compressor performance as explained before, have been calculated for each Vs value.

Each compressor SC and the associated air storage tank are considered as a compressor-storage configuration and denoted by a code and presented in Table 6-20. For example, for the compressor-storage configuration of SC=8.9 m^3/h and Vs=6.35 m^3 is denoted as C3.

Table 6-20: Compressor-storage configurations and SC and Vs values

Configuration	SC (m^3/min)	Vs (m^3)
Base case	10.135	2
C1	10.135	7.24
C2	3.25	2.3
C3	8.9	6.35
C4	6.9	4.92
C5	5.8	4.14
C6	4.7	3.35
C7	3.6	2.57
C8	2.9	1.66
C9	2.3	1.31
C10	1.77	1.01

As an illustration, the of Vs in Configuration C3 by using Equation 6-8 have been presented below. This is followed by the of the LF.

<u>Calculation of Vs and LF for SC=8.9 m^3/min and NC=20:</u>

Substituting SC=8.9 m^3/min, NC=20, and x=0.39 (calculated before) in Equation 6-8:

$$\mathrm{V}_S = \frac{8.9 * 60 * [0.39 - (0.39)^2]}{20 * \ (7.5 - 6.5)} = \ 6.35\ m3$$

Thus, the optimum Vs for a compressor with SC=8.9 m^3/min and NC=20 in Configuration C3 is 6.35 m^3.

Having determined that the Vs for SC=8.9 m^3/min is 6.35 m^3, LF can be calculated by using Equation 6-10. The of LF involves CAD, which varies throughout the production shift, as stated before. Because the compressor will be subjected to varying CADs, the LF for Configuration C3 (Vs=6.5 m^3, SC=8.9 m^3/min) can be calculated for different CAD intervals. Based on this, the average CAD value of each CAD interval and the associated frequencies presented in Table 6-17 can be used to calculate the LF in each CAD interval and the overall average LF.

For example; LF for Configuration C3 for ***CAD interval 6<=CAD<6.5, average CAD=6.06 m^3/min,*** is calculated as follows:

Unload mode period using Equation 6-11,

$$\mathrm{t_u} = \frac{6.35\mathrm{x}(7.5 - 6.5)}{6.06} = 1.04\ min$$

Load mode period using Equation 6-12

$$\mathrm{t_l} = \frac{6.35\mathrm{x}(7.5 - 6.5)}{8.9 - \ 6.06} = 2.23\ min$$

Using Equation 6-4, LF will be:

$$\mathrm{LF} = \frac{2.23}{1.04 + 2.23} = 0.68$$

Thus, the LF for Configuration C3 for *CAD interval 6<=CAD<6.5, average CAD=6.06 m^3/min* is 68%. Because there are other CAD intervals and their durations are different, LF for each CAD intervals and then an overall average LF have been be determined using Equation 6-13.

The above calculations have been repeated for compressor-storage configurations C2, C3, C4, C5, C6, C7, C8, C9, and C10 and the results are presented in Table C-19 - C-27 in Appendix C. Table 6-21 is shown as an example for the configuration C2. As seen in Table 6-21, the load mode time for Configuration C2 was found to be negative for the CADs higher than 3.25 m3/min. Similarly, the load mode time ends up with negative values for Configurations C5, C6, C7, C8, C9, and C10 for the CADs greater than their SCs which are 5.8 m^3/min, 4.7 m^3/min, 3.6 m^3/min, 2.9 m^3/min, 2.3 m^3/min, and 1.7 m^3/min, respectively. In these CAD periods, the compressors are undersized, and the CAD of the plant cannot be met by the compressors. The SC of the compressors are smaller than the CAD so that the load time results in a negative value. (In real life application, the system pressure will drop below the lower activation point. Because the ΔP in Equation 6-8 is fixed to 1 bar in the calculations, the pressure drop cannot be observed; but the loading periods results in negative values). Bearing this in mind, overall average LF have been calculated only based on the CAD intervals in which the compressor SCs are not undersized. These CAD intervals and associated other values in these tables are highlighted for the readers notice.

Table 6-21: LF of Configuration C2 (SC=3.25m^3/min, Vs=2.3 m^3)

CAD interval	***Average CAD (m3/min) (a)***	***Frequency (b)***	***Frequency % (c)***	***Total CAD m3 (d=a*b)***	***SC (m3/min)***	***Vs (m3)***	***tu (min)***	***tl (min)***	***Average CT (min)***	***LF***	***weighted LF (LF*c)***
0.5<=CAD<1	0.93	10	2.20	9.30	3.24	2.3	0.25	0.10	0.35	28.70	63.1
1<=CAD<1.5	1.23	203	44.62	249.69	3.24	2.3	0.01	0.01	0.01	37.96	1693.7
1.5<=CAD<2	1.66	91	20.00	151.06	3.24	2.3	0.02	0.02	0.03	51.23	1024.7
2<=CAD<2.5	2.23	37	8.13	82.51	3.24	2.3	0.03	0.06	0.09	68.83	559.7
2.5<=CAD<=3.25	2.85	42	9.23	119.70	3.24	2.3	0.02	0.14	0.16	87.96	812.0
3.25<CAD<3.5	3.38	10	2.20	33.80	3.24	2.3	0.07	-1.64	-1.57	104.32	229.3
3.5<=CAD<4	3.74	15	3.30	56.10	3.24	2.3	0.04	-0.31	-0.27	115.43	380.5
4<=CAD<4.5	4.27	21	4.62	89.67	3.24	2.3	0.03	-0.11	-0.08	131.79	608.3
4.5<=CAD<5	4.77	15	3.30	71.55	3.24	2.3	0.03	-0.10	-0.07	147.22	485.3
5<=CAD<5.5	5.24	9	1.98	47.16	3.24	2.3	0.05	-0.13	-0.08	161.73	319.9
5.5<=CAD<6	5.91	1	0.22	5.91	3.24	2.3	0.39	-0.86	-0.47	182.41	40.1
6<=CAD<6.5	6.06	1	0.22	6.06	3.24	2.3	0.38	-0.82	-0.44	187.04	41.1
total		**455**	**100.00**	**646.12**						**AVG LF=**	**49.34**

6.3.1.6 DESIGN OF A MULTIPLE COMPRESSOR SYSTEM FOR THE SUBJECT PLANT

As already shown before, the CAD of the subject plant is very dynamic and fluctuating. For such kind of CAD cases, a VSD compressor can be a very promising option (Mousavi et al., 2014). A comparison of VSD and FSD compressors in terms of energy efficiency is provided for a wide range of air flow outputs in Figure 6-23; as seen, VSD compressor requires less power input for a wide range of part-load working conditions in comparison to FSD compressor delivering the same amount of compressed air. Taking this account, a VSD compressor can be a more viable option for long periods of part-load operation (Mousavi et al., 2014). In regard to full-load working conditions, as seen in Figure 6-23, an FSD compressor requires less energy; thus, it is more energy efficient than a VSD compressor and a more promising option for working conditions with long periods of full-load working (Mousavi et al., 2014).

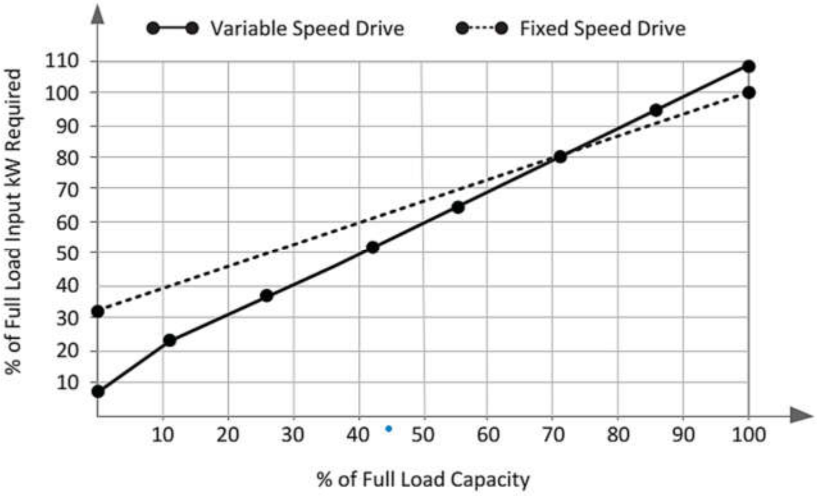


Figure 6-23: Energy efficiency comparison of VSD and FSD compressors (Mousavi et al., 2014)

Bearing the above facts in mind, an important implication regarding the design of a multiple CAS with a base-load and trim compressors can be made for the subject plant which have a very dynamic and fluctuating CAD:

- The bulk of the base-load can be supplied by using an appropriate size FSD compressor with load/unload control so that it can efficiently run at full-load and varying loads greater than the SC of the base-load FSD compressor can be met by an appropriate size VSD compressor; or, the vice versa sequence can be designed.

- A single VFD compressor can be employed to supply the entire CAD of the subject plant.

One of the FSD compressors used in the compressor-air storage configurations C8, C9, and C10 in the preceding section, which have LF of about 52.5%, 60.04%, and 74.06%, respectively, can be used as a base-load compressor of the multiple compressor system for the subject plant and the capacity of the trim VSD compressor must be determined.

In addition to the above, as explained before, there are two FSD compressors of 10.153 m^3/min and 3.24 m^3/min already installed in the subject plant CAS. The 10.153 m^3/min compressor can be converted to VSD compressor by fitting a VFD to the compressor driver and can be used as a single VSD compressor because its rated SC is enough to cover all CADs of the subject plant. Alternatively, the 3.25 m^3/min compressor can be used a base-load compressor together with the VFD-fitted 10.153 m^3/min compressor as a top-up supplier (i.e. trim compressor). What is more, the 1.77 m^3/min-FSD compressor and the VFD-fitted 10.153 m^3/min can be used together in a multiple compressor system combination in which the 1.77 m^3/min one is a base-load compressor whereas the other one is a trim compressor given that it is converted to a VFD one. Overall, there can be defined 6 scenarios of which details are presented in Table 6-22.

Table 6-22: Single VSD and multiple compressor system design scenarios

Scenario	SC for Base-load compressor	SC for Trim compressor
1	10.153 m^3/min-VFD (single VSD compressor)	
2	3.25 m^3/min-FSD	10.153 m^3/min-VSD
3	1.77 m3/min-FSD	10.153 m3/min-VSD
4	1.77 m^3/min-FSD	To be determined
5	2.3 m^3/min-FSD	To be determined
6	2.9 m^3/min-FSD	To be determined

In the following, the optimum capacity of VSD trim compressors for Scenario 4, Scenario 5, and Scenario 6 will be determined together with their running hours. Thereafter, the energy consumption in each multiple compressor system scenario will be estimated and compared.

6.3.1.7 DETERMINING THE SC OF VFD COMPRESSORS

For Scenario 4:

In Scenario 4, the 1.77 m^3/min-FSD compressor will work as a base-load compressor and it will be operating as long as the CAD of the subject plant is less than its SC (i.e. 1.77 m^3/min). When 1.77 m^3/min FSD base-load compressor cannot meet the demand, the VFD trim compressor will immediately work and supply compressed air to the system. It must be sized such that it can handle the maximum CAD. From Table 6-17, the maximum CAD of the subject plant is 6.056 m^3/min. A safety factor of 1.2 can be applied to this value and the corrected maximum CAD is assumed as 7.26 m^3/min. As stated, the VSD trim compressor will be covering the CAD greater than the SC of the FSD base-load compressor. Because the SC of the base-load compressor is 1.77 m^3/min, the SC of the VSD trim compressor, as also demonstrated in Figure 6-24, should be at least 5.8 m^3/min (i.e.7.26 m^3/min minus 1.77 m^3/min) to ensure an uninterrupted air supply.

Similar to the above, the capacities for the VSD trim compressors to be used together with the other two FSD base-load compressors of 2.9 m^3/min in Scenario 5 and 2.3 m^3/min in Scenario 6 have been determined. The SC of the VFD trim compressors to be used in Scenario 4 and Scenario 5 must be at least 4.36 m^3/min and 4.96 m^3/min, respectively. These are also shown in Figure 6-24.

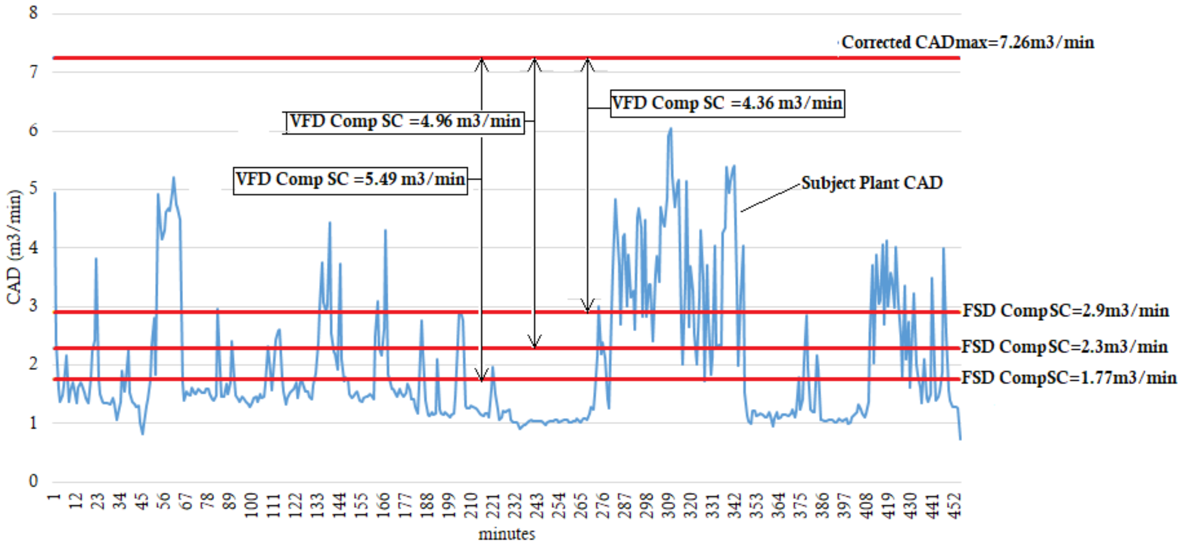


Figure 6-24: Demonstration of subject plant CAD, SCs of the FSD base-load compressor and required minimum rated SCs for VSD trim compressors

Bearing these values in mind, three VSD compressors of appropriate sizes have been chosen from a vendor (Copco, 2018) and the associated data have been obtained and presented in Table 6-23. As also given in Table 6-23, the power ratings-SCs for the VSD trim compressors to be used in Scenario 3, Scenario 4, and Scenario 5 are 30 kW- 5.84 m^3/min, 25 kW - 5.11 m^3/min, and 22 kW - 4.46 m^3/min, respectively. Having identified the SC of the VSD trim compressors, the power consumption of the multiple compressor system in each scenario will be estimated in the following.

6.3.1.8 DETERMINING THE POWER CONSUMPTIONS OF MULTIPLE COMPRESSOR DESIGNS

Because a multiple compressor system is comprised of two compressors, an FSD and VSD compressor in this case, the power consumption of the overall system is the sum of the power consumptions of each compressor. It is easier to calculate the power consumption for a load/unload-controlled FSD screw compressor. Because this kind of compressor produces compressed air at a fixed rate and operates only in two modes of load and unload; thus, the power consumption has two constituents: productive load mode power consumption and non-productive unload mode power consumption.

On the contrary, a VSD compressor can generate compressed air at part loads and the associated power consumption will vary depending on the compressor load. In other words, a VSD compressor will have several part-load SPCs against various compressed air generation capacities. Therefore, the part-load SPC values are needed to determine the overall power consumption of a VSD compressor. Considering this, the part-load SPCs of the VSD compressors of 30 kW- 5.84 m^3/min, 25 kW - 5.11 m^3/min, and 22 kW - 4.46 m^3/min for various part loads are also provided in Table 6-23 based on the vendor's data. The original datasheets are provided in Appendix C (The data in these sheets have been converted to SI units and then presented in in Table 6-23). These data will be used to estimate the power consumption of the VFD trim compressors.

Table 6-23: SPC of VFD compressors for part-loads

drive motor power rating (kW) - rated capacity (m3 /min)	**Part loads (m^3/min)**	**SPC (kW.min/m^3)**
30 kW (40hp) - 5.84 m3/min *(to be used with 1.77 m3/min-FSD compressor in Scenario 4)*	5.84	6.7
	5.16	6.56
	4.36	6.26
	2.71	6.19
	1.06	7.35
	0.90	7.77
25 kW (35 hp) - 5.11 m3/min *(to be used with 2.3 m3/min-FSD compressor in Scenario 5)*	5.11	6.75
	4.73	6.64
	3.90	6.59
	2.68	6.64
	1.02	8.43
	0.87	9.08
22 kW - 4.46 m3/min *(to be used with 2.9 m3/min-FSD compressor in Scenario 6)*	4.46	6.39
	3.92	6.22
	3.62	5.50
	1.87	6.36
	1.05	7.05
	0.89	7.42
55kW – 10.154 m3/min *(to be used with 1.77 m3/min-FSD compressor in Scenario 3)*	4.46	6.39
	3.92	6.22
	3.62	5.50
	1.87	6.36
	1.05	7.05
	0.89	7.42

Regarding the conversion of the existing 10.153 m^3 compressor to a VSD compressors, the manufacturer`s data for part-load SPC of these compressors are not available. For this reason, the part load SPC data of a similar sized VSD compressor was collected from the vendor and presented in Table 6-23 to use for the conversion of the existing FSD compressors to VSD ones. Such an assumption is reasonable because the only structural difference between a VSD and FSD compressor is just an VFD and a controller attached to an FSD compressor to vary its compressed air output.

As an example, the overall power consumption of the compressors in Scenario 3 can be calculated as follows.

The multiple compressor system in Scenario 3 consists of a 1.77 m^3/min FSD base-load compressor and a 5.84 m^3/min VSD trim compressor. The 1.77 m^3/min FSD base-load compressor can only supply 1.77 m^3/min of the overall CAD. The surplus CAD will be supplied by the 5.84 m^3/min VSD trim compressor. Therefore, the overall power consumption will be the sum of the power consumption by the 1.77 m^3/min FSD base-load compressor and 5.84 m^3/min VSD trim compressor as can be expressed as follows:

Overall power consumption =power consumption by FSD baseload compressor + power consumption by VSD trim compressor

(Eq. 6-14)

<u>Power consumption of 1.77 m^3/min FSD base-load compressor:</u>

As explained above, the power consumption of an FSD screw compressor consists of two components: load mode power consumption and unload mode power consumption. The power demand in load mode will be about 105-115% of its power rating while it will be 20-60% in unload mode. Keeping this in mind, 1.77 m^3/min-11 kW base-load compressor will draw 12.1 kW (i.e.110% of 11 kW) in load-mode and 3.3 kW (i.e. 30% of 11 kW) in unload-mode. The total power consumption in load mode will be the load mode power demand (P_{load}) multiplied by the load mode period (t_{load}). By the same token, the total power consumption in unload mode (P_{unload}) will be the unload power demand multiplied by the unload mode period (t_{unload}). These can be expressed as follows:

$$\textit{power consumption in load mode} = P_{load} * t_{load}$$

and

$$\textit{power consumption in load mode} = P_{unload} * t_{unoad}$$

and

The total power consumption for FSD compressor:

$$overall\ power\ consumption = P_{load}{*}t_{load} + P_{unload}{*}t_{unoad}$$

Eq.6-15

P_{load} and P_{unload} values are known as explained in the above paragraph. t_{load} and t_{unload} values can be estimated based on the LF of 1.77 m^3/min base-load compressor. The LF of the compressor was calculated earlier and found to be 74.06%. The total running time, which is the sum of t_{load} and t_{unload}, for the compressor is 304 minutes.

Using LF= 76.26% and t_{load}+t_{unload} =283 minutes in Equation 6-4; t_{load} and t_{unload} can be estimated as follows:

$$0.7626 = \frac{t_{load}}{t_{load} + t_{unload}} = \frac{t_{load}}{283}$$

$$t_{load}=215.8\ min$$

and

$$215.8\ min + t_{unload} = 283\ minutes$$

$$t_{unload} = 67.2\ minutes$$

Having determined t_{load} and t_{unload}, the overall power consumption can be calculated using Equation 6-15 as follows:

$$overall\ power\ consumption = 12.1kW{*}215.8min + 3.3kW{*}67.2min$$

$$overall\ power\ consumption = 47.21\ kWh$$

Hence, the 1.77 m^3/min base-load compressor will consume 47.21kWh throughout the daytime shift. In this following, the power consumption of the other component of the multiple compressed system, the VSD trim compressor, will be estimated.

Power consumption by 5.84 m^3/min VSD trim compressor:

As explained above, the power consumption a VSD compressor will vary depending on the CAD. The CAD profile of the subject plant was generated with 1-minute resolution. Therefore, it is possible to calculate the power consumption of the VSD trim compressors for each 1 minute throughout the entire compressor operation period.

As stated above, the trim compressor will be responsible for supplying the CADs greater than the SC of the base-load compressor. Therefore, subtracting the SC of the trim compressor from the CAD of the subject plant in each time step, a top-up CAD profile that the VSD trim compressor will be responsible to supply can be generated. From this top-up CAD profile, the part-load SPC values for the VSD trim compressors for each time step can be determined through linear interpolation from Table 6-23. The power consumption of the VSD compressor at a specific time step will be the SPC (kW.min/m^3) multiplied by the CAD (m^3/min). This can be expressed for i_{th} time step as follows:

$$power\ consumption\ at\ i_{th}\ minute = SPC\ i * CAD\ i$$

(Eq. 6-16)

In the same manner, the power consumption for all time steps can be calculated and the sum of them will give the overall VFD trim compressor power consumption for the entire operation period and can be expressed as follows:

$$\sum_{i=1}^{n} SPCi * CADi$$

(Eq. 6-17)

Example: Power consumption by 5.84 m^3/min VSD trim compressor:

The CAD at t=1 minute is 4.95 m^3/min. The top-up CAD which the 5.84 m^3/min VSD trim compressor must supply at t=1 minute will be 4.95 m^3/min minus 1.77m^3/min, which makes 3.9 m^3/min. The SPC of the trim compressor to supply the part load of 3.9 m^3/min would be 6.43 kW.min/m^3 through linear interpolation from Table 6-23. The power demand for the VSD trim compressor to produce 3.19 m^3/min of compressed air at t=1 min can be calculated using Equation 6-16 as follows:

$$power\ consumption\ at\ 1th\ minute = 6.19\ kW.min/m^3 * 3.19\ m^3/min = 0.33\ kWh$$

Following the same approach presented above, the part-load power consumption of the 5.84 m^3/min VSD trim compressor for all time steps from 1 min to 455 min have been calculated and their sum, which gives the overall power consumption of the trim compressor for the entire operation period, has been found to be 26.33 kWh.

Having determined the power consumption of the FSD base-load compressor and VSD trim compressor for the entire operation period, the overall power consumption of the multiple compressor system Scenario 3 can be calculated by using Equation 6-17:

$$\text{Overall power consumption} = 65.27\ kWh + 26.33\ kWh = 91.6\ kWh$$

Thus, the multiple compressor system in Scenario 4 consumes 91.6 kWh per day whereas the existing CAS with the 10.154 m3/min FSD compressor consumes 338.8 kWh/per day. Thus, the ESP through the multiple compressor system in Scenario 4 will be:

$$ESP = \text{Energy consumption in base-case} - \text{energy consumption in Scenario 4}$$

$$ESP = 338.8 - 91.6 = 247.2\ kWh/day$$

$$\text{annual } ESP = ESP * \text{annual working days} = 247.2\ kWh * 295\ days = 72{,}924\ kWh$$

In the above, the approach to determine the power consumption of trim compressor and base-load compressor has been presented and the power consumptions for 1.77 m^3/min FSD base-load compressor and 5.84 m^3/min VSD trim compressor for the entire operation period have been presented. Following the same approach, the overall power consumption of the FSD-VSD compressor combinations for other scenarios defined in Table 6-22 have been calculated and presented in Appendix C. The ESPs through each scenario and the associated annual ESP, PESP, ESCP, and CO_2 ERP values are presented in Table 6-24 and Table 6-25.

As shown in Table 6-25, if the existing Compressor 1 is converted to a VSD compressor, the power consumption of the new 55 kW-VSD compressor is 224.73 kWh whereas it was 338.8 kWh before the VFD retrofit. This means an ESP of 34.7% compared to the base-case and the associated annual ESP PESP, ESCP, and CO2 ERP are 33,650.65 kWh, 83,117.11 kWh, €2,205.46, 16,488.82 kg-CO_2, respectively.

If the existing FSD 3.25 m^3/min compressor (i.e. Compressor 2) is used with the VSD converted 10.154 m3/min compressor in Scenario 2, the power consumption of the new multiple compressor system will be 87.9 kWh. This means an 74.1% of ESP compared to the base-case; and the associated annual ESP PESP, ESCP, and CO_2 ERP are 74,015.50 kWh, 182,818.29 kWh, €4,850.98, and 36,267.60 kg-CO_2, respectively.

If the multiple compressor in Scenario 3, which consists of a 1.77 m^3/min-11 kW FSD base-load compressor and the VSD converted 10.154 m^3/min-55kW trim compressor, is employed, the power consumption will be 91.12 kWh. This means an 73.2 % of ESP compared to the base-case; and the associated annual ESP PESP, ESCP, and CO_2 ERP are 73,065.60 kWh, 180,472.03 kWh, €4,788.72, and 35,802.14 kg-CO_2, respectively.

If Scenario 4, which incorporates the 1.77 m^3/min-11 kW FSD base-load compressor and 5.84 m3/min - 30kW VFD trim compressor, the power consumption will be 91.6 kWh. This corresponds to an 73.1% of ESP compared to the base-case; and the associated annual ESP PESP, ESCP, and CO_2 ERP are 72,924 kWh, 180,122.28 kWh, €4,779.44, and 35,732.76 kg-CO_2, respectively.

If Scenario 5, which incorporates the 2.3 m^3/min-22 kW FSD base-load compressor and 5.11 m3/min - 25kW VFD trim compressor, is employed, the power consumption will be 135,02 kWh. This corresponds to an 60.1% of ESP compared to the base-case; and the associated annual ESP PESP, ESCP, and CO_2 ERP are 60,115.10 kWh, 148,484.3 kWh, €3,939.94, and 29,456.4 kg-CO_2, respectively.

As for Scenario 6, which uses the 2.9 m^3/min-25 kW FSD base-load compressor and 4.46 m^3/min - 22kW VFD trim compressor, the overall power consumption of the system will be 112.76 kWh. This corresponds to an 66.7 % of ESP compared to the base-case; and the associated annual ESP PESP, ESCP, and CO_2 ERP are 66,681.80 kWh, 164,704.05 kWh, €4,370.33, 32,674.08 kg-CO_2, respectively.

As the above results shows, Scenario 2, Scenario 3, and Scenario 4 provides the highest ESPs. As seen, the ESP % and annual ESP for Scenario 2, Scenario 3, and Scenario 4 are 74% and 74.015.5kWh, 73.2% and 73,065.60 kWh, and 73% and 72,924 kWh, respectively. Because these ESP require investment, their LCC assessments together with cost structures are given in Appendix C. The evaluation of their cost effectiveness is presented in Chapter 7.

Table 6-24**:** consumption in each multiple compressor system scenarios and ESPs

Scenario	**FSD base-load compressor specs (SC-power rating)**	**VSD trim compressor specs (max SC-power rating)**	**FSD baseload compressor power consumption (kWh)**	**VSD trim compressor power consumption (kWh)**	**Total power consumption (kWh)**	**ESP (kWh)**
Base-case	Existing 55 kW comp	-	338.8	-	338.8	-
Scenario 1	-	Existing 55 kW comp	-	224.73	224.73	114.07
Scenario 2	Existing 18 kW comp	Existing 55 kW comp	79.6	8.3	87.9	250.9
Scenario 3	1.77m3/min-11kW	Existing 55 kW comp	65.27	25.85	91.12	247.68
Scenario 4	1.77m3/min-11kW	5.84 m3/min - 30kW	65.27	26.33	91.6	247.2
Scenario 5	2.3m3/min-22kW	5.11 m3/min - 25kW	114.02	21	135.02	203.78
Scenario 6	2.9m3/min-25 kW	4.46 m3/min - 22 kW	101.46	11.3	112.76	226.04

Table 6-25: ESPs in each scenario and the associated annual ESP PESP, ESCP, and CO_2 ERP values

Scenario	**ESP no**	**ESP%**	**Annual ESP (kWh)**	**Annual PESP (kWh)**	**Annual ECSP (€)**	**Annual CO2-ERP kg-CO2/kWh**
Scenario 1	ESP 6-3	33.7	33,650.65	83,117.11	2,205.46	16,488.82
Scenario 2	ESP 6-4	74.1	74,015.50	182,818.29	4,850.98	36,267.60
Scenario 3	ESP 6-5	73.1	73,065.60	180,472.03	4,788.72	35,802.14
Scenario 4	ESP 6-6	73	72,924.00	180,122.28	4,779.44	35,732.76
Scenario 5	ESP 6-7	60.1	60,115.10	148,484.30	3,939.94	29,456.40
Scenario 6	ESP 6-8	66.7	66,681.80	164,704.05	4,370.33	32,674.08

Having analysed Compressor 1, the following subsection will be dealing with Compressor 2.

6.3.2 IDENTIFYING ESPS IN COMPRESSOR 2

6.3.2.1 EXISTING PERFORMANCE OF COMPRESSOR 2

As mentioned previously, the plant management uses Compressor 2 during night shifts because they think that CAD will be lower during night shifts and there is no need to operate Compressor 1 in night shifts as it is bigger in size.

The specifications for Compressor 2 were given in Table 6-9. Its power rating is 18 kW and SC is 3.25 m^3/kW. Its control type is load/unload with auto shutoff. By the help of the auto shutoff control, the compressor automatically shuts off itself when it is in the unload mode thus saves energy. Load/unload control type has been explained in detail in the previous sections, so it is not mentioned again in this subsection.

The approach which have been used to analyse the existing performance of Compressor 1 in the previous section will be followed to analyse the performance of Compressor 2 in the following subsections.

In order to see the baseline performance of Compressor 2 under the present conditions, the power demand of Compressor 2 was recorded in a typical production night shift between 16:30 and 01:30 hrs. The overall power profile has been broken down into consecutive periods through the software of PEL 103, and the corresponding power demand profiles for each period have been produced as one can see in Appendix C. Figure 6-25 is presented as an example below. Compared to the power demand profile of Compressor 1, the power steps and cycling nature of power profile of Compressor 2 are more distinct.

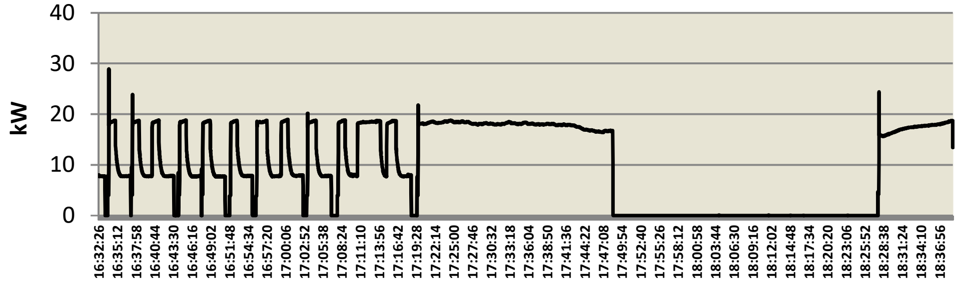


Figure 6-25**:** Compressor 2 power demand profile between 16:32 – 18:36

In Figure 6-25 and Figure C-11-14 in Appendix C, the power signature in load and unload modes are evident. In some periods, there are rapid fluctuations in power demand while in some period less. Also, there are some periods where the compressor **operates** fully loaded or unloaded for long times. This is owing to the changing compressed air demand of the plant. As it can be remembered that **Compressor 1 was responding to increasing compressed air demands with very frequent cycling rates, thus the power demand profiles for Compressor 1 had a very frequent cyclic nature.** As for **Compressor 2,** load mode times are not constant, rather have a changing characteristic. There are some periods with long load mode while there are very long unload mode periods, as well.

6.3.2.2 DETERMINING LF OF COMPRESSOR 2 AND ANALYSIS OF CAD

The LF for each cycle of Compressor 2 throughout its operation period between 16:45-01:30 have been calculated through the method described in Section 6.3.1.3. In total, 85 cycles have been identified. The length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles have been determined and presented in tables in Appendix C. As an example, the cycles and the values for various associated parameters such as power demands in load and unload modes of each cycle, etc between in 16:30pm and 18:30pm are presented in Table 6-26. Other cycles can be found in Appendix C.

Based on the duration of load and unload modes, the LF for each cycle have been calculated using Equation 6-4. Figure 6-26 shows the LF of all compressor cycles throughout the entire compressor operation between 08:35am and 16:45pm. As seen, the LF for Compressor 2 is scattered. This is due to the varying CAD by the subject plant. Table 6-27 shows the descriptive statistics for LF% of the cycles of Compressor 2. As seen, the maximum, minimum, and average LF values are 90%, 15%, and 35%, respectively. Compared to Compressor 1, Compressor 2 has relatively better LF values; however, the average LF for Compressor 2 is 35%, which cannot be regarded to be high enough in terms of the compressor capacity utilisation and efficient compressor operation.

Table 6-26**:** Load time, unload time, cycle time, power demands in load and unload mode, CAP, and CAD in cycles in 16:30-18:30

period	**Cycle No**	**Load time (sec)**	**Power Demand in Load Mode (kW)**	**unload time (no power) (sec)**	**unload time (with power) (sec)**	**Unload time (sec)**	**Power demand in unload mode (kW)**	**Cycle time (sec)**	**CYCLE time (min)**	**LF (%)**	**CAP (m3)**	**CAD (m3/min)**	**CAD (m3/sec)**
16:30-18:30	1	60	18.66	22	70	92	8.81	152	2.53	39.47	3.28	1.29	0.0216
	2	60	18.54	5	145	150	6.76	210	3.50	28.57	3.25	0.93	0.0155
	3	60	18.46	0	116	116	6.21	176	2.93	34.09	3.24	1.10	0.0184
	4	60	18.52	40	143	183	6.18	243	4.05	24.69	3.25	0.80	0.0134
	5	65	18.52	0	145	145	6.07	210	3.50	30.95	3.52	1.01	0.0168
	6	60	18.51	38	143	181	6.20	241	4.02	24.90	3.25	0.81	0.0135
	7	90	18.46	30	144	174	6.20	264	4.40	34.09	4.86	1.11	0.0184
	8	63	18.61	0	124	124	6.53	187	3.12	33.69	3.43	1.10	0.0183
	9	75	18.53	31	143	174	6.28	249	4.15	30.12	4.07	0.98	0.0163
	10	60	18.54	53	145	198	7.03	258	4.30	23.26	3.26	0.76	0.0126
	11	203	18.47	0	110	110	6.32	313	5.22	64.86	10.97	2.10	0.0351
	12	81	18.49	0	57	57	6.32	138	2.30	58.70	4.38	1.91	0.0318
	13	1729	17.92	51	147	198	6.20	1927	32.12	89.72	90.69	2.82	0.0471
	14	1314	17.33	1308	10	1318	6.29	2632	43.87	49.92	66.65	1.52	0.0253
	14	3980				3220	7200	7200.00	120.00		208.11		

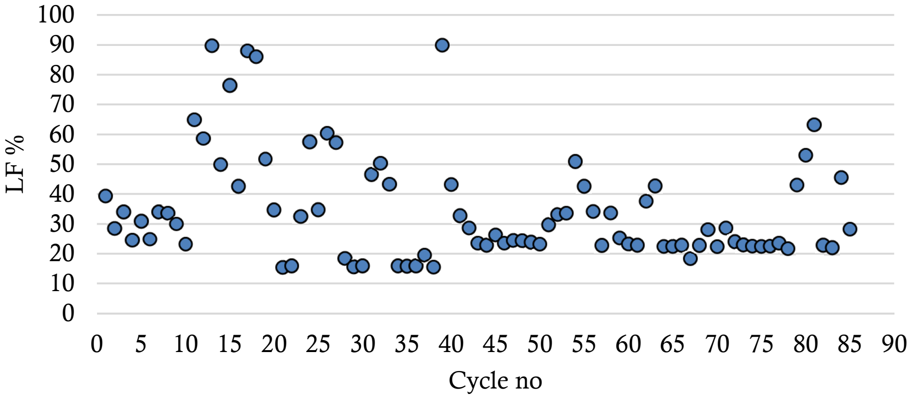


Figure 6-26**:** LF for each cycle in night time production shift between 16:30-00:30

Table 6-27: Descriptive statistics for LF% of cycles for Compressor 2

Mean	0.35
Standard Deviation	0.18
Range	0.75
Minimum	0.15
Maximum	0.90
Count	85.00

Having determined the LF profile of Compressor 2, the next step is to check that whether the compressor does "short-cycling" or not by examining the NC done by the compressor.

The operation period between 16:30am and 01:30pm have been divided into consecutive periods of three 2-hours and one 1-hour, and the average values for load mode time, unload mode time, cycle time, load mode and unload mode power demands, NC, and CS parameters in these periods have been calculated and presented in Table 6-28.

Table 6-28**:** Average load and unload time, average power demand, and LF values in 2-hours intervals

interval	Average Load time (sec)	Average Unload time (sec)	Average Cycle time (sec)	NC in interval	CS (1/h)	Average Power Demand (W) in Load	Average Power Demand (W) in Unload	Average LF %
16:30-18:30	284.3	230	514.3	14	7	18.34	8.35	40.50
18:30-20:30	120.7	179.3	300	24	12	18.5	8.55	39.6
20:30-22:30	207	178	384	19	9.7	18.55	8.7	33.03
22:30-01:30	69.5	179.5	249.	29	14.5	18.62	28.8	17.15

As shown in Table 6-28, the CS values are 7, 12, 9.7, and 14.5 for intervals 16:30-18:30, 18:30-20:30, 20:30-22:30, 22:30-01:30, respectively, whereas the maximum CS (maximum allowed NC in an hour) for the 18.5 kW electric motor of Compressor 2 is 25 as shown in Table 6-11. Therefore, it is obvious that Compressor 2 is not doing short cycling as its CS is within an acceptable limit.

This also indicates that the air storage volume for Compressor 2 is appropriately sized. Despite this, the LF for Compressor 2 can be regarded as low which indicates that the SC of Compressor 2 (i.e. 3.25 m^3/h) might be oversized for the CAD of the subject plant in night-time shift.

In the following, the CAD of the subject plant will be determined and compared with the SC of Compressor 2.

6.3.2.3 ANALYSIS OF THE CAD OF THE SUBJECT PLANT IN THE NIGHT TIME PRODUCTION SHIFT

CAD by the subject plant can be calculated as explained previously while analysing Compressor 1 in Section 6.3.1. The CAP in the load mode period of a cycle can be estimated by using Based on Equation 6-5 and 6-6, the CAP and CAD in each cycle throughout the nightshift together with the associated load time (sec), unload time (sec), cycle time (min), load mode power demand (kW), unload mode power demand (kW), LF (%) values have been calculated and presented in tables in Appendix C. As an example, the CAD and CAP values of the cycles between 16:30-18:30 are given in Table 6-29.

Table 6-29: CAP and CAD values for each cycle during 16:30-18:30

interval	Cycle No	CAP (m3)	CAD (m3/min)	CAD (m3/sec)
16:30-18:30	1	3.22	1.27	0.0212
	2	3.22	0.92	0.0153
	3	3.22	1.10	0.0183
	4	3.22	0.80	0.0133
	5	3.49	1.00	0.0166
	6	3.22	0.80	0.0134
	7	4.83	1.10	0.0183
	8	3.38	1.08	0.0181
	9	4.03	0.97	0.0162
	10	3.22	0.75	0.0125
	11	10.90	2.09	0.0348
	12	4.35	1.89	0.0315
	13	92.80	2.89	0.0482
	14	70.53	1.61	0.0268

Table 6-30 gives the descriptive statistics for the CAD of the subject plant in the night-time production shift. Figure 6-27 shows the distribution of night-time CAD of the subject plant. As seen in Table 6-30, the average, maximum, and minimum CAD values are 1.12 m^3/min, 2.93 m^3/min, 0.5 m^3/min, respectively. The total CAD in the night-time production shift is 960.8 m^3.

Table 6-30: Descriptive statistics for CAD (m3/min) of the subject plant in the night-time production shift (m^3/min)

Mean	1.12
Standard Deviation	0.57
Range	2.42
Minimum	0.5
Maximum	2.93
Sum (total CAD)	960.8 m^3

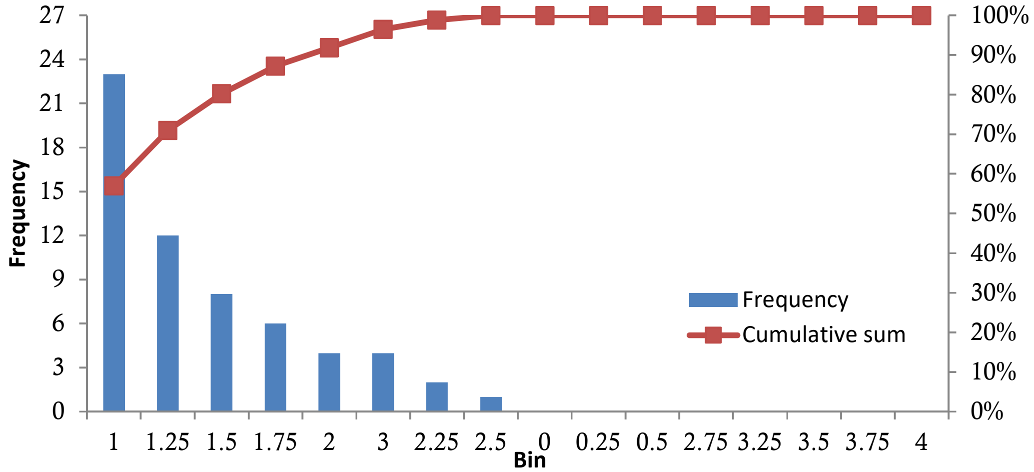


Figure 6-27**:** The distribution of CAD of the subject plant

While the SC of Compressor 2 is 3.25 m^3/min, the average and maximum night-shift CAD is 1.12 m^2/min and 2.93 m^2/min, respectively. As seen in Figure 6-38, the majority of night-shift CAD values are around 1 and 1.5 m^3/min. As a result of this, Compressor 2 experiences relatively lower LF as discussed in the previous section. Despite this, fortunately, the compressor does not do short-cycling by virtue of the adequate volume of the air storage tank. What is more, because the unloads periods are long enough as a result of the long-cycling, the auto-shut off control system works and shuts-off the compressor while it is in long unload modes and avoids non-value-added power consumption. The length of unload modes with no power consumption and power consumption have been counted. It has been found that the total duration of unload modes without power consumption is 1279 secs whereas it is 3927 secs for with power consumption. Thus, the compressor was turned-off for 24.5% of overall unload mode time and considerable amount of energy was saved.

As mentioned above, the lower LF of Compressor 2, which is relatively higher compared to the case of Compressor 1, has indicated that the Compressor 2 can be regarded as oversized for the night-shift CAD; but sometimes there are some CADs which makes the compressor to work with very high LFs. As explained before, a VSD compressor can be a promising option for such varying

CAD conditions. In this respect, conversion of Compressor 2 to a VSD one can be considered as an energy saving measure. However, it has been found that the compressor does do short-cycling and load and unload mode periods are quite long so that the compressor can shut-off itself and operate efficiently. Determining the length of unload modes in a VSD compressor scenario requires a dynamic simulation of compressor operation, which is beyond the scope of this study.

Bearing the above in mind, it is concluded that Compressor 2 operates efficiently for night-time CAD of the subject plant.

6.3.3 ESP BY FIXING AIR LEAKS IN THE CAS

Air leaks in the compressed air system cause artificial compressed air demands and leads the air compressor to work unnecessarily. It will take for the compressor energy to compress the air lost through leaks. Thus, there will be an energy waste. In the subject plant, it has been observed that there are many air leaks in the compressed air system. Even in noisy production times, the hissing sound due to the air leaks was easily noticeable. The subject plant personnel were aware of the air leaks, but they did not appreciate the impact of these over energy consumption. Interestingly, the compressed air was considered as to be free in the plant.

As such, an air leak detection activity has been conducted by listening to the `hissing` sound when the production is idle. In total, there have been determined 20 holes with various diameters which have air leaks. The most common areas having air leaks are shown in Figure 6-28. These include hoses, couplings, fittings, pipe joints, etc.

Figure 6-28: Most common areas which have air leaks in the subject plant compressed air system

Besides the hissing sound and leak detection activity, the presence of air leaks was noticed in the power measurement of Compressor 1. The power measurement for Compressor 1 was conducted in a Monday. Interestingly, the compressor unusually worked in load mode for quite long time compared to the other cycles when it was first powered on. This can be seen in Figure Figure 6-29.

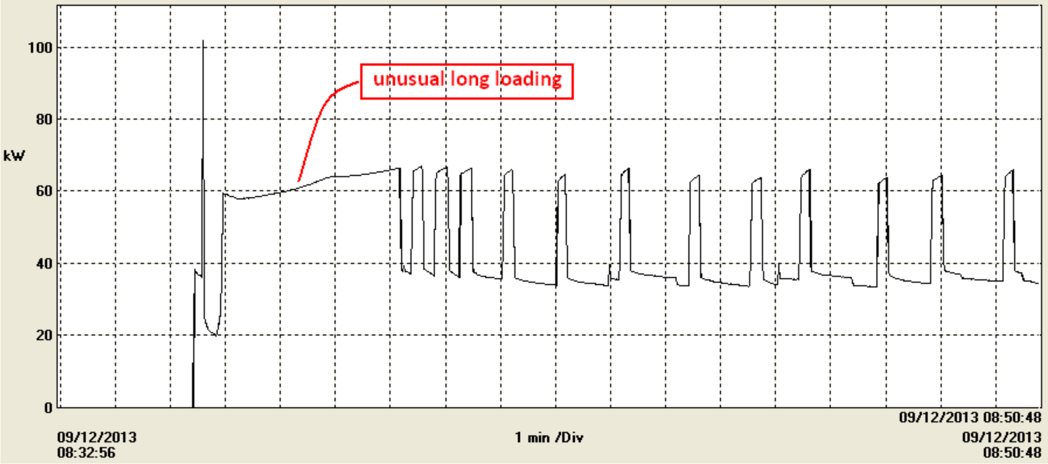


Figure 6-29**:** Power demand profile when the compressor started

One can expect that the compressed air demand by production activities would not be that much so that the compressor will work in such long time at the beginning of production shift. If so, where does this air demand come from so that the compressor tries to cover it? This is obviously due to the air leaks which consumed the compressed air in the storage tank on Sunday. There was no production activity on Sunday and the compressed air in the air storage tank remaining from Saturday shift was consumed by the air leaks. Hence, in Monday morning when the compressor was powered on, it had a quite long load mode to produce compressed air due to low pressure in the air storage tank and system. From this and the results of the leak detection activity, it is obvious that the plant has a problem with air leaks. In the following, energy losses from the air leaks will be estimated.

6.3.3.1 DETERMINING ENERGY LOSSES DUE TO THE AIR LEAKS

The energy consumption due to the air leaks can be estimated by determining the air flow rate from the leaks. Then, the power required by the compressor to compress this air flow can be calculated. The air leak flow rate depends on the line pressure, the compressed air temperature at the point of the leak, the air temperature at the compressor inlet, and the area of the leak.

The volumetric flow rate of free air, Vf, exiting all the leaks of a given size under choked flow conditions is calculated as follows (Cerci et al., 1995):

$$Vf = \frac{NLx(T_i + 273)x\left(\frac{P_1}{P_i}\right)xC_1xC_2xC_d\;x\;(\frac{\pi D^2}{4})}{C_3 * \sqrt{T_i + 273}} \qquad \text{(Eq.6-18)}$$

where;

Vf is the volumetric flow rate of free air, m^3h^{-1}

NL is the number of air leaks

T_i is the average temperature of the air at the compressor inlet °C

P_1 is the line pressure at leak in question, kPa_a

P_i the inlet (atmospheric) pressure kPa_a

C_1 is the isentropic sonic volumetric flow constant, 7.3587 $s^{-1}K^{0.5}$

C_2 is the conversion constant 3600 sh^{-1}

C_d is the coefficient of discharge for square edged ofrice, 0.8

D is leak diameter mm (estimated based on the observations)

C_3 is the conversion constant $10^6 mm^2 m^{-2}$

T_1 is the average line temperature °C.

The power loss from leaks is estimated as the power required to compressed the volume of air lost from atmoshpheric pressure (P_i) to the compressor discharge pressure (P_o) power loss for each size of leak present for given conditions are calculated as follows (Cerci et al., 1995):

$$PL = \frac{P_i x \left(\frac{1}{C_2}\right) x V_f x \frac{k}{k-1} x N x \left(\left(\frac{P_1}{P_i}\right)^{\frac{(k-1)}{k*N}} - 1\right)}{E_a x E_m} \qquad \text{(Eq. 6-19)}$$

where;

PL is the power loss from a given air leak, kW

k is the specific heat ratio of air (1.4)

N is the number of stages

E_a is the compressor isentropic (adiabatic) efficiency

E_m is the compressor motor efficiency

As an example, the power loss and energy consumption due to the air leaks from the holes with diameter D=0.4mm is calculated in the following:

Firstly, it is checked whether the flow is choked at the leak holes or not. The condition for the flow to be chocked is:

$P_i / P_1 < 0.5283$

Then,

$P_i / P_1 = 101.3 / 644 = 0.1572 < 0.5283$

Therefore, the flow at the leaks is chocked. Then, Equation 6-18 can be used to determine volumetric flow rate of free air, V_f. Number of leaks at 0.4 mm, NL = 2. The average temperature of the air the compressor inlet, T_i, was measured to be 21.4°C. Compressor 1 operates at around 7 bar (700 kPa). Assuming the line losses leads to 8% pressure drop (Cerci et al., 1995), the line pressure, P_1, will be 644 kPa. The average line temperature, T_1, can be assumed the same as the temperature at the compressor inlet. Thus, T_1 will be 21.4°C. The inlet pressure will be atmospheric pressure P_i = 101.3kPa. Hence, using these values in Equation 6-18, V_f can be found as 1.405 m^3h^{-1}.

Now, the power required to the compress this volume of air leak can be calculated. The number of stages of the subject compressor, N, is 1. The isentropic efficiency for screw compressors can be accepted as E_a= 0.82. The motor efficiency of the subject compressor E_m is 0.939. The operating pressure for the subject compressor, P_o, is 700 kPa. Hence, using these values in Equation 6-19, PL can be found as 0.036 kW. This is the power that is consumed to compress the air flow of 1.405 m^3h^{-1} at the holes with diameter D=0.4mm from atmoshpheric pressure to the compressor discharge pressure.

Using PL=0.036 kW , the annual energy consumption can be estimated as follows:

Annual energy cosumption =Annual Energy Loss = PL x Annual working hours

Annual energy cosumption = Annual Energy Loss = 0.036kW x 5029.75h = 181.07 kWh

The corresponding annual energy cost and CO_2 emissions can be calculated as follows:

*Annual Energy Cost = Annual energy cosumption * unit cost*

Annual Energy Cost = €19.8

Similarly, volumetric flow rates and corresponding power, energy and CO_2 values at other leaks have been calculated and presented in Table 6-31 below.

Table 6-31: Volumetric flow rate from the leaks and corresponding power, annual ESP, Annual ECSP, and Annual CO_2 ERP

D (mm)	**NL**	**Vf (m^3/h)**	**PL (kW)**	**Annual Energy Consumption =Annual ESP (kWh)**	**Annual ECSP (€)**	**Annual CO_2 ERP**
0.4	8	2.32	0.06	301.8	19.8	147.6
0.8	7	8.12	0.207	1,041.2	68.2	509.1
1.6	5	23.23	0.6	3018	197.7	1,475.7
Total				4361	285.6	21,32.4

As shown in Table 6-31, the annual total energy consumption due to the air leaks is 4,361 kWh. If the air leaks are repaired, this unnecessary consumption can be saved. Therefore, the annual ESP will be 4,361 kWh. The associated annual ECSP and CO_2 ERP will be €285.6 and 2,132.4 kg-CO_2, respectively.

6.3.4 OVERALL REVIEW OF THE ESPS IDENTIFIED IN THE CAS

The energy audit analyses have revealed the identification and application of seven ESPs in the CAS:

- ESP 6-3 by ESP by converting the existing 55kW compressor to a VSD one (Scenario 1)
- ESP 6-4 by using the existing Compressor 1 and Compressor 2 as a multiple compressor system (Scenario 2),
- ESP 6-5 by using a multiple compressor system (1.77m3/min-11kW- 10.150 m3/min) (Scenario 3),
- ESP 6-6 by using a multiple compressor system (1.77m3/min- 5.84 m3/min) (Scenario 4),
- ESP 6-7 by using a multiple compressor system (2.3m3/min-5.11m3/min) (Scenario 5),
- ESP 6-8 by using a multiple compressor system (2.9 m3/min-4.46m3/min) (Scenario 6),
- ESP 6-9 by fixing air leaks.

These ESPs are summarised and documented in Table 6-32.

Table 6-32: : Summary of ESPs identified in the CAS of the Subject Plant

ESP no	**Measure**	**ESP%**	**Annual ESP (kWh)**	**Annual PESP (kWh)**	**Annual ECSP (kWh)**	**Annual CO_2-ERP(kg-CO_2)**
ESP 6-3	ESP by converting the existing 55kW compressor to a VSD one	33.7	33,650.65	83,117.11	2,205.46	16,488.82
ESP 6-4	ESP by using the existing 18kW and 55kW compressor combination	74.1	74,015.50	182,818.29	4,850.98	36,267.60
ESP 6-5	ESP by using a multiple compressor system (1.77m3/min-11kW- 10.150 m3/min)	73.1	73,065.60	180,472.03	4,788.72	35,802.14
ESP 6-6	ESP by using a multiple compressor system (1.77m3/min-5.84 m3/min)	73	72,924.00	180,122.28	4,779.44	35,732.76
ESP 6-7	ESP by using a multiple compressor system (2.3m3/min-5.11m3/min)	60.1	60,115.10	148,484.30	3,939.94	29,456.40
ESP 6-8	ESP by using a multiple compressor system (2.9 m3/min-4.46m3/min)	66.7	66,681.80	164,704.05	4,370.33	32,674.08
ESP 6-9	ESP by fixing air leaks	3.30%	4,361	10,771.70	285.6	2132.4

6.4 COOLING TOWERS

A cooling tower is an important element of the HVAC systems in manufacturing plants where cooling of various processes or systems is required. There are many kinds of cooling towers in terms of size and design, but the principle function of all is cooling of a process or system by removing the extracted heat from that process or system to the atmosphere (i.e. air) through a combination of heat and mass transfer mechanisms. A cooling tower can be described by two pumping systems: an open-loop pumping system and a closed-loop one. The closed-loop pumping system takes the hot water from the system or process to be cooled and pumps it to a heat exchanger. The water in the heat exchanger is cooled down by the cooler water that is circulated between the heat exchanger and cooling tower in the open-loop pumping system.

The subject plant employs two cooling towers of the same type. The tower which serves for the induction furnaces will be called as Cooling Tower System 1 and the other one which is jointly used for quenching pool and sand reclamation system will be called as Cooling Tower System 2. Cooling Tower Systems in the subject plant are highly energy intensive. Based on the power consumption measurements and calculations by the Author, the overall collective annual energy consumption of the cooling towers is 482,811.8 kWh which is 16.3% of the overall plant annual energy consumption.

6.4.1 COOLING TOWER SYSTEM 1

6.4.1.1 DESCRIPTION

The induction furnace coil needs to be cooled continually as it is heated because of the current flowing through it and the molten metal through the lining. Otherwise, a dangerous heat build-up can lead to coil insulation damage, coil arcing, steam build-up and water leaks. These could then lead to a major explosion that could occur within minutes. The subject plant uses a wet cooling tower, which is shown in Figure F-1 in Appendix F, for the cooling of three induction furnaces used in the plant. The simplified scheme of Cooling Tower 1 is shown in Figure 6-30 whereas the detailed one is presented in Figure 6-31.

The coolant water for furnace coils is circulated in a closed loop circuit between the furnaces and a plate type heat exchanger. The circulation is achieved through a single stage centrifugal pump driven by an electric motor. The coil coolant water in the closed loop circuit absorbs the heat from furnace coils and pumped to the heat exchanger. The absorbed heat is then transferred from the coil coolant water to the cooling tower water of the open loop circuit through plates in the heat exchanger. Then, the cooling tower water is pumped by a single stage centrifugal pump to the cooling tower where it is cooled by the evaporation mechanism explained before.

As seen in Figure 6-30, there are two pumps which provide the water circulation between the heat exchanger, induction furnaces and cooling tower. The pump types are a single stage centrifugal pump and driven through electric motors.

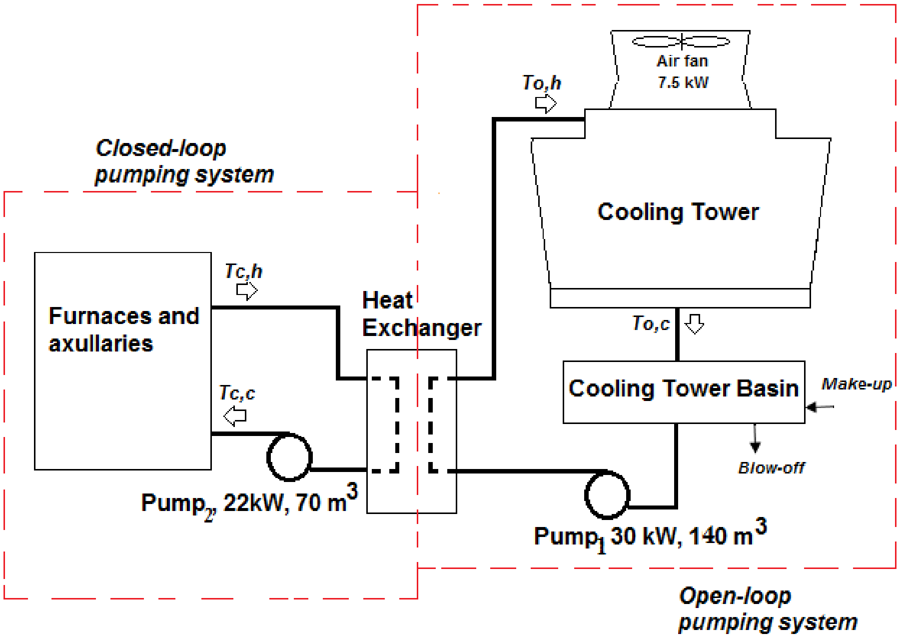


Figure 6-30: Simplified Schematic Representation of the Cooling Tower System of Induction Furnaces in The Subject Plant

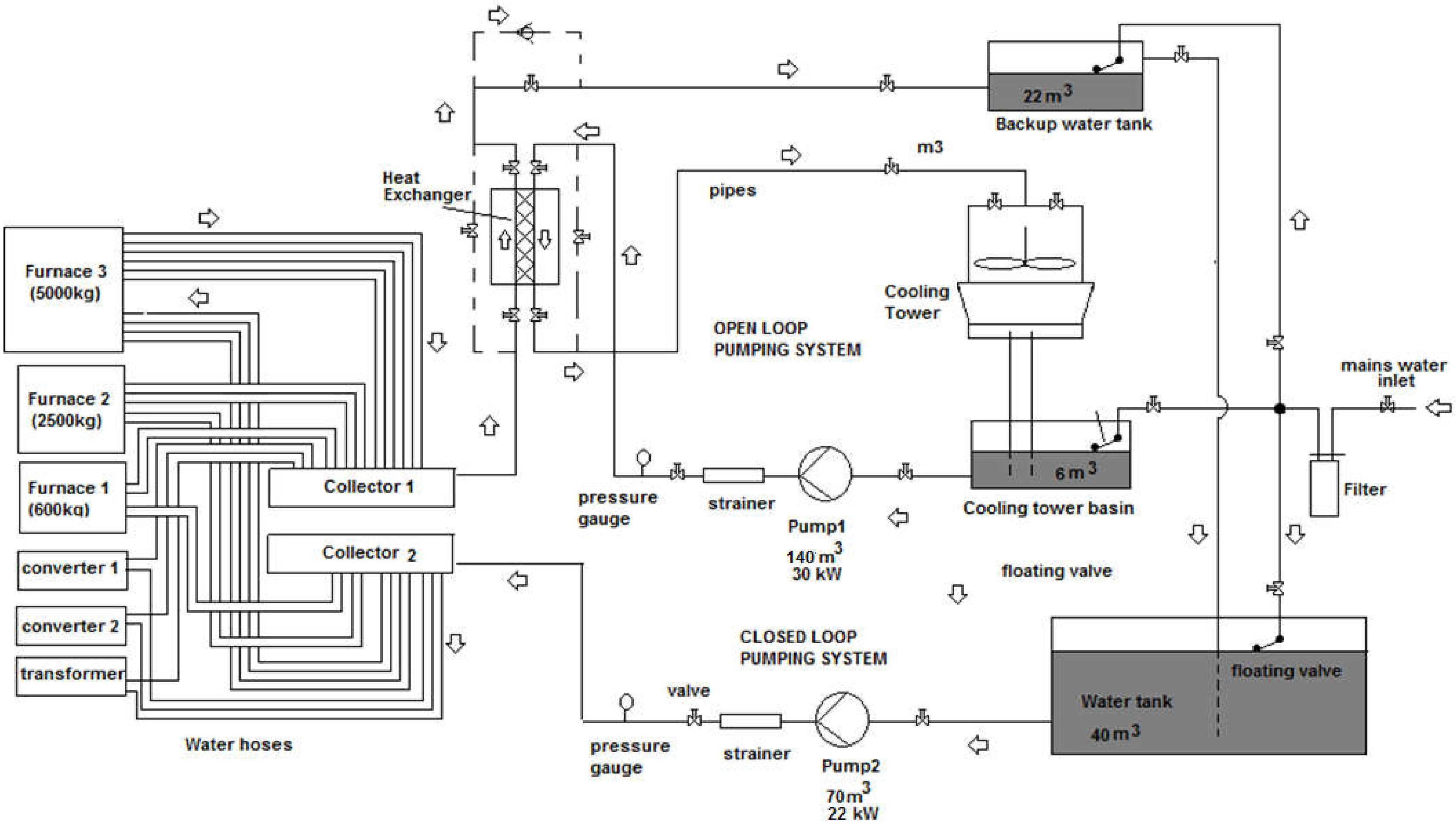


Figure 6-31: A detailed representation of the cooling tower system of induction furnaces in the subject plant

6.4.1.2 IDENTIFYING ESPS IN COOLING TOWER SYSTEM 1

6.4.1.2.1 Existing Performance Of Cooling Tower System 1

The power and energy measurements for the energy using elements of the cooling tower, that are water circulation pumps and air fan, have been conducted by using PEL 103 logger at 1 second intervals. Figure 6-32 shows the overall power demand of the whole system (i.e. Pump 1, Pump 2, and Air fan) which is 57.8 kW. To see the power consumption portion of each system elements, the power demands of Pump 2 and air fan were also measured. Based on the measurement results as given in Figure 6-33 and Figure 6-34, the average power demand of Pump 2 and air fan of the cooling tower are 22.8 kW and 6.4 kW, respectively. Therefore, the remaining 28.6 kW of 57.8 kW belongs to Pump 1.

All the components of Cooling Tower 1 operate continuously 6 day a week, which makes 7080 hours a year. Because average power demand is 57.8 kW, this corresponds to annual electricity consumption of 409,224 kWh which makes annual energy cost of €26,820.5 and annual CO_2 emission of 200,110.5 kg-CO_2. This is about 13% of plant electricity consumption which is a significant share.

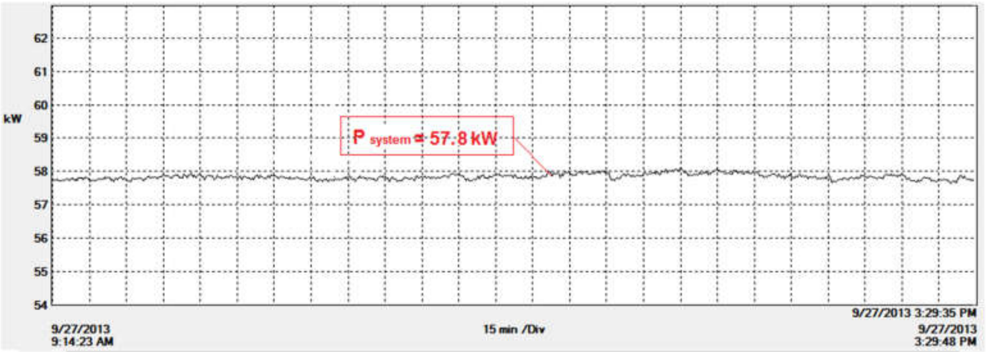


Figure 6-32: Power demand of cooling tower pumping system (Pump1 + Pump2)

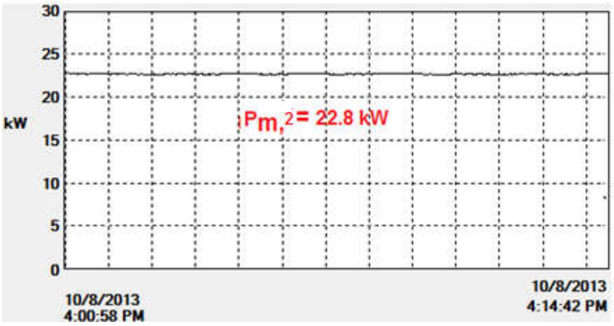


Figure 6-33: Power demand of Pump 2

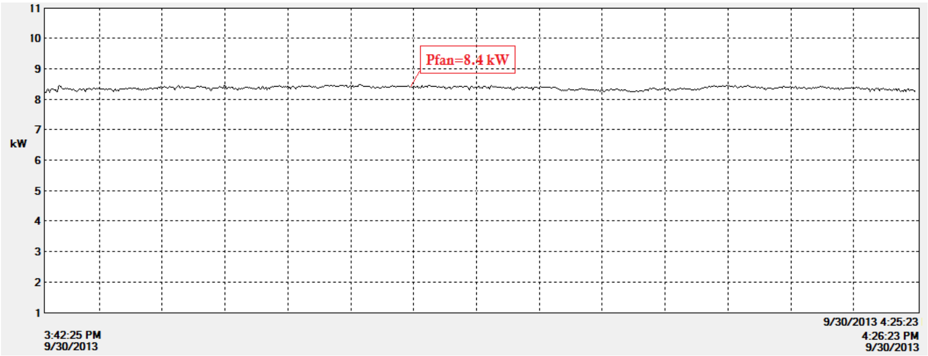


Figure 6-34: Power demand of Cooling Tower Air Fan

As one can see in Figure 6-32, Figure 6-33, and Figure 6-34, the power demands are constant which implies that all the system elements are running at constant speed. However, the cooling demand of the furnaces would not be constant, it would be rather variable. This is because the cooling tower serves 3 induction furnaces in a series connection, they do not always work at the same time. There are some days when the biggest furnace does not work. Therefore, cooling demand by the furnace coils and other auxiliary equipment would be less and the cooling tower load will be less. Furthermore, the relative humidity of the air will not be constant and so the evaporation rate of the cooling water will vary, as well. Despite these, the fan, which circulates the air to enhance the evaporation, runs constantly. The fan should work based on the actual requirement. This can be achieved through the use of a VFD which will control the speed of the fan with respect to the need. The need can be decided by thermostat controls and appropriate programming. Hence, there is an ESP by employing a VFD control for the cooling tower air fan.

In addition to the air fan, the pumps of the cooling tower should be assessed for their efficiency. A detailed information and analysis method for pumping systems energy efficiency is given in Appendix D. Their performance will be assessed in the following.

6.4.1.2.2 Analysis of the air fan

As mentioned previously, the fan operates constantly at full capacity (Qmax) although the demand is variable. Thus, it draws full capacity power demand. The speed of the fan should match the actual requirement. Otherwise, there will be there will be energy waste because a minor change in speed can result in major changes in energy consumption. Although the power rating of the fan electric motor is 7.5 kW, which is quite small compared to the other fan applications in the plant, long working hours (with 100% load factor) of it makes attractive for seeking an ESP.

The most efficient way of fan speed control is to use variable frequency driver (VFD). As the system demand changes, the VFD adjusts the speed of fan to meet the changing demand. Thus, it saves energy by reducing the fan speed which is unnecessary. An automation system is needed to control the VFD. For this purpose, a controller which will measure the temperature of the water and send signal to the VFD to increase or decrease the fan speed so as to maintain the process fluid temperature at the desired set-point. The temperature of the water can be measured at the outlet of the cooling tower by means of a thermocouple and the temperature signal can be transmitted by temperature transmitter (Miller et al., 2012). A VFD together with the automation system for the cooling tower in the subject plant will have the following components:

- a VFD.
- a thermocouple.
- a controller.
- miscellaneous components such cables, cables tray, junction box, etc.

In the current case study, the fan operates at design capacity (100% of Q) and produces maximum air flow. For the purpose of this study, the fan will operate at various percentages of its design capacity for various time percentages. For this reason, ten different percentages of the design capacity levels will be defined from 10% to 100% by 10% increments and various utilisation of the time percentages will be given corresponding to these capacity levels as tabulated in Table 6-33

Table 6-33: Assumed case study input data [Percentage of capacity and percent of time the fan operates at this capacity]

Percentage of design capacity (Q_{max})	**Percentage of time at this capacity**
10%	0%
20%	0%
30%	10%
40%	0%
50%	0%
60%	20%
70%	35%
80%	30%
90%	0%
100%	5%

The fan draws about Pdesign =8.4 kW at the maximum capacity as can be seen in Figure 6-34. The corresponding annual energy consumption can be calculated as follows:

$$Annual\ Energy\ Consumption = Pdesign * annual\ running\ hours$$

$$Annual\ Energy\ Consumption = 8.4\ kW * 7080\ hours/year$$

$$\text{Annual Energy Consumption} = 59{,}472\ \text{kWh}$$

Now, the impact of the VFD controlling strategy over the air fan energy consumption can be evaluated. For this purpose, power demand at percent design capacity is needed to be calculated. For this purpose, modified version of the fan law, which uses a square instead of cube relationship between speed (N) and power (P) can be used (Turner and Doty, 2008):

$$P2 = P1 * (N2/N1)^2$$

As air flow is proportional to rpm, this can be re-written as:

$$P2 = P1 * (Q2/Q1)^2$$

Hence, the power demand at 10 % of the design capacity can be calculated by using the above equation as follows:

$$P2 = P1 * (Q2/Q1)^2$$

$$P2 = 8.4\ kW * (10/100)^2$$

$$P2 = 0.084\ kW$$

Other power demands at various percentages of the design capacities are calculated and presented in Table 6-34. By using the percent time at those capacities, annual energy consumption, when VFD is used, have been calculated and presented in Table 6-34.

Table 6-34: Power demand and annual energy consumption values when VFD is used

Percent of Capacity (cfm) (a)	**Power Demand (kW)** (b)	**Percent of time at this capacity (%)**(c)	**Hours** (d)	**Efficiency of VFD** (e)	**Energy Consumption (kWh)** (f)
assumed	calculated as shown above in te text	assumed	d=c*7080	Assumed	f=(b*d)/e
10%	0.084	0%	0		0
20%	0.336	0%	0		0
30%	0.756	10%	708		508.4
40%	1.344	0%	0		0
50%	2.1	0%	0		0
60%	3.02	20%	1,416	95%	4,062.4
70%	4.1	35%	2,478		9,652
80%	5.37	30%	2,124		10,835.7
90%	6.8	0%	0		0
100%	8.4	5%	354		2825
Total			7,080		27,993.5

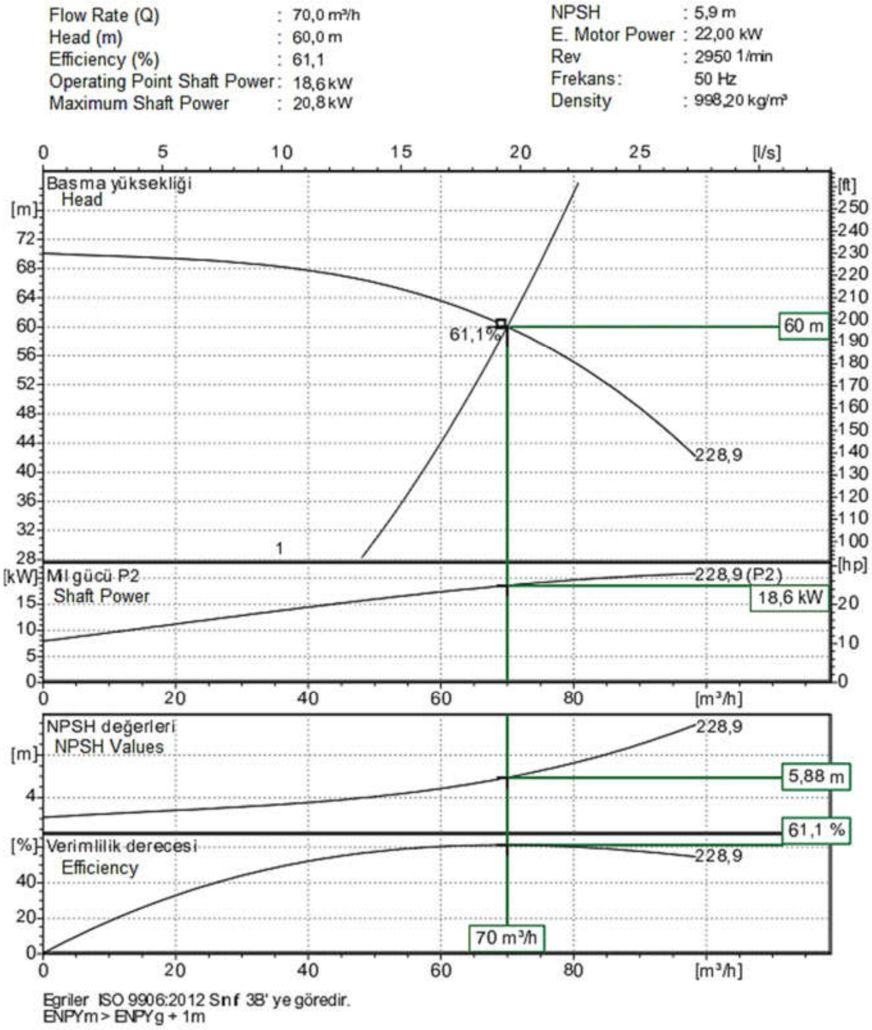
As seen in Table 6-34, annual energy consumption when a VFD is used is 27,993.5 kWh, which is quite low compared to the case for which the fan runs at a full capacity. Hence, the annual ESP and corresponding monetary and environmental benefits can be calculated as presented in Table 6-35 .

Table 6-35: ESP by using VFD for the cooling tower air fan

Existing Annual Energy Consumption (a)	**Annual Energy Consumption when VFD is used** (b)	**Annual ESP** (c)	**ESP%** (d)	**Annual PESP** (e)	**Annual ECSP** (f)	**Annual CO_2 ERP** (g)
measured	Calculated above in the text	c=a-b	d=c/a %	Using Equation 3-1	Using Equation 3-2	Using Equation 3-3
59,472 kWh	27993.5 kWh	31,478.5 kWh	53%	77,751.89 kWh	€ 2,063.10	15,424.45 kg-CO_2/year

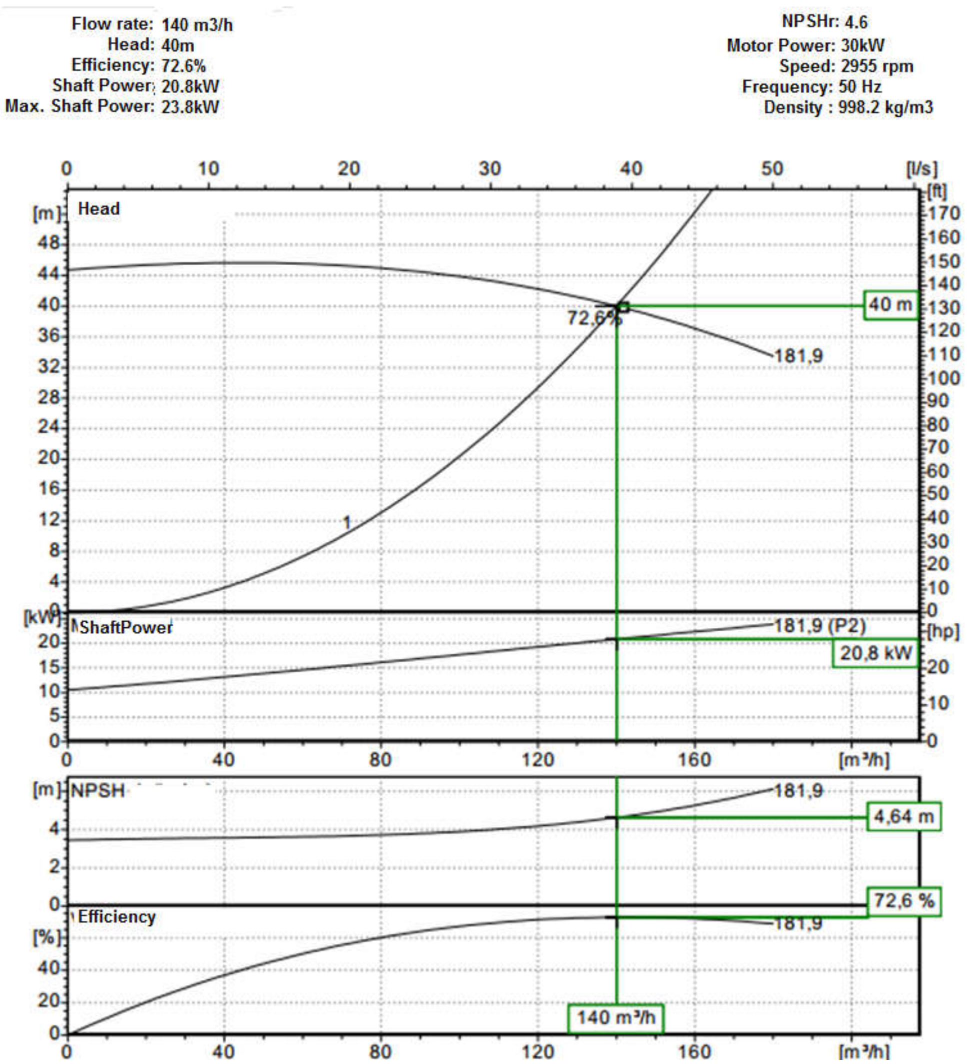
6.4.1.2.3 Identifying ESPs in Pump 2 and Pump 1

In this subsection, by following the steps explained in Appendix D, it will be investigated whether Pump 2 and Pump 1 are operating efficiently or not. A detailed information and analysis methodology for design and existing pumping systems are given in Appendix D. As mentioned in Appendix D, employing an efficient pump does not mean it is being used efficiently. Efficiency of a pump varies depending on the operating characteristics and performance of the pump at different operating characteristics (Flow rate, head) defined by their performance curves. The performance curves and nominal efficiency values of Pump 2 and Pump 1 are given in Figure 6-35 and Figure 6-36, respectively. The rated technical specifications of the pumps based on Figure 6-35 and Figure 6-36 are given in Table 6-37. The rated specifications of the electric motors of Pump 2 and Pump 1 are presented in Table 6-38.


Flow Rate (Q) : 70,0 m³/h
Head (m) : 60,0 m
Efficiency (%) : 61,1
Operating Point Shaft Power : 18,6 kW
Maximum Shaft Power : 20,8 kW
NPSH : 5,9 m
E. Motor Power : 22,00 kW
Rev : 2950 1/min
Frekans : 50 Hz
Density : 998,20 kg/m³

Egriler ISO 9906:2012 Snf 3B' ye göredir.
ENPYm > ENPYg + 1m

Figure 6-35: The performance curve of Pump 2



Flow rate: 140 m3/h
Head: 40m
Efficiency: 72.6%
Shaft Power: 20.8kW
Max. Shaft Power: 23.8kW

NPSHr: 4.6
Motor Power: 30kW
Speed: 2955 rpm
Frequency: 50 Hz
Density : 998.2 kg/m3

Figure 6-36: Performance curve of Pump 1

Table 6-36: Technical specifications of Pump 2 and Pump 1 (Source: Manufacturer`s data)

	Pump2	**Pump 1**
Electric Motor Power (kW)	22 kW	30 kW
Shaft Power (kW)	18.6 kW	20.8 kW
Working Point Maximum Shaft Power (kW)	20.8 kW	23.8 kW
Head (m)	60 m	40 m
Flow Rate (m^3/h)	70 m^3/h	140 m^3/h
BEP Pump Efficiency (%)	61.10%	72.60%
$NPSH_r$	5.9 m	4.6 m

Table 6-37: Rated specifications of the electric motors of the circulations pumps in Cooling Tower 1 (Source: Manufacturer`s data)

	Electric Motor of Pump 2	**Electric Motor of Pump 1**
Maker	WAT Arcelik	WAT Arcelik
Power rating	22 kW	30kW
Energy Efficiency Class	EFF2	EFF2
Rated Efficiency	90.50%	91.40%
Speed	2940 rpm	2945 rpm

6.4.1.2.3.1 Analysis of Pump 2

As given in Table 6-36, the efficiency of Pump 2 is 61.1 %. This is the efficiency when the pump operates at its Best Efficiency Point (BEP). The BEP for Pump 2 is (Q_{bep}, H_{bep}) = (60m, 70 m^3/h). To check whether the pump is operating efficiently or not, the pump duty which indicates the actual working points (Q_{duty}, H_{duty}) of the pump should be determined.

Pump Duty: Flow Rate (Qduty) for Pump 2

Q_{duty} can be calculated by using the affinity laws. P_{rating} and corresponding Q_{rating} are 18.6 kW and 70 m^3/h, respectively. P_{duty} that the mechanical energy input to the pump can be estimated as follows:

$$P_{duty}=P_m= P_m*\eta= 22.8*0.905=20.6 \text{ kW}$$

By using Equation D15 and Equation D17,

$$\frac{20.6}{18.6} = \left(\frac{Qduty}{70}\right)^3$$

$$Q_{duty}=72.4 \text{ m}^3/\text{h}$$

Q_{duty} can be found as 72.4 m^3/h which is slightly greater than the BEP flow rate value of Pump 2, which is 70 m^3/h.

Pump Duty: Total pump head (Hduty) for Pump 2

The total pump head for Pump 1, H_{duty}, can be estimated by Equation D1 in Appendix D. As presented in Equation D1, it is the sum of the total discharge head (h_d) and total suction head (h_s). h_d and h_s are calculated in the following parts to calculate the H_{duty} for Pump 2 as their sum.

<u>h_d, total discharge head for Pump 2</u>

Pump 1 has a pressure gauge at the discharge exit as can be seen Figure 6-31. It shows the total discharge head h_d of Pump 2 when the pump is in operation. Based on the pressure gauge, the total discharge head (h_d) of Pump 2 was read to be about 5.5 bar as seen in Figure 6-37. This corresponds to 56.1-meter discharge head.

Figure 6-37: Pressure gauge of Pump 2 showing the total discharge head in bar

<u>h_s, total suction head for Pump 2</u>

Because there is no pressure gauge on the suction side of Pump 2, the total suction head, hs, can be estimated by using Equation D3. As Equation D3 in Appendix D also shows, hs is the sum of static suction head (h_{ss}) from x to y, suction pipe friction head (h_{pfs}), and suction fitting heads (h_{fls}). h_{ss} is 2.58m (measured by the Author during in the energy audit) as shown in Figure 6-38.

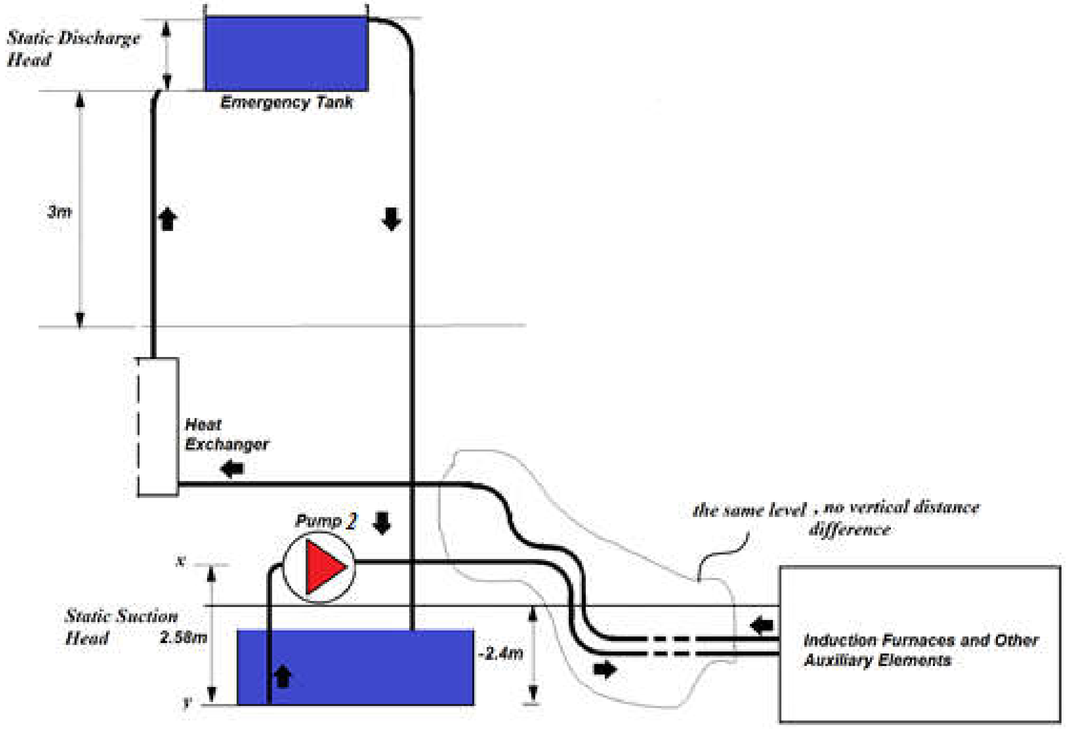


Figure 6-38: Static heads for Pump 2

h_{pfs}, suction pipe friction head, from X to Y can be estimated by using Equation D4 given in Appendix D. To use Equation D4, following inputs are used:

- L=2.58 m (measured).
- D=0.22m (measured).
- $Q=Q_{duty}=72.4\ m^3/h$ (calculated).
- V=0.53 m/s (calculated).
- f, friction factor.

f, friction factor must be calculated. The Reynolds number for the flow in the suction side of the pump can be calculated by using Equation D6. υ, water kinematic viscosity at T=29°C is found to be $0.7979x10^{-6}$ from thermodynamics tables. Thus, the Re number for the flow in the suction side of Pump 2 can be found as 145,873. Therefore, the flow is turbulent because the Reynolds number is greater than 4,000 as explained in Appendix D. The Moody`s diagram is used to estimate the friction factor, f. The relative roughness of the pipe is needed to be used together with the Re number in the Moody`s diagram. The relative roughness can be estimated by using Equation D7. The material of the pipes is stainless steel, so, ε, the roughness for steel pipe is 0.025 mm. Thus, using ε and D in Equation D7, the RR is found to be as $1.136x10^{-4}$. By using the RR and Re number on Moody`s diagram, the f can be found as 0.017, as shown in Figure 6-39.

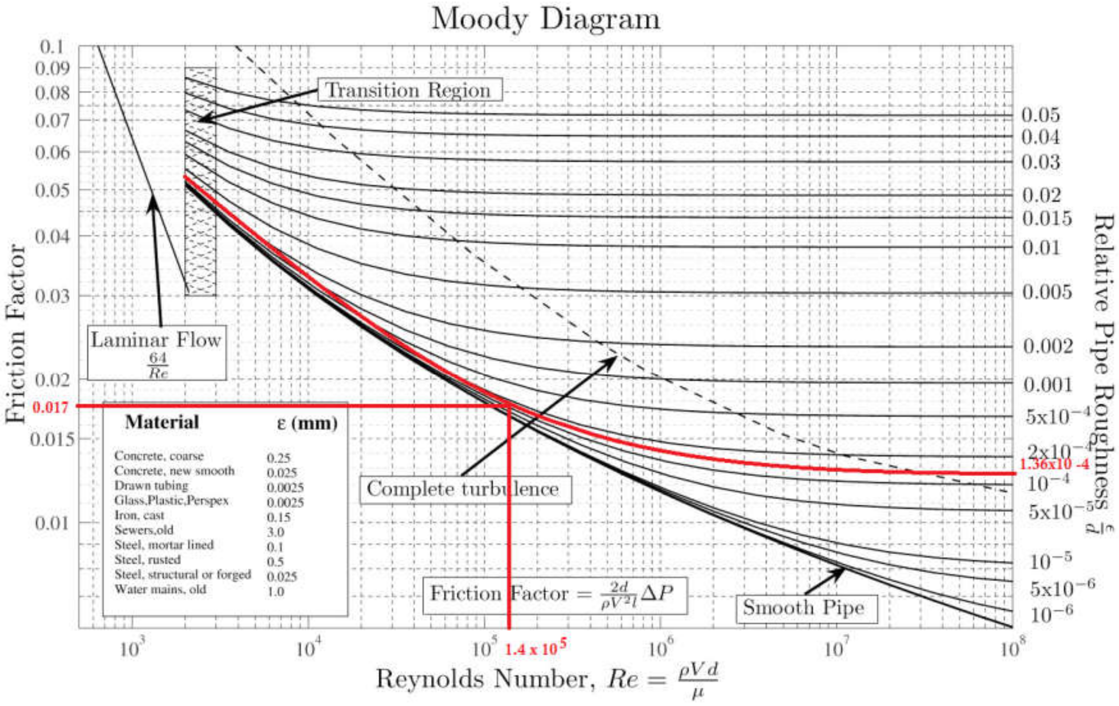


Figure 6-39: Moody`s diagram: f, friction factor estimation for Pump 2

Hence, h_{pfs} can be estimated by using Equation D4 as follows:

$$h_{pfs} = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right) = 0.017x\frac{2.85}{0.22}x\frac{(0.53)^2}{2.9.81}$$

$$h_{pfs} = 0.00315\text{m}$$

The next step is to determine $h_{fls,}$ head losses due to the local losses. The suction side has the following fittings (their quantities in bracket):

- Right angle turns (2)
- Screen (1)
- Fully open Angle valve (1)

The local resistance coefficients for right angle turns, screen, fully open angle valve, and union are 0.3, 0.2, and 2, respectively. Therefore, substituting this value into Equation D8:

$$h_{fls} = \Sigma K\left(\frac{V^2}{2g}\right) = (2x0.3 + 0.2 + 2)x\left(\frac{0.53^2}{2g}\right)$$

$$h_{fls} = 0.043m$$

Having estimated the total friction at the suction side, the total suction head can be calculated by using Equation D2 as follows:

$$h_s = 2.58+0.00315+0.043m$$

$$h_s = 2.62m$$

The total system head for Pump 2 will be:

$$H_{duty} = h_d + h_s = 56.1 + 2.6 = 58.7m$$

Hence, the total pump head that Pump 2 is operating at is 58.7m. This head is required to overcome all the static head and pipe friction and fitting loss heads as well as to provide enough pressure to cooling tower sprays.

<u>Operating efficiency of Pump 2</u>

By substituting the operating flow rate and total pump head values into Equation D14, the operating efficiency of Pump 2 can be estimated as:

$$\eta_{op\_P1} = \frac{(72.4\ /3600)\ x\ 58.7\ x\ 998.2\ x\ 9.81}{20.6\ x1000} = \frac{11.56}{20.6} = 56\%$$

The hydraulic power needed by the water is 11.56 kW whereas the pump needs 20.6 kW to produce 11.56 kW of hydraulic energy. Thus, the operating efficiency of Pump 2 is 56% whereas its best efficiency is 61.1% as indicated Table 6-37 and Figure 6-35. There is around 8% difference between the operating efficiency and best efficiency of Pump 2. When the operating duty points (Hduty, Qduty) = (58.7m, 72.4 m^3/h) are compared with the design BEP= (60, 70 m^3/h) and it can be said that existing Pump 2 is correctly sized for the application it serves.

Even if a pump is correctly sized for the application it serves, as discussed in Appendix D, its efficiency should be questioned. One should ask the question: Is there a more efficient pump for the same flow and head conditions? A more efficient pump would need less power input for the same work output. Besides, if the electric motor to drive the pump has an energy efficient class, the overall efficiency of the pumping system will be highest.

The overall efficiency of the system can be improved by a combination of the following measures:

- Using a pump with higher mechanical efficiency (i.e. efficient pump),
- Using an energy efficient electric motor to drive the pump.

It should be noted that, the above analyses for Pump 2 did not consider the aspects related to piping circuit improvements since the total contribution of piping factor is insignificant.

All in all, the above analysis suggests the following potential ESP for Pump 1:

1. ESP by using an efficient pump driven by an energy efficient electric motor instead of Pump 2 in the cooling tower closed loop pumping system.

This will be investigated as an ESP for Pump 2. For this purpose, the software PUMP-FLO®, which has an extensive database of pumps manufacturers` catalogues and data (PumpFlo, 2015), has been used to search for efficient pumps. In searching for a new pump, an additional parameter, Net Positive Suction Head (NPSHa) to avoid cavitating condition is needed as a design input. This will be estimated in the following.

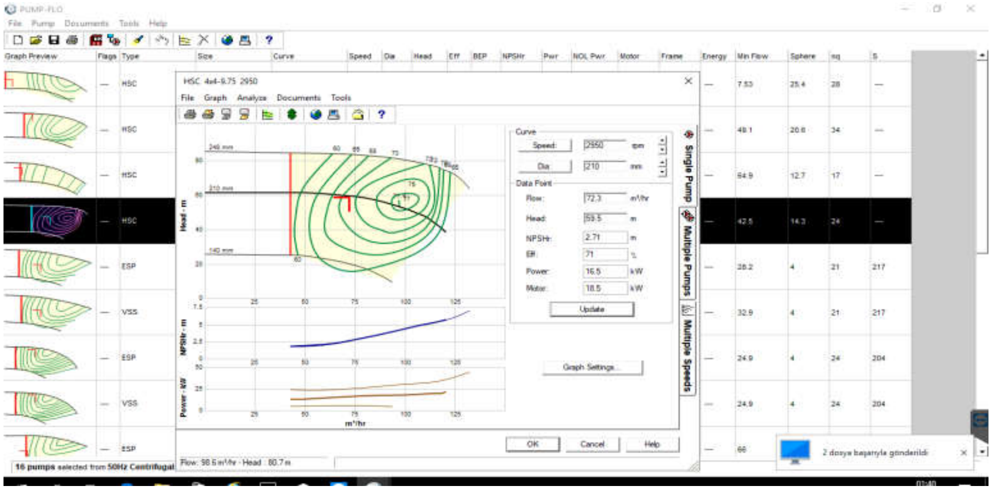
$NPSH_a$

The $NPSH_a$ for the pump has been calculated to be 8.19 m by using Equation D13. To use Equation D13, following inputs are used:

- H_a=1 atm=10.33m.
- H_z= -2.58m (vertical distance between the surface of the water in the cooling tower tank and the centreline of the pump, shown in Figure 9-12).
- Hf= h_{fs} = 0.0179 (total friction losses in the suction piping (m), calculated before).
- H_{vp}= 0.40 m (absolute vapor).

Choosing an efficient pump

A more efficient pump has been chosen based on the duty point Q, H = (58.7m, 72.4 m^3/h) and NSPH$_a$=8.16m, by using the software Pump-Flo®. A screenshot of the pump selection in Pump Flo can be seen in Figure 6-40. The pump curve and specifications of the suggested pump can be seen in Figure 6-41 and Table 6-38, respectively.



Curve
Speed: 2950 rpm
Dia: 210 mm

Data Point
Flow: 72.3 m³/hr
Head: 59.5 m
NPSHr: 2.71 m
Eff: 71 %
Power: 16.5 kW
Motor: 18.5 kW

16 pumps selected from 50Hz Centrifugal

Flow: 98.6 m³/hr - Head : 80.7 m

Figure 6-40: Pump Flo pump selection

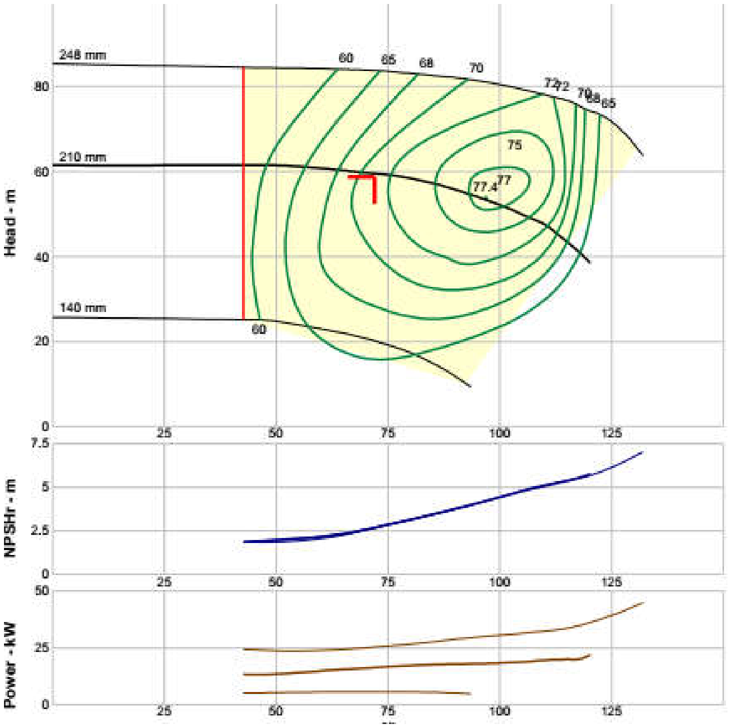


Figure 6-41: Pump performance curve of the chosen pump for Pump 2

Table 6-38: Specifications of the suggested pump instead of Pump 2

Maker	Olympus Pumps
Best Efficiency	77.40%
BEP Flow Rate	96.7 m^3/h
Mechanical Power Use for BEP	
Electric Motor Power Rating	18.5kW
Speed	2950 rpm
NPSHr	2.69
Efficiency at Design Point	70.90%
Mechanical power use at Design Point (72.4 m^3/h, 58.7m)	16.5 kW

Thus, the power rating of the electric motor is chosen as 18.5 kW. As seen, while the power rating of the electric motor of the existing pump is 22 kW, it is 18.5 kW for the chosen pump. As noted before, the existing Pump 2 draws about 22.8 kW and the mechanical power transferred to the pump is 20.6 kW due to the motor efficiency. The suggested more efficient pump demands 16.5 kW for the same pump work. A high efficiency motor to drive the pump is also chosen to improve the overall system efficiency: an ABB 18.5 kW electric motor with IE3 energy efficiency class and 93.1% efficiency (ABB, 2014). Thus, new pump will draw about 17.7 kW (i.e. 16.5 kW/0.931). The associated ESP by using the suggested pump instead of Pump 2 and its monetary and environmental benefits are estimated in Table 6-39.

Table 6-39: ESP by replacing Pump 2 with an efficient and right size pump and electric motor

Annual Operating Hours (a)	**Existing Average Power Demand** (b)	**New power demand** (c)	**Differenceof Power Demand** (d)	**%E SP**(e)	**Annual ESP** (f)	**Annual PESP** (g)	**Annual ECS** (h)	**Annual CO_2 ERP** (i)
	measured	Calculated in the text above	d=b-c	e=d/b%	f=d*a	(Equation 3-1)	(Equation 3-2)	(Equation 3-3)
7080	22.6 kW	17.7 kW	4.9 kW	21.50%	34,692 kWh	85,689.24 kWh	€ 2,273.70	16,999 kg.CO_2

6.4.1.2.3.2 Analysis of Pump 1

As seen in Figure 6-31, Pump 1 of Cooling Tower 1 operates in an open loop pumping system and provides the water circulation between the cooling tower and the heat exchanger. The specifications of Pump 1 and its pump curve are presented in Table 6-36 and Figure 6-36, respectively.

Q_{duty} can be calculated by using the affinity laws. P_{rating} and corresponding Q_{rating} are 20.8 kW and 140 m^3/h, respectively. P_{duty} that the mechanical energy input to the pump can be estimated as follows:

$$P_{duty} = P_m * \eta_{motor}$$

$$P_{duty} = 26.6*0.914=24.31\ kW$$

By using Equation D14 and D15, Q_{duty} can be found as 147.4 m^3/h which is slightly higher than the BEP flow rate value of Pump 2, which is 140 m^3/h.

<u>Pump Duty: Total pump head (Hduty) for Pump 1</u>

Because there is no pressure gauge on the suction side of Pump 1, the total suction head can be estimated by . It is the sum of static suction head (h_{ss}) from A to C and friction and fitting heads (h_{pfs}+ h_{fls}). h_{ss} is -6.67m as shown in Figure 6-42. The above calculations done for Pump 2 have been repeated for Pump 1 to find out its operating efficiency. Therefore, these calculations are not presented in detail, only summary of them are given and details are provided where appropriate in the followings.

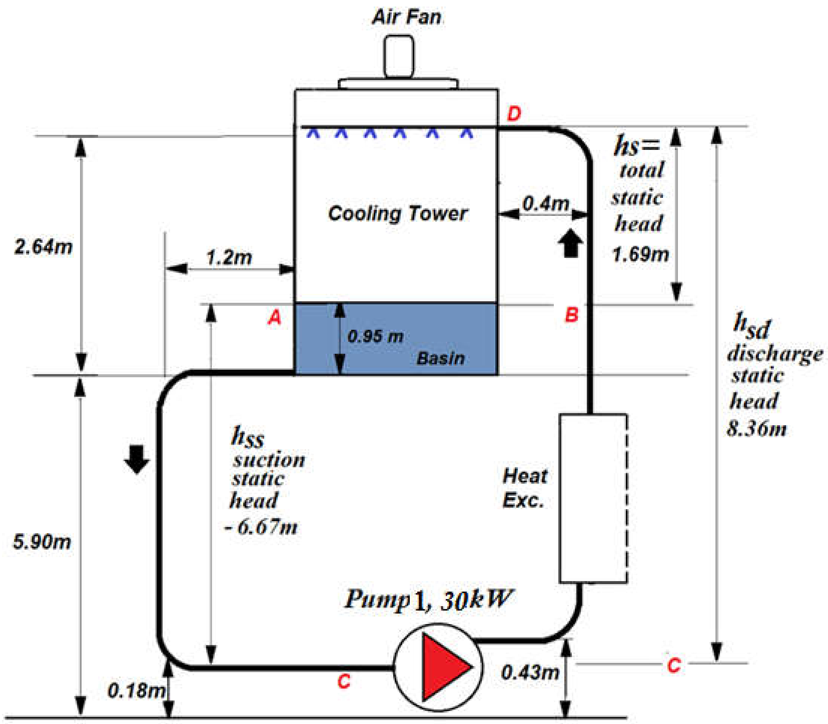


Figure 6-42: Static heads for Pump 1

As one can see in Figure 6-32, the average power drawn by the electric motor of Pump 1 is 28.6 kW at a constant rate. Based on that the electric motor efficiency is 93.1% as given in Table 6-38, P_{in_duty}, power input into Pump 1 was found to be 28.6*0.914=24.31 kW above.

As indicated in Table 6-36 and Figure 6-36, the BEP of Pump 1 is 40 m of head and 140 m^3/h of water flow. The efficiency of the pump at these operating points is 72.6% which is the maximum efficiency that Pump 1 can reach and it can only by achieved on the condition that the pump is operating at its BEP. The duty point of Pump 1 will be investigated in the following paragraphs and operating efficiency will be determined. To find out the pumping operating efficiency, water flow rate (Q_{duty}) and total head (H_{duty}) must be known.

__Pump Duty: Total pump head (Hduty) for Pump 1__

Following the same steps in Section 6.4.1.2.3.1, H_{duty} is calculated in this subsection. As given in Equation D1 in Appendix D, H_{duty} is the sum of h_d and h_s. They will be calculated in the following.

h_d, total discharge head for Pump 1

Pump 1 has a pressure gauge at the discharge exit as can be seen in Figure 6-43. It shows the total discharge head h_d of Pump 1 when the pump is in operation. Based on the pressure gauge, the total discharge head (h_d) of Pump 1 was read to be about 3.3 bar as seen in Figure 6-43. This corresponds to 33-meter discharge head. Therefore, hd is 33m.

Figure 6-43: Pressure gauge for Pump 1 showing the discharge head in bar

h_s, total suction head for Pump 1

Because there is no pressure gauge on the suction side of Pump 1, the total suction head, h_s, can be estimated by . As given in Equation D3, h_s is the sum of static suction head (h_{ss}) from A to C, pipe friction (h_{pfs})and fitting heads (h_{fls}). h_{ss} is -6.67m as shown in Figure 6-42 (measured by the Author during the energy audit).

The suction fitting losses, h_{fls} from X to Y can be estimated by using Equation D4, D5, D6, D7, and D8 in Appendix D. The Re number for the flow in the suction side of Pump 1 can be found as 295,024.4. Therefore, the flow is turbulent and the Moody`s diagram is used to estimate the friction factor, f. The relative roughness, the RR is found to be as $1.136x10^{-4}$. By using the RR and Re number, the f can be found as 0.0155, as shown in Figure 6-44.

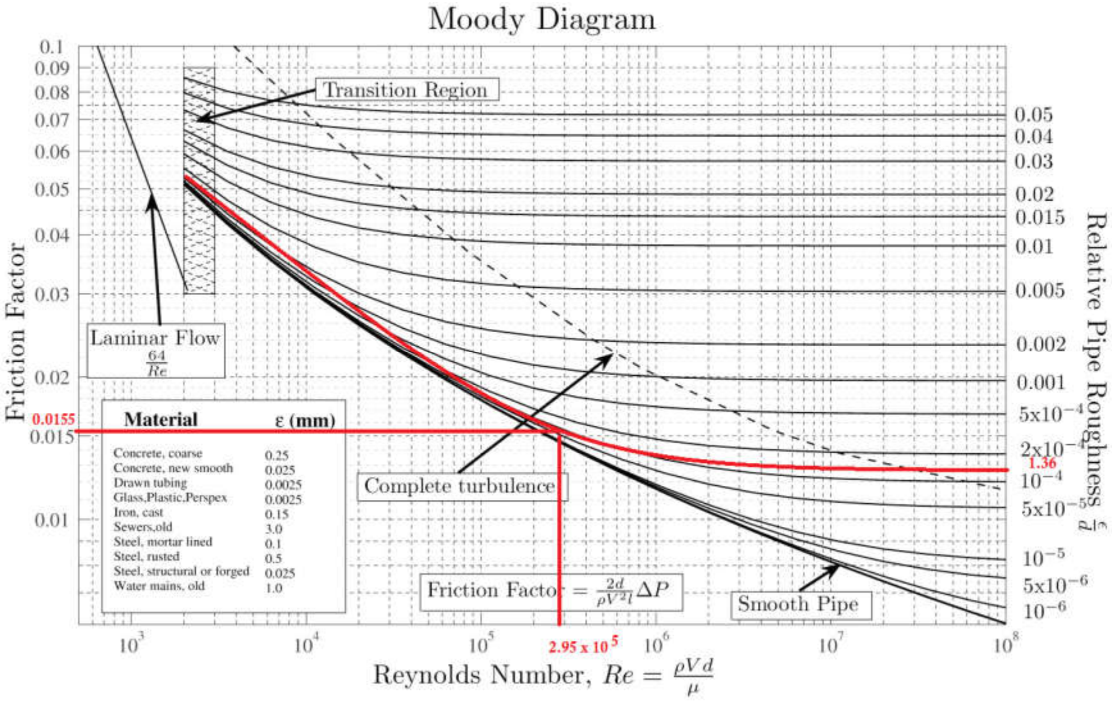


Figure 6-44: Moody`s diagram: friction factor estimation for Pump 2

Hence, h_{pfs} can be estimated as follows:

$$h_{pfs} = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right) = 0.0155x\left(\frac{8.12}{0.22}\right)\left(\frac{1.07^2}{2.9,81}\right)$$

$$h_{fls} = 0.033\text{m}$$

The next step is to determine $h_{fps,}$ head losses due to the fitting losses. The suction side has the following fittings (their quantities in bracket):

- Right angle turns (3)
- Fully open Angle valve (1)

The local resistance coefficients for right angle turns, and fully open angle valve are 0.3 and 2, respectively. Therefore, substituting this value into Equation D8:

$$h_{fls} = \ \ \Sigma K\left(\frac{V^2}{2g}\right) = (2x0.3 + 2)x\left(\frac{1.07^2}{2g}\right)$$

$$h_{fls} = 0.15$$

Having estimated h_{ss} from A to C, h_{pfs}, and h_{fls}, the total suction head, hs, can be calculated by using Equation D3 as follows:

$$h_s = h_{ss} + h_{pfs} + h_{fls} = -6.67 + 0.033 + 0.15$$

$$h_s = -6.48\text{m}$$

The total system head, H_{duty}, for Pump is calculated by using Equatin D1 as follows:

$$H_{duty} = h_d + h_s = 33 + (-6.48) = 26.5\text{m}$$

Hence, the total pump head that Pump 1 is operating at is 26.5m.

Operating efficiency of Pump 1

By using Qduty and Hduty, the operating efficiency of Pump 2 can be calculated by using Equation D14 as follows:

$$\eta_{op\_P1} = \frac{(147.4/3600)x\ 26.5\ x\ 998.2\ x\ 9.81}{24.31} = \frac{10.66}{24.31} = 43.8\%$$

The hydraulic power needed by the water is 11.66kW whereas the pump needs 24.31 kW to produce 11.66 kW of hydraulic energy. Thus, the operating efficiency of Pump 1 is 43.8% whereas its best efficiency is 72.6 % as indicated in Table 6-36. There is almost 40% difference between the operating point efficiency and BEP efficiency. This is a significant difference and it can be said that the pump is not correctly sized for the application. Therefore, there is a likely ESP by using a right size and efficient pump instead of the existing Pump 1. In addition to this, additional energy can be saved by driving the pump using an electric motor of high efficiency class.

Like the analysis of Pump 2, the analyses for Pump 1 did not consider the aspects related to piping circuit improvements. This is because a major part of the piping distribution network at the discharge side of Pump 1 was place under the ground and its details are not known.

All in all, the above analysis suggests the following potential ESP for Pump1:

- ESP by using a right size and efficient pump driven by an energy efficient electric motor instead of the existing Pump 1 in the cooling tower open loop pumping system.

This will be investigated as an ESP for Pump 1. In searching for an efficient pump by using Pump-Flo® an additional parameter, NPSHa is needed as a design input. This will be estimated in the following.

<u>NPSHa</u>

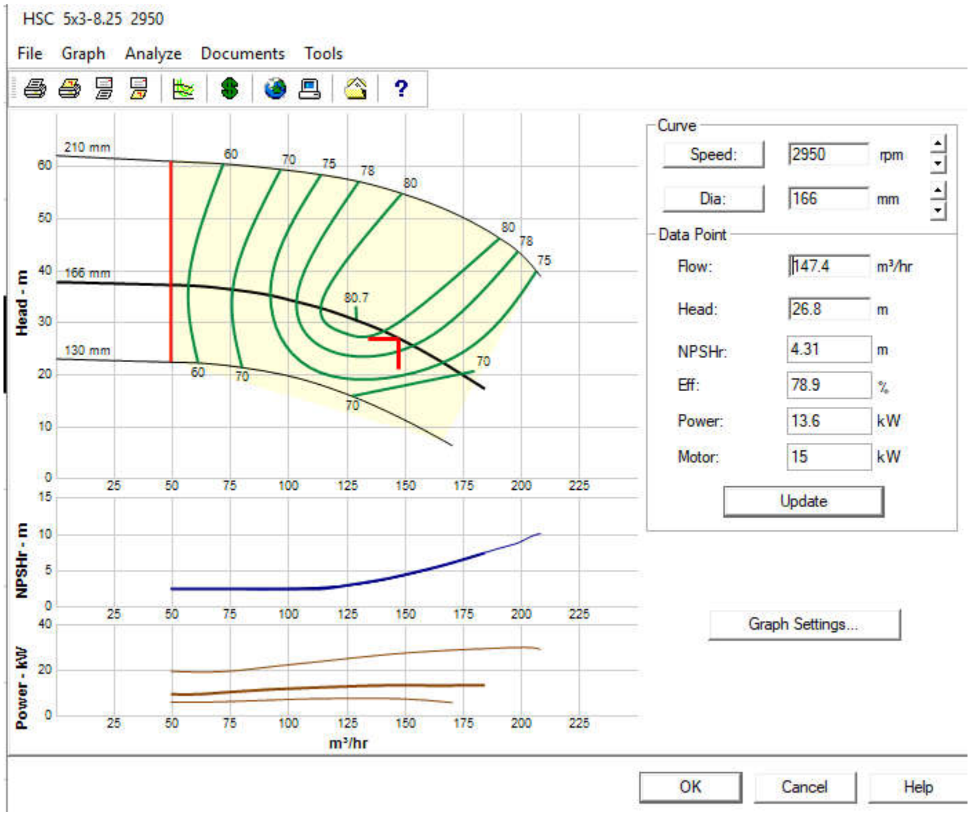
$NPSH_a$ can be calculated by using Equation D13 as follows:

$$NPSH_A = 10.1 + 6.67 - 0.0095 - 0.3$$

$$NPSH_A = 16.4m$$

<u>Choosing an efficient pump</u>

A more efficient pump has been chosen based on the duty points Q, H = (147.4 m^3/h, 26.6m) and $NSPH_a$=16.4, by using the software Pump-Flo®. A screenshot of the specification of the chosen pump from Pump Flo can be seen in Figure 6-45. The specifications of the suggested pump can be seen Table 6-40.



Speed: 2950 rpm

Dia: 166 mm

Flow: 147.4 m³/hr

Head: 26.8 m

NPSHr: 4.31 m

Eff: 78.9 %

Power: 13.6 kW

Motor: 15 kW

Figure 6-45: PumpFlo ® output for pump selection for Pump1

Table 6-40: Specifications for the chosen pump instead of Pump 1

Maker	
Best Efficiency	80.70%
BEP Flow Rate	130
BEP Head	30 m
Mechanical Power Use for BEP	13.6 kW
Electric Motor Power Rating	15 kW
Speed	2950 rpm
NPSHr	4.31
Efficiency at Design Point	78.90%
Mechanical power use at Design Point (147.4 m^3/h, 26.6m)	13.6 kW

As one can see in Figure 6-45, the chosen pump instead of Pump 1 will operate very close to its BEP point (i.e. right side of the BEP, red thick on Figure 6-45). The design point efficiency of the existing pump, Pump 1, is 43.8% and demands 24.31 kW to generate hydraulic power of 10.66 kW. On the other side, the suggested pump demands just 13.6 kW to generate the same pump work, thus, its operating point mechanical efficiency is 78.9% which is very high compared to Pump 1. While the power rating of the electric motor of Pump 1 is 30 kW, it is 15kW for the chosen pump. The next step will be to choose an electric motor. An ABB 15 kW with IE3 energy efficiency class and 93.1% efficiency is chosen as an electric motor to drive the pump. In this case, the power drawn by the electric motor will be 14.6 kW (i.e. 13.6/0.931). The corresponding ESP by using the suggested pump instead of Pump 1 and its monetary and environmental benefits are estimated in Table 6-41.

Table 6-41: ESP by replacing Pump 1 with an efficient and right size pump and electric motor

Hours (a)	**Existing Average Power Demand** (b)	**New power demand** (c)	**Difference of Power Demand** (d)	**ESP (%)** (e)	**Annual ESP** (f)	**Annual PESP** (g)	**Annual ECSP** (h)	**Annual CO_2 ERP** (i)
Measured	Measured	Calculated above in the text	d=b-c	e=c/b %	f=d*a	Equation 3-1	Equation 3-2	Equation 3-3
7,080	26.6 kW	14.6 kW	12 kW	45%	84,960 kWh	209,851.2 kWh	€5,568.2	41,630.4 kg.CO_2/year

As seen in Table 6-41, the annual ESP by replacing Pump 1 with an efficient and right size pump driven by a high efficiency electric motor is 84,960 kWh. The associated annual ECSP and annual CO_2 ERP are €5,568.5 and 41,630.4 kg.CO_2/year, respectively.

6.4.2 COOLING TOWER SYSTEM 2

6.4.2.1 DESCRIPTION

The subject plant uses a wet cooling tower, which is shown in Figure 6-46, for sand reclamation system and quenching pool. The tower is used jointly for these separate systems. Based on the plant management, there are 5 small air fans in the cooling tower. However, their specifications are not known while the power rating for each is estimated to be 1.5 kW by the plant electrician.

Figure 6-46: Cooling Tower used for sand reclamation system and quenching pool in the subject plant

As the previous chapter described, the quenching pool is used for the quenching of casting at high temperatures. High temperature castings are quenched by being submerged into a pool filled with low temperature quenching fluid (water or oil). The high heat is removed through quenching with the aid of a heat exchanger and cooling tower mechanism. The circulation between the heat exchanger and cooling tower is provided by a 37-kW circulation pump. This pump will be called as Pump 1. The heat exchanger, circulation pump, and Cooling Tower 2 can be seen in Figure 5-42 in Chapter 5.

The other user of the cooling tower is the sand reclamation system which is a mechanical type. In the sand reclamation system, the moulds are demolished after casting and the moulding sand is somewhat at high temperature which needs to be cooled to be reused. The specifications of the circulation pump and its electric motor are given in Table 6-42. This pump will be called as Pump 2.

Based on the analyses conducted in the following sections, Cooling Tower System 2 is responsible for about 73,587.8 kWh of annual energy consumption. The associated energy cost and CO_2 emissions are 4,823 kWh and 36,058 kg-CO_2, respectively.

6.4.2.2 IDENTIFYING ESPS IN COOLING TOWER SYSTEM 2

6.4.2.2.1 Analysis of the air fans

As mentioned above, Cooling Tower 2 is equipped with 5 0.75-kW-air fans. Therefore, the total power rating of the fans is 3.75 kW. The air fans run at full capacity when they are powered on. Assuming that the fans electric motor load factor is 85%, the average power drawn by the fan will be 3.18 kW (i.e. 0.85*3.5). The daily running hours for these fans are equal to daily production shifts which is 17.5 hours. Thus, the annual running hours for these fans is 5162.5 hours. Using these values, the corresponding annual energy consumption can be calculated as follows:

$$Annual\ Energy\ Consumption = P^{*}\ annual\ running\ hours$$

$$Annual\ Energy\ Consumption = 3.18\ kW * 5162.5\ hours/year$$

$$Annual\ Energy\ Consumption = 16{,}416.8\ kWh/year$$

Due to the technical and physical constraints, it was not possible to conduct power measurement on the air fans. The technical specifications of the fans are not known. Therefore, it was not possible to do an analysis to identify any ESPs.

6.4.2.2.2 Analysing Pump 1

The power rating for this pump is 37 kW. The rated head and flow characteristics are not known. Running hours for this pump is the same of that of quenching pool circulation pump (i.e. 4 hours) as they are connected to the same heat exchanger. Assuming that the electric motor of this pump will have approximately the same load factor as the quenching pool circulation pump which is 77%, it will draw about 28.5 kW (i.e. 77%*37kW). Using these values, the corresponding annual energy consumption can be calculated as follows:

$$Annual\ Energy\ Consumption = P^{*}\ annual\ running\ hours$$

$$Annual\ Energy\ Consumption = 28.5\ kW * 4\ hours/day * 295\ days/year$$

$$Annual\ Energy\ Consumption = 33{,}630\ kWh/year$$

It was not possible to do power measurement on Pump 1 due to the technical constraints and technical specifications such as rated head and flow characteristics are not available. Also, there is no pressure gauge which will give an idea about the total discharge head. Therefore, it was not possible to do an analysis to identify any ESPs on Pump 1. However, the specifications of the electric motor of Pump 1 is known as presented in Table 6-42 so that its efficiency can be assessed to identify ESP.

Table 6-42: Specifications of the electric motor of Pump 1 (Source: manufacturer`s data)

Maker	Watt Arcelik
Power rating	37 kW
Energy Efficiency Class	EFF2 (IE1)
Rated Efficiency	92%

As noted in Table 6-42, the energy efficiency class for Pump 1 is EEF2, which is an old efficiency class and corresponds to IE1 class in IEC 60034-30 classification standard as explained in Appendix B. Hence, there is an ESP by replacing the existing electric motor with premium efficiency electric motor in IE3 class.

6.4.2.2.2.1 ESP by using more efficient electric motor

The specifications of the proposed energy efficient electric motor are given in Table 6-43. Following Equation B-7 and B-8 in Appendix B, energy, environmental and monetary benefits of using more efficient electric motor have been calculated and presented in Table 6-44.

Table 6-43: Specifications of the proposed electric motor (Source: manufacturer`s data)

Maker	ABB
Power rating	37 kW
Energy Efficiency Class	IE3
Rated Efficiency	95.20%

Table 6-44: Annual ESP, PESP, ESCP, CO_2 ERP to Premium Efficiency Electric Motor

Annual ESP (a)	1196.4 kWh/year	Equation B-8
Annual Energy Use (b)	33,630 kWh/year	Calculated in Section **6.4.2.2.2**
Annual PESP (c)	2,955.10	Equation 3-1
Annual ECSP (d)	€78.4/year	Equation 3-2
ESP % (e)	3.55%	e=b/a %
Annual CO_2 ERP (€)	586.2 kg-CO_2/year	Equation 3-3

As Table 6-44 summaries, annual ESP% by using a premium efficient electric motor for the existing electric motor of Pump 1 is 3% and the associated Annual ESP, PESP, ECSP, and Annual CO_2 ERP will be 1196.4 kWh/year, €78.4, and 508.6 kg-CO_2/year, respectively.

6.4.2.2.3 Analysing Pump 2

Figure 6-47 shows the power demand of Pump 2. The average power drawn by Pump 2 during operation is 6.65 kW. The duration of Pump 2 operation in a day based on the measurement (Figure 6-47) is 12 hours. Therefore, the daily electricity consumption is 79.8 kWh and annual electricity consumption is 23,541 kWh. The specifications for reclamation system circulation Pump 2 and its electric motors are given in Table 6-45 and Table 6-46, respectively.

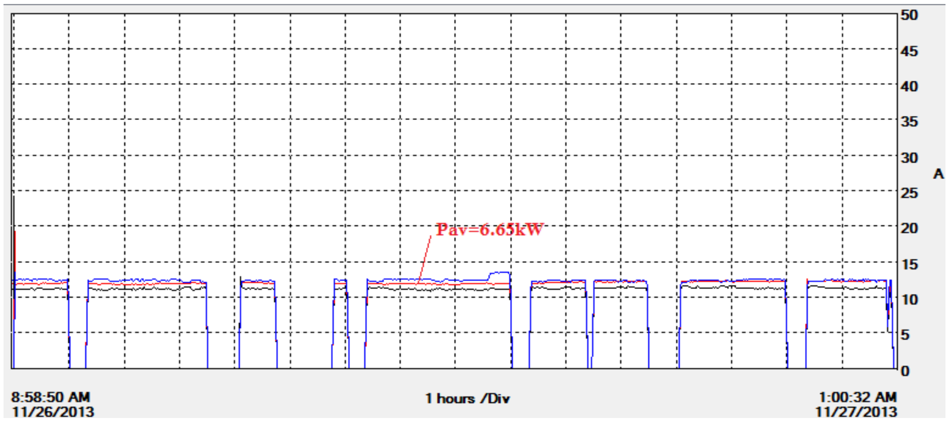


Figure 6-47: Pump 2 power demand profile

Table 6-45: Specifications for the electric motor of the reclamation system circulation (Source: Manufacturer's data)

Maker	Arcelik
Power Rating (kW)	15kW
Efficiency Class	Eff2 (IE1)
Efficiency %	91.10%

Table 6-46: Technical specifications for Pump 2 (Source: Manufacturer's data)

	Pump 1
Electric Motor Power (kW)	15 kW
Working Point Maximum Shaft Power (kW)	11.3 kW
Head (m)	40 m
Flow Rate (m^3/h)	58 m^3/h
Pump Efficiency (%)	61%

By following the steps explained in Appendix D, it will be investigated whether Pump 2 is operating efficiently or not. As seen in Figure 6-47, the average power drawn by the electric motor Pump 2 is 6.65 kW. The power transmitted to the Pump 2 is 6.06 kW based on motor efficiency is 91.1%.

Pump Duty: Flow rate (Qduty) for Pump 2

Q_{duty} can be calculated by using the affinity laws by using Equation D15 and Equation D17. P_{rating} and corresponding Q_{rating} are 15 kW and 58 m^3/h, respectively. By substituting P_{rating} and Q_{rating} into Equation D17, Q_{duty} is found as 44.22 m^3/h.

Pump Duty: Total head (Hduty) for Pump 2

The total pump head for Pump 2 can be calculated by using Equation D1.

h_d, total discharge head for Pump 2

Pump 2 has a pressure gauge at the discharge exit as can be seen in Figure 6-48. It shows the total discharge head h_d of Pump 2 when the pump is in operation. Based on the pressure gauge, the total discharge head (h_d) of Pump 2 was read to be about 2.4 bar as seen in Figure 6-48. This corresponds to 24.48-meter discharge head.

Figure 6-48 Pressure gauge for Pump 2

<u>hs, total suction head for Pump 2</u>

hs can be calculated Equation D3.

h_{ss}, suction static head:

h_{ss} for Pump 2 is 4.2m (measured by the Author during in the energy audit) as shown in Figure 6-49.

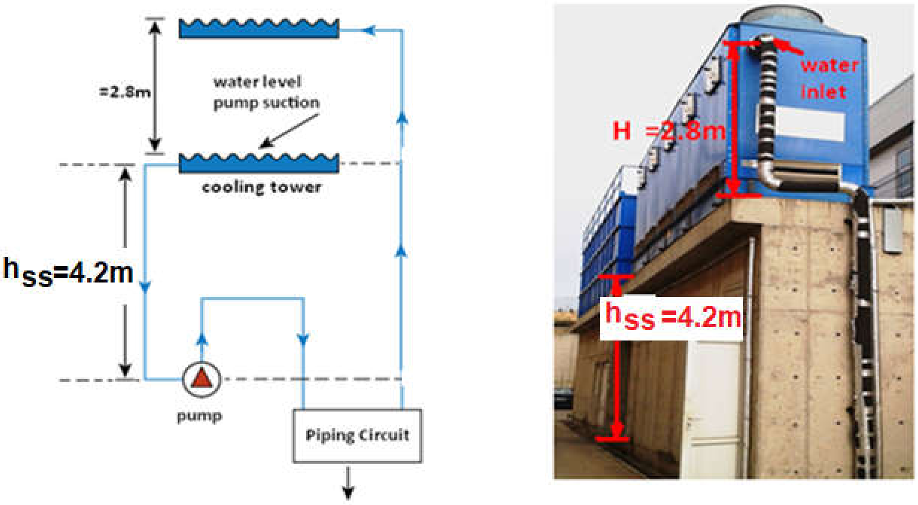


Figure 6-49: Static head for Pump 2 in Cooling Tower 2

h_{pfs}, head due to the suction pipe friction:

By using Equation D2, D3, D4, D5, and D6 in Appendix D; Re number has been found to be 207,976 which means that the flow at the suction side is turbulent. Therefore, Moody`s diagram is employed to find out the friction factor, f.

Relative roughness = ε / D

ε, relative roughness for steel pipe = 0.0000157 m

Thus,

ε / D = 0.0000157/0.09 = 0.0001744

Using ε / D and Re number, the f friction factor has been found to be 0.016. Hence, h_f, the head loss due to the pipe friction can be found by using Equation D4:

$$h_{psf} = 0.016\left(\frac{5.2}{0.09}\right)\left(\frac{1.93^2}{2x9.81}\right)$$

Suction side pump length, L=5.2m.

hf=0.09m

h_{fls}, head due to the suction pipe fitting losses:

There are 1 butterfly valve before the pump and 2 right angle turns at the suction side. The loss coefficients for butterfly valve and right-angle turn are 2 and 0.139, respectively. Using these values and water velocity in Equation D8, h_L can be estimated as follows:

$$h_{fls} = K\frac{V^2}{2g} = (2 * 0.13 + 2 * 1)\frac{1.93^2}{2 * 9.81} = 0.43\ m$$

Thus, total suction head for Pump 2 can be found as follows:

hs =- 4.2 + 0.43+0.09= -3.68m

The total pump head, H_{duty}, for Pump 2 will be the sum of h_d and h_s based on Equation D1. Thus,

H_{duty}=24.48-3.68=20.8m.

Based on the above analysis, the system duty for Pump 2 is (Q_{duty}, H_{duty})= (44.22 m^3/h, 20.8m)

Operating efficiency of Pump 2

Substituting Q_{duty}, H_{duty}, and P_{in} values estimated in the preceding subsections in Equation D14 in Appendix D;

$$\eta = \frac{44.22 * 20.81 * 998.2 * 9.81}{5.14} = \frac{2.51}{5.14} = 48.6\%$$

The operating efficiency of Pump 2 is 48.6% whereas its BEP is 61% as noted in Table 6-46. Therefore, Pump 2 is not operating efficiently. This is because the pump capacity is bigger than the duty point. As the above analysis has shown, the system duty for the pump is Q_{duty}=44.22 m^3/h and H_{duty}=20.81 m^3/h whereas the BEP system characterises are Q, H= (58 m^3/h,40 m^3/h). This is means that the pump is oversized for the application and operating inefficiently.

In light of the above analysis, it is obvious that there is an ESP by replacing the subject pump with a right size and suitable alternative for the application. In addition to this, as given in Table 9-14, the efficiency class of the electric motor of Pump 2 is EEF2 which means that there is another ESP by using more efficient electric motor.

In searching for an efficient pump by using Pump-Flo® an additional parameter, NPSHA is needed as a design input. This will be estimated in the following.

<u>NPSHa</u>

By using Equation D13 given in Appendix D, $NPSH_A$ can be calculated as follows:

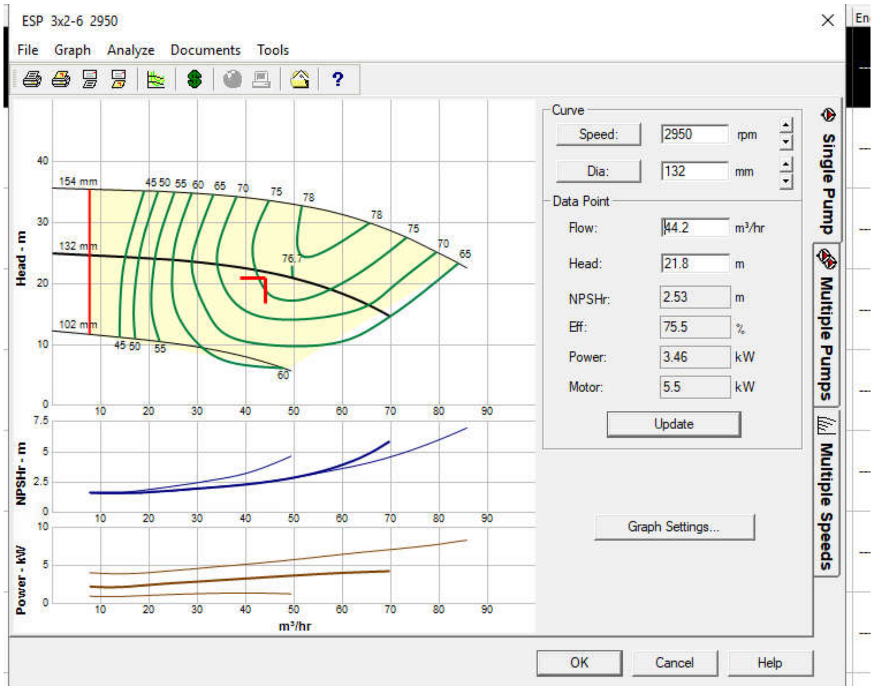
Substituting H_a = 1 atm = 1.01325 bar = 10.334 m (atmospheric pressure, because cooling tower is open to the atmosphere), H_z = 4.2 m, H_f = 0.09m, and H_{vp} = 0.234 m @20°C water:

$$NPSH_A = 10.1\text{-}4.2 + 0.09 + 0.43$$

$$NPSH_A = 6.39 \text{ m}$$

<u>Choosing an efficient pump</u>

A more efficient pump has been chosen based on the operating design points Q, H = (44.22m3/h, 20.81) and NSPHa=6.39, by using the software Pump-Flo®. The pump curve and specifications of the suggested pump can be seen in Figure 6-50 and Table 6-47, respectively.



Curve

Speed: 2950 rpm

Dia: 132 mm

Data Point

Flow: 44.2 m³/hr

Head: 21.8 m

NPSHr: 2.53 m

Eff: 75.5 %

Power: 3.46 kW

Motor: 5.5 kW

Figure 6-50**:** PumpFlo® output for pump selection for Pump 2

Table 6-47 : Specifications of the chosen more efficient pump instead of Pump 2

Maker	
Best Efficiency	76.70%
BEP Flow Rate	50 m^3/h
BEP Head	20m
Mechanical Power Use for BEP	4.14
Electric Motor Power Rating	5.5 kW
Speed	2950 rpm
$NPSH_r$	2.53
Efficiency at Duty point	75.75%
Mechanical power use at duty point (44.2 m^3/h, 21.8m)	3.46 kW

As one can see in Figure 6-50, the chosen pump instead of Pump 2 will operate at very close its BEP point. As seen in 9-15, the BEP of the suggested pump is 76.7 % whereas the efficiency at the duty point (44.2 m^3/h, 21.8m) is 75.75%. The duty point efficiency of the exiting Pump 2 is 48.7% using 5.14 kW to produce 2.51 kW of mechanical energy. The suggested pump uses only 3.46 kW to produce the same amount of mechanical energy.

The next step will be to choose an electric motor. An ABB 5.5 kW with IE3 energy efficiency class and 89.2% efficiency is chosen as an electric motor to drive the pump. In this case, the power drawn by the electric motor will be 3.88 kW (i.e. 3.46/0.931). The associated ESP by using the suggested pump instead of Pump 1 and its monetary and environmental benefits are estimated in Table 6-48.

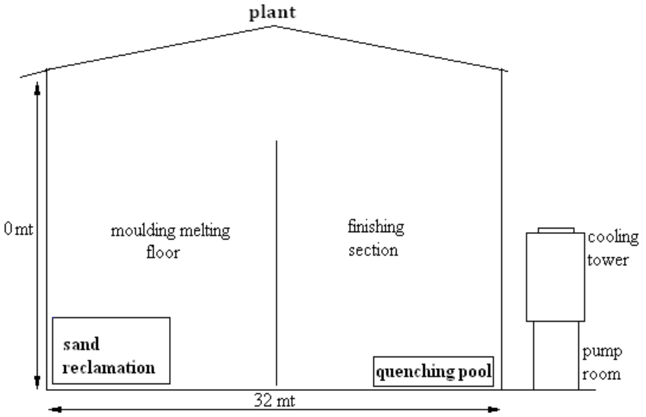
Table 6-48: ESP by replacing Pump 2 with an efficient and right size pump and electric motor

Annual Operating Hours (a)	Existing Average Power Demand (b)	- New Power Demand (c)	Difference of Power Demand (e)	%ESP (f)	Annual ESP (g)	Annual PESP (h)	Annual ECSP (i)	Annual CO_2 ERP (j)
measured	measured	calculated in the text above	d=b-c	e=d/b%	f=d*a	(Equation 3-1)	(Equation 3-2)	(Equation 3-3)
3,540 hours	6.65 kW	3.88 kW	2.77 kW	41.6	9805.8 kWh	24,220.32 kWh	€42.6	4,804.8 kg.CO_2

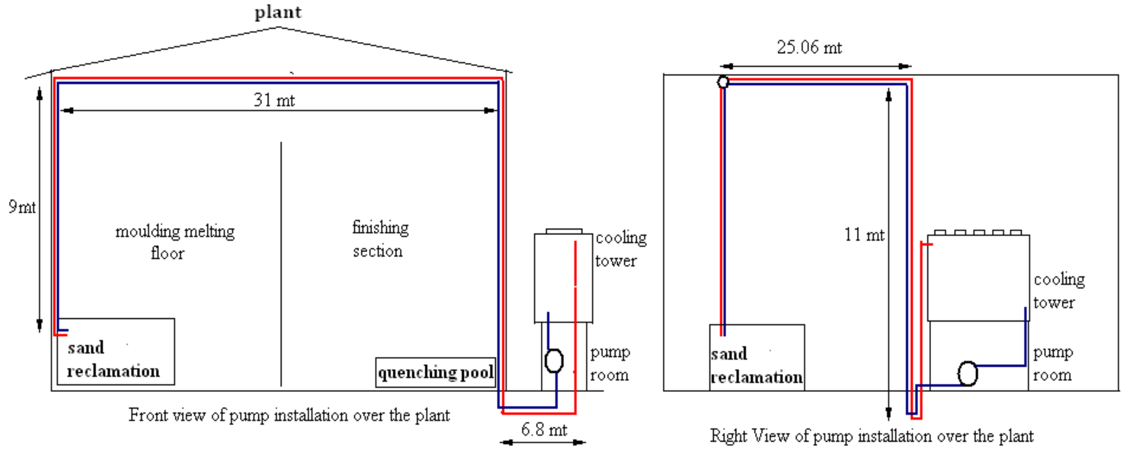
6.4.2.2.3.1 Energy efficiency aspects in Pump 2 piping design

In this subsection, poor piping of Pump 2 in Cooling Tower 2 and energy efficiency aspects related to it will be discussed based on the Author`s observations during the energy audit.

Figure 6-51 shows the pumping location of the cooling tower. As seen, the cooling tower is located close to the quenching pool. This is an advantage in terms of the quenching pool since less piping will be required resulting in less work for the pipe head losses. But, in terms of the sand reclamation system, as seen in Figure 6-51, this is in the contrary since the system is located with the possible maximum horizontal distance to the cooling tower. Due to the functional layout of the plant, quenching pool and sand reclamation system cannot be located in similar location for just cooling tower. However, a small cooling tower could be located to the other side of the plant close to the sand reclamation system as demonstrated in Figure 6-52. Considering the fact that the existing cooling tower has somewhat bigger capacity than what the sand reclamation system needs – this was because it is designed to serve for quenching pool (of which cooling requirement is quite bigger than sand reclamation) - a smaller cooling tower to be located close to the sand reclamation system would have been more efficient. This is because the pipe losses due to the long pipes, elbows and joints would be eliminated. As seen in Figure 6-51, the pipes for sand reclamation system is travelling both vertically and horizontally from one side to another side of the plant. After cooling tower, the pipes go 6.8 m from on the plant ground and 11m vertically up, then 25.06 m horizontally left, then 31 m horizontally towards to sand reclamation system and 9 m vertically down and finally arrive in sand reclamation system. After cooling the sand, it follows the same way back to the cooling tower. In total, the fluid has to travel 165.72 m. Not to mention the elbows and fittings. All these mean frictions between fluid and pipe walls and losses and additional head onto the pump which has to be chosen bigger size and result in waste of energy and high initial investment.

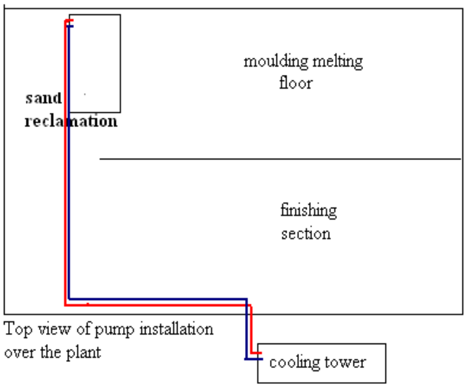


Front View of location of cooling tower and sand reclamation system in the plant



Front view of pump installation over the plant

Right View of pump installation over the plant



Top view of pump installation over the plant

Figure 6-51: Pumping installation of the cooling tower of sand reclamation system

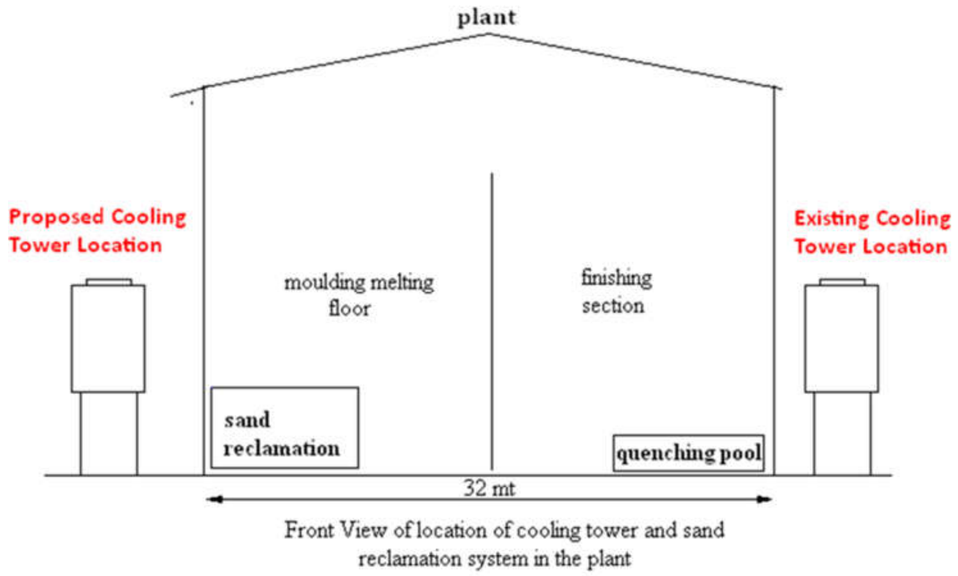


Figure 6-52: Proposed location for the cooling tower of the sand reclamation system

In addition to the above points, during the audit, it has been observed that the piping design of the system is very poor. The pipefitter of the plant had used sharp right-angled turns very often although it was possible to avoid it. Right angle turns lead to significant friction as in the case with long pipes discussed above. Figure 6-53, Figure 6-54, and Figure 6-55 show example of right angle turns in the cooling tower pump pipe instalments although they were avoidable as shown in the Figures.

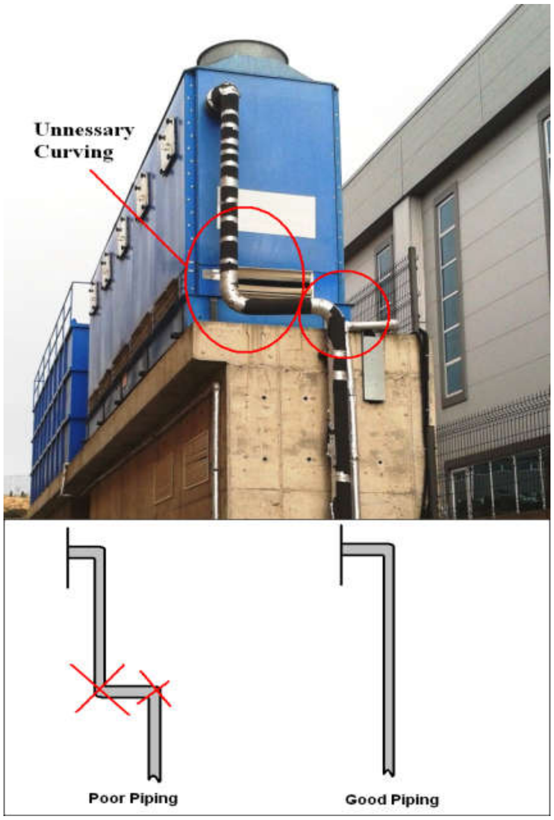


Figure 6-53: Example of poor piping design in the subject plant

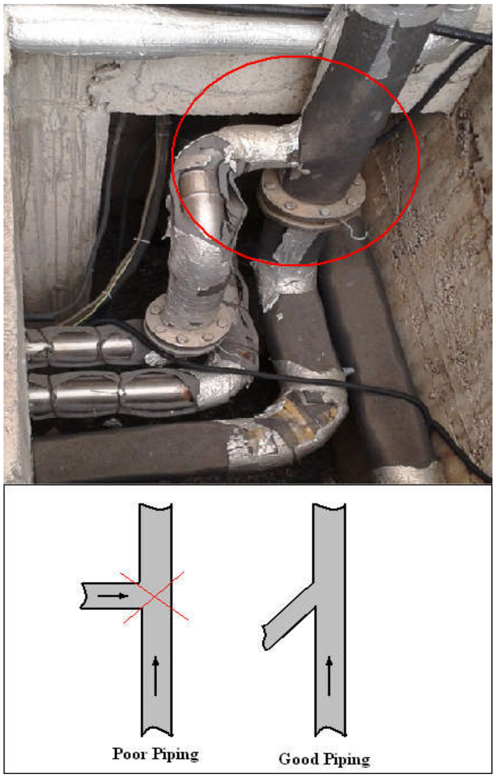


Figure 6-54: Example of poor piping design in the subject plant

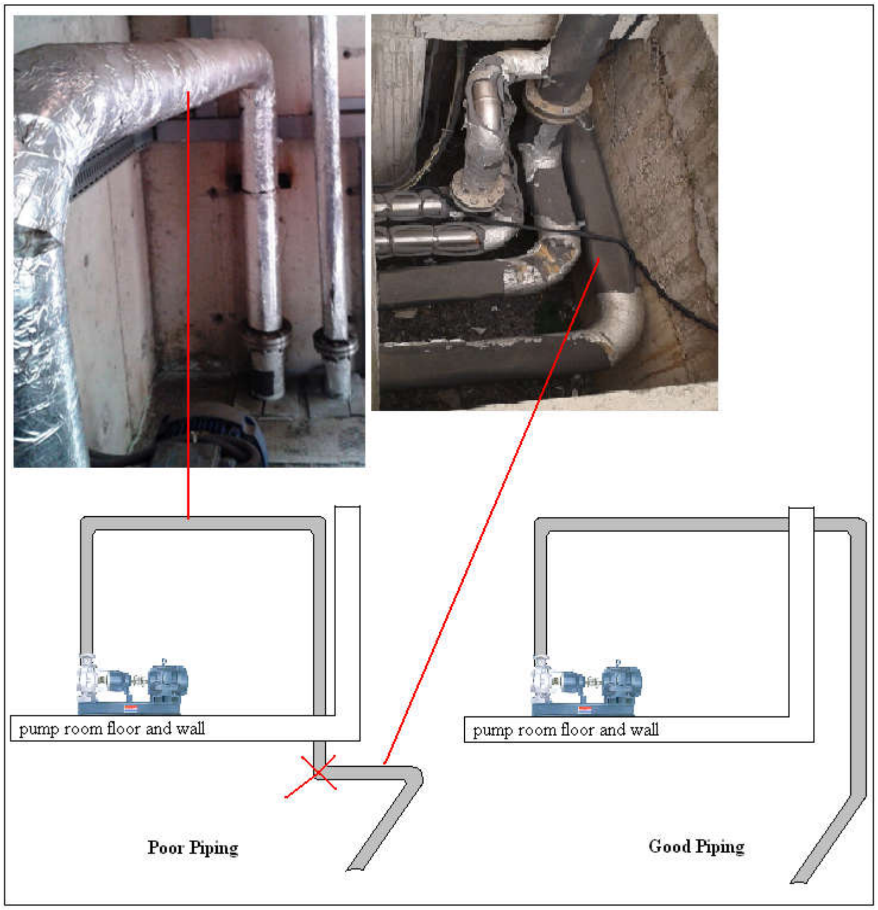


Figure 6-55: Example of poor piping design in the subject plant

From the standpoint of energy efficiency, these are the example of poor piping. Pipes in a pumping system should be short and fat and turns of pipes should have a geometry which will minimise friction rather than right angle geometry. If right angle turns are not avoidable, then they should be as smooth as possible.

The above issues have been discussed with the plant personnel and they stated that the pipes are somewhat cheap material and there was no hesitation to do long piping. As for the right angle turns, they stated that the plant manager asked them to do piping in such way which looks as esthetical as possible and for this reason the pipefitter laid the pipes in a way which followed the crooks of ground they laid on. Also, it was learnt that the pipefitters did not aware of the above-said losses as they were not trained as required.

6.4.3 OVERALL REVIEW OF THE ESPS IDENTIFIED IN THE COOLING TOWERS

There have been identified 5 ESPs. Namely:

- ESP 6-10, ESP by Using VFD For the Cooling Tower Air Fan in Cooling Tower 1
- ESP 6-11, ESP by Replacing Pump 2 System in Cooling Tower 1 With an Efficient Pump and Premium Efficiency Electric Motor
- ESP 6-12, ESP by Replacing Pump 1 System in Cooling Tower 1 with an Efficient and Right Size Pump and Electric Motor
- ESP 6-13, ESP by Replacing the Existing Electric Motor of Pump 1 System in Cooling Tower 2 with Premium Efficiency Motor
- ESP 6-14, ESP by Replacing Pump 2 System in Cooling Tower 2 With an Efficient and Right Size Pump and Premium Efficiency Motor

These ESPs and are summarised and documented in Table 6-49 below. If the all ESPs are materialised, the total annual ESP is 162,076.6 kWh per year. The associated annual PESP, annual ESCP, and annual CO_2 ERP are 400,329 kWh, €10,622.5, and 79,417.4 kg-CO_2, respectively.

Table 6-49: ESPs identified in the cooling tower systems of the subject plant

ESP No:	**ESP Measure**	**EPS (%)**	**Annual ESP (kWh/year)**	**Annual PESP (kWh/year)**	**Annual ECSP (€/year)**	**Annual CO2 ERP (kg-CO_2/year)**
6-10	ESP by using VFD for the cooling tower air fan in Cooling Tower 1	53%	31,478.50	77,751.90	2,063	15,424.45
6-11	ESP by replacing Pump 2 system in Cooling Tower 1 with an efficient pump and premium efficiency electric motor	21.50%	34,692	85,689.24	2,273.71	16,999.08
6-12	ESP by replacing Pump 1 system in Cooling Tower 1 with an efficient and right size pump and electric motor	45%	84,960	209,712.14	5,568.20	41,630.40
6-13	ESP by replacing the existing electric motor of Pump 1 system in Cooling Tower 2 with premium efficiency motor	3.50%	1,196.40	2,955.11	78.41	586.24
6-14	ESP by replacing Pump 2 system in Cooling Tower 2 with an efficient and right size pump and premium efficiency motor	42%	9,806	24,220.50	643	4804.9

Overall ESPCoolingTowers	39.60%	162,076.60 kWh	400,329 kWh	€ 10,622.50	79,417.40

6.5 LIGHTING SYSTEM

6.5.1 DESCRIPTION OF THE LIGHTING SYSTEM

Lighting system for the case plant is an important production support process. It is responsible for approximately 53,633.07 kWh of electricity consumption in a year based on the power measurements conducted in the energy audit. As well as for economic and environmental considerations, the lighting system is important for providing required illuminance to the workers.

In the subject plant, the lighting system exists in three main premises: foundry floor; basement floor where machine shop, storages, and model making room are located; and offices. The office lighting consumes a very small percentage of the total energy consumption of the overall lighting system. This is because there are around 3-4 rooms of offices with southward-facing windows and make the most of natural lighting. Besides, the lighting system in hallways, toilets, and stairs where occupancy is infrequent are controlled with occupancy sensors and thus unnecessary lighting is prevented and energy is saved. The major energy consumer for the lighting system of the basement floor is the machine shop because it is the most occupied area while other sections such as storages and model making room are used very rarely. Also, the foundry floor is also a major energy consumer for lighting because of the larger floor area lighted up by large number of lighting bulbs.

As a result, the energy audit for the lighting systems is focused on the machine shop and foundry sections which will be described in the following sections.

6.5.2 IDENTIFYING THE ENERGY SAVING POTENTIALS IN THE LIGHTING SYSTEMS

The subject plant uses Compact High Intensity Discharge (HID) lamp type for lighting requirement of the foundry floor, which consists of two main sections: melting shop and finishing section. HID lamps produce light by discharging an electric are through a tube filled with gases as in fluorescent lamps (Doty and Turner, 2012). They have relatively high efficacies and long lamp lives which reduces maintenance and re-lamping costs (Doty and Turner, 2012). Figure 6-56 shows the HID lamp used in the foundry floor and the specification of the lamp are given in Table 6-50. There are also task specific lightings in grinding stations and fluorescent lamps in the core production unit in the finishing section. But, these lamps will not be considered for energy saving purposes because they are small in number.

Figure 6-56: HID lamp used in the foundry floor (Photo taken by the Author)

Table 6-50: Specifications for the HID lamp used in the foundry floor (Source: Product datasheet)

Brand	MASTER Colour CDM-T 250W/830 G12 1CT
Light bulb power (LBP)	271 W
Lamp voltage	95 V
Lamp current	2.99 A
Luminous efficacy (LE)	111 Lm/W
Luminous flux (LFX)	27541 Lm
Energy consumption (kWh/1000 hour)	273 kWh
Energy efficiency label	A+

Although there is a great opportunity for daylighting through the plant roof, as shown in Figure 6-57 unfortunately this was not exploited at the design stage of the plant. Fully electric lighting was preferred in the plant. As seen in Table 6-50, the energy efficiency label for the lamp used in the foundry floor is A+. This is the most energy efficient class based on the EU Commission Regulation No. 874/2012 (EU, 2012) and other classes are shown in Table 6-51. Therefore, ESP will not be sought for replacing this lamp with a more efficient one. However, there is a great potential of energy saving by using daylight to illuminate the foundry floor. Daylighting is left to the consideration of the following sections.

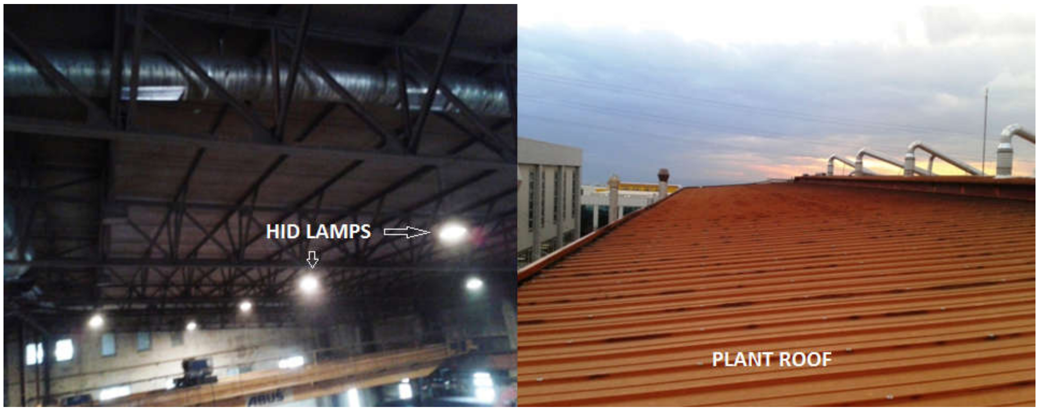
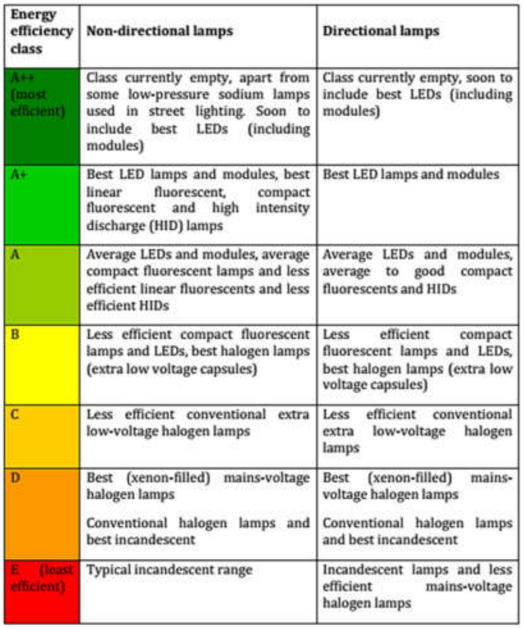


Figure 6-57: No daylighting in the subject plant

Table 6-51 Energy efficiency classes for lighting lamps in EU Commission Regulation with regard to energy labelling of electrical lamps and luminaries (EU, 2012)



Energy efficiency class	Non-directional lamps	Directional lamps
A++ (most efficient)	Class currently empty, apart from some low-pressure sodium lamps used in street lighting. Soon to include best LEDs (including modules)	Class currently empty, soon to include best LEDs (including modules)
A+	Best LED lamps and modules, best linear fluorescent, compact fluorescent and high intensity discharge (HID) lamps	Best LED lamps and modules
A	Average LEDs and modules, average compact fluorescent lamps and less efficient linear fluorescents and less efficient HIDs	Average LEDs and modules, average to good compact fluorescents and HIDs
B	Less efficient compact fluorescent lamps and LEDs, best halogen lamps (extra low voltage capsules)	Less efficient compact fluorescent lamps and LEDs, best halogen lamps (extra low voltage capsules)
C	Less efficient conventional extra low-voltage halogen lamps	Less efficient conventional extra low-voltage halogen lamps
D	Best (xenon-filled) mains-voltage halogen lamps Conventional halogen lamps and best incandescent	Best (xenon-filled) mains-voltage halogen lamps Conventional halogen lamps and best incandescent
E (least efficient)	Typical incandescent range	Incandescent lamps and less efficient mains-voltage halogen lamps

6.5.2.1 EXISTING PERFORMANCE OF FOUNDRY FLOOR LIGHTING SYSTEM

In order to find the baseline power consumption for foundry floor lighting system, power consumption measurement was carried out. Because the power boxes for the lamps of melting section and finishing section are separated, power measurement was conducted separately for these two sections at 1 second intervals for a typical day and night production shift. Figure 6-58 and Figure 6-59 show demand profile for the melting shop section and finishing section, respectively.

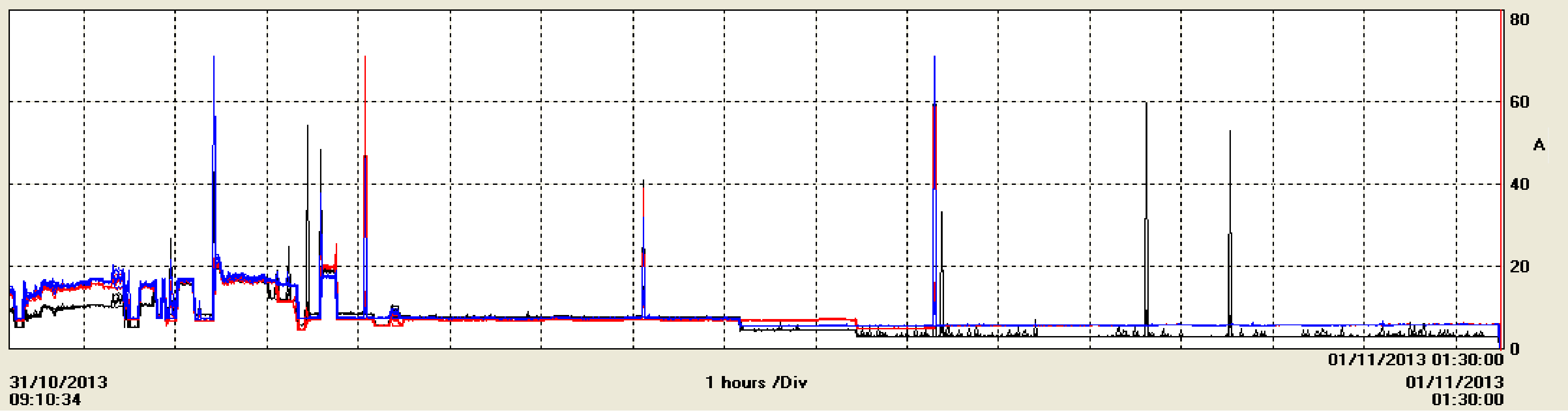


Figure 6-58: Melting Shop Section lighting power demand for typical day and night production shift

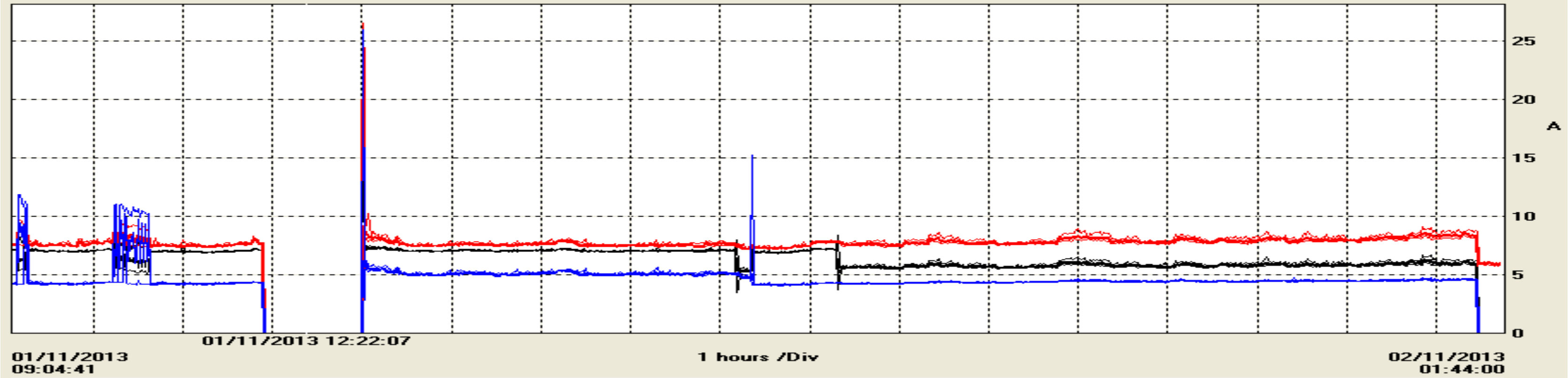


Figure 6-59: Finishing Section lighting power demand for typical day and night production shift

The daily energy consumption can be calculated by using the following equation:

$$\text{Energy consumption} = APD * hours * NS$$

(Eq. 6-20)

where; APD is average power demand (kW). hours is number of hours in a production shift. NS is number of production shifts in a day.

The APDs for Melting Shop Section Lighting System and Finishing Section Lighting System was measured to be 5.09 kW and 4.30 kW, respectively. The number of hours and NS for both sections are 8.75 and 2, respectively. Using these values in Equation 6-20, the daily energy consumption for both section can be calculated as follows.

Daily energy consumption for Melting Shop Section Lighting System

$$\text{Energy consumption} = 5.09 * 8.75 * 2 = 89.092 \text{ kWh / day}$$

Daily energy consumption for Finishing Sectionn Lighting System

$$\text{Energy consumption} = 4.30 * 8.75*2 = 75.39 \text{ kWh/day}$$

The average number of light bulbs (ANLB) used per day in each section can be estimated by dividing the APD by LBP as expressed as follows:

$$ANLB = APD / LBP$$

(Eq. 6-21)

where; LBP is the power demand of a light bulp.

The APD for Melting Shop Section and Finishing Section are 5.09 kW and 4.30 kW, respectively, as calculated above. The LBP for the HID lighting used in the foundry floor is 0.271 kW as given in Table 6-50. Using these values in Equation 6-21, the ANLBs for Melting Shop Section and Foundry Section can be estimated as follows.

APD for Melting Shop Section Lighting System

$$ANLB = 5.09/0.271$$

$$ANLB = 18$$

APD for Finishing Section Lighting System

$$ANLB = 4.3/0.271$$

$$ANLB = 14$$

The daily energy consumption and APD values for Foundry Floor Lighting system are summarised in Table 6-52 together with the values of other key parameters.

Table 6-52: Power and Energy consumption of foundry floor lighting system

Melting Shop Section- Lighting System	
Average power demand	5.09 kW
Hours in a production shift	8.75 hours
Number of shifts in a day	2
Energy use per day	89.092 kWh / day
Average light bulb used per day	18
Finishing Section- Lighting System	
Average power demand	4.30 kW
Hours in a production shift	8.75 hours
Number of shifts in a day	2
Energy use per day	75.39 kWh/day
Average light bulb used per day	14

From Table 6-52 the lighting system daily electricity consumption for Melting Shop And Finishing Section are 89.092 kWh and 75.39 kWh, respectively, which together make an overall daily electric consumption of 164.482 kWh for the Foundry Floor Lighting System. This is the baseline electric energy consumption of the Foundry Floor of the subject plant with the present electric lighting system. The Foundry Floor lighting systems annual energy consumption, corresponding energy cost and CO_2 emissions are summarised in Table 6-53 below.

Table 6-53: Calculatios for foundry floor lighting systems annual energy consumption, and corresponding energy costs and CO_2 emission

		Source/calculation /equation
Annual working days (a)	295 days	
Daily energy consumption of Melting Shop Section (b)	89.092 kWh	
Daily energy consumption of Finishing Section (c)	75.39 kWh	
Daily total energy consumption of Foundry Floor (d)	164.482 kWh	d=b+c
Annual energy consumption of Foundry Floor (e)	48,522.2 kWh	e=d*a
Annual primary energy consumption of Foundry Floor (f)	119,849.8 kWh	f=e*PECF
Annual energy cost of Foundry Floor (g)	€3178.2	h=c*EUCR
Annual CO_2 emission of Foundry Floor (i)	23,727.35 kg-CO_2	i=c*CO_2 EF

As calculated and presented in Table 6-53, the annual lighting system energy consumption in the Foundry Floor is 48,522.2 kWh/year. The associated annual primary energy consumption, annual energy cost, and annual CO_2 emissions are 119,849.8 kWh, €3178.2, and 23,727.35 kg-CO_2, respectively.

As mentioned previously, using daylighting to provide illuminance to Foundry Floor will be investigated as an energy saving measure. Before doing that, lighting system design basics will be addressed in the following section to provide a basis for the evaluation of daylighting energy saving measure.

6.5.2.2 LIGHTING SYSTEM DESIGN BASICS

While reducing the energy consumption of a lighting system, some issues are of importance to consider. These are the two objective of the lighting system design: 1) provide the right quantity (level) of light, and 2) provide the right quality of light (Turner and Doty, 2008). Any lighting system such as daylighting to be introduced into the lighting system of a plant should satisfy these two objectives.

6.5.2.2.1 Lighting level

Lighting level refers to th e amount of light provided to a space (Turner and Doty, 2008). It is of importance that lighting system should provide appropriate level of light into a work plane for worker safety and productivity. The output of a lamp or lighting system is expressed in lumens and describes how much light is produced by the lighting system (Turner and Doty, 2008). Lighting amount that actually reaches the work plane is expressed in foot-candles (fc) (Turner and Doty, 2008). The ratio of lighting output to power input is defined as efficacy and shows the performance of a lighting system as given by the following (Turner and Doty, 2008):

$$efficacy = \frac{lighting\ output}{power\ input} \quad \left(\frac{lumen}{watt}\right)$$

Eq.6-22

Keeping the power input the same, lighting systems with higher lumens will have higher efficacy and thus higher performance.

6.5.2.2.2 Lighting quality

Lighting quality can be expressed by four main aspects: uniformity; glare; colour rendering index (CRI); and coordinated colour temperature (CCT) (Turner and Doty, 2008). Uniformity basically refers to how evenly the lighting level is distributed over an area and this can be easily achieved through evenly positioning of lamps. Glare can be defined as a sensation caused by relatively bright objects in a worker`s field of view and this can create discomfort and reduce the productivity of a worker in a plant (Turner and Doty, 2008). Glare can occur if a too much bright object has a dark background. This is difficult to observe in an industrial plant environment as the lighting is achieved through high bay lighting and there is no direct bare lamp in the worker`s field of view. CRI and CCT are colour related elements of lighting quality. They have critical influence on maintaining an appropriate lighting quality (Turner and Doty, 2008). CRI provides an evaluation of how colours appear under a given light sources while CCT describes the colour of light sources and it is indicated by a temperature scale (degrees Kelvin) (Turner and Doty, 2008). CRI index range is from 0 to 100 (Turner and Doty, 2008). As the CRI value of a light source increases, it is easier for human eye to accurately distinguish the colours (Sharp et al., 2014). Therefore, it is of importance to provide a light source with high CRI for workers.

In result, a lighting system should provide sufficient level of light as well as sufficient quality of light. These two factors will be borne in mind in the daylighting feasibility in the following sections.

6.5.2.3 DAYLIGHTING

Daylighting can be defined as (IES, 2013) "*The art and practice of admitting beam sunlight, diffuse skylight and reflected light from exterior surfaces into a building to contribute to lighting requirements and energy savings through the use of electric lighting control.*"

In other words, it is the introduction of natural light into interior spaces (Sharp et al., 2014) and saving of electric energy and energy cost by avoiding the use of electric lights. Reduction of energy use will reduce the energy associated environmental emissions. Also, when electric lighting bulbs are used, they have to be replaced regularly as they burn out. Compared to lighting bulbs, daylighting devices (e.g. skylight panels) require very little maintenance and replacement (sometimes no replacement) costs over their life cycles. Thus, daylighting devices have lower life cycle costs in comparison to electric lighting bulbs.

Besides the above-said monetary and environmental aspects, daylighting benefits have another dimension: health and productivity. It makes a workplace more a psychologically positive and comfortable thereby provides a workplace more efficient and healthier (Sharp et al., 2014). "Studies have shown that worker productivity increases with access to an outdoor view with the general reason being that the mood of the worker is better (Edwards and Torcelini, 2002)." According to Edwards and Torcelini (2002) productivity increases from 5% to 16% when daylight or natural light was used in an office environment. Work productivity is particularly important for an industrial plant in terms of profitability (Balzli and Wagner, 1998).

6.5.2.3.1 Daylighting devices

Daylighting systems can be divided into three main groups: skylights, tubular daylighting devices (TDDs) and solar collectors and solar concentrators (IES, 2013). Skylights are a very common way to introduce daylight into interior spaces and are ideal for sites with open area between the fenestration point and the space to be lit (DiLaura et al., 2011; Sharp et al., 2014). TDDs capture and convey daylight into the space to be lit through a tube or pipe (DiLaura et al., 2011) and they are a better option when lighting small interior rooms with high attics that is not conductive to traditional skylight installations (Sharp et al., 2014). Some interior spaces cannot have a direct access to the outside through a roof or window. Solar concentrators and collectors are the best solution for these spaces with no accesses to outside. These devices can capture the light from the outside and transfer into the places via pipes or fibre optic cables and distributes by diffusion fixtures (Sharp et al., 2014).

Within the above explanations, the most convenient way of utilising daylight in terms of industrial plants where high bay lighting is used is skylights. An example of daylighting via skylights in an industrial plant the author visited is shown in Figure 6-60. As seen, the plant interior space is a wide-open area and separated from outside by the plant roof and there is, therefore, no need for a complicated daylighting system such as TDDs or solar concentrators and collectors. This case is the same for the subject plant as seen in Figure 6-57. Therefore, skylights will be used as daylighting devices for the subject plant.

Figure 6-60: Daylighting via skylights in Gurdesan, Turkey (Photo taken by the Author)

6.5.2.3.2 Lighting level and quality consideriations in daylighting

The sun produces a broad spectrum of light with adequate wavelengths for most people to distinguish most colours (Sharp et al., 2014). The sun light has a CRI of 100 which is good for human eye as explained earlier and a CCT of around 5000K (DiLaura et al., 2011).

“The psychological aspect of lighting combined with proper light levels, an adequate spectrum of light, and a proper photopic characteristics all work together to facilitate humans to fully and effectively function in interior spaces. While improving the colour characteristics and usage of electrical lighting can help attain these goals, daylighting is the most direct and most effective way to provide improvement in lighting energy consumption, a full light spectrum, and outdoor view (Sharp et al., 2014)”.

6.5.2.4 ESP BY USING A DAYLIGHTING SYSTEM FOR THE FOUNDRY FLOOR

The daylight benefits were described as energy saving, reduction of associated environmental emissions and productivity benefits of worker wellbeing. These benefits should be considered in a feasibility analysis. While energy saving, and emission reductions are tangible and quantifiable, it is difficult to quantify the productivity gains. Therefore, only energy savings and emissions reductions will be considered and quantified in this analysis.

As discussed previously, the skylights daylighting system should meet the required lighting level in the plant. This is of important in terms of health and safety considerations. Therefore, the following section will first determine the required internal lighting level.

6.5.2.4.1 Internal lighting level

To determine the required internal lighting level (baseline lighting level) on the foundry floor of the subject plant, the lighting levels with the existing HID lamps can be used. To do this, foundry floor dimensions, luminous flux of the existing HID lamps, and average lamp numbers used per day required to be used. The average lamp numbers used per day for each section was presented in Table 6-52. The geometric dimensions of the foundry floor are shown in Figure 6-61.

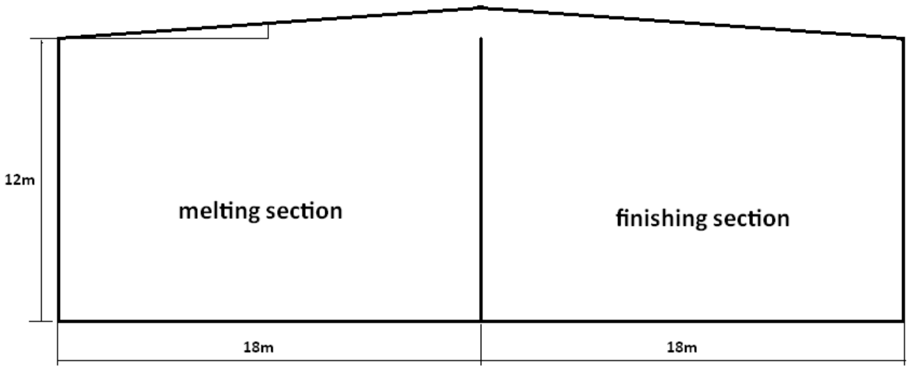


Figure 6-61 Plant geometry and dimensions

There are 36 fixtures in total with each fixture having 1 HID lamp. However, the ANL used per day is 18 for Melting Shop Section and 14 for Finishing Section in a typical day and night production shift as shown in Table 6-52. The lighting output (luminous flux) of a HID lamp used in the plant is 27,540 Lm (Table 6-50). Thus, the total luminous flux (TL) by the lamps over the work floors will be LFX of a lamp multiplied by ANL used per day. This can be expresed as follows:

$$TLFX= LFX*ANL \tag{Eq. 6-23}$$

Using Equation 6-23, TLFX for Melting Shop Section (TLFX_meltingsection) and TLFX for Foundry Floor (TLFX_finishingsection) can be calculated as follows:

TLFX for Melting Shop Section Lighting System

$$TLFX\_meltingshopsection =27540 * 18 = 495720 \text{ Lm}$$

TLFX for Finishing Section Lighting System

$$TLFX\ \_finishingsection = 27540 * 14 = 385560\ Lm$$

The total work floor area (WFA) for both melting and finishing (considering that the width and length of each work floors are 18m and 72 m) can be calculated as follows:

$$WFA = width * length = 18*72 = 1296\ m^2$$

The LFX per m^2 will be TLFX divided by WFA as expressed as follows:

$$TLFX/m^2 = TLFX\ /WFA \tag{6-24}$$

Using Equation 6-24, TLFX/m^2 for Melting Shop Section and TLFX/m^2 for Finishing Floor can be calculated as follows:

TLFX/m^2 for Melting Shop Section Lighting System

$$TLFX\_meltingshopsection/m^2 = 495720Lm\ /1296\ m^2$$

$$TLFX\_meltingshopsection/m^2 = 382.5\ Lm/m^2$$

TLFX/m^2 for Finishing Section Lighting System

$$TLFX\_finishingsection/m^2 = 385{,}560\ Lm\ /1296\ m^2$$

$$TLFX\_finishingsection/m^2 = 297.5\ Lm/m^2$$

Hence, the skylight to be used should achieve a target of lighting output of 297.5 Lm/m^2 for Finishing Section and 382.5 Lm/m^2 for Melting Shop Section. After determining the required lighting level, the lighting output which can be produced by the skylights in the region where the plant is settled has to be determined. The light output of the skylight is directly related to the external illuminance from the solar radiation and will show some seasonal and daily variation. Due to this variance, daylight might sometimes be insufficient to meet the required lighting level for the work plane. In these cases when the daylight is insufficient, a combination of daylight and electric light can be used together to achieve the target lighting level. Such an integrated system can be called as **Hybrid Daylighting System**. In order to find out the number of hours which daylight can satisfy the target lighting level, the lighting levels produced by daylighting via skylights should be determined. To determine this, LightSim daylighting analysis software developed by the University of Dayton IAC will be used.

6.5.2.4.2 Lightim software

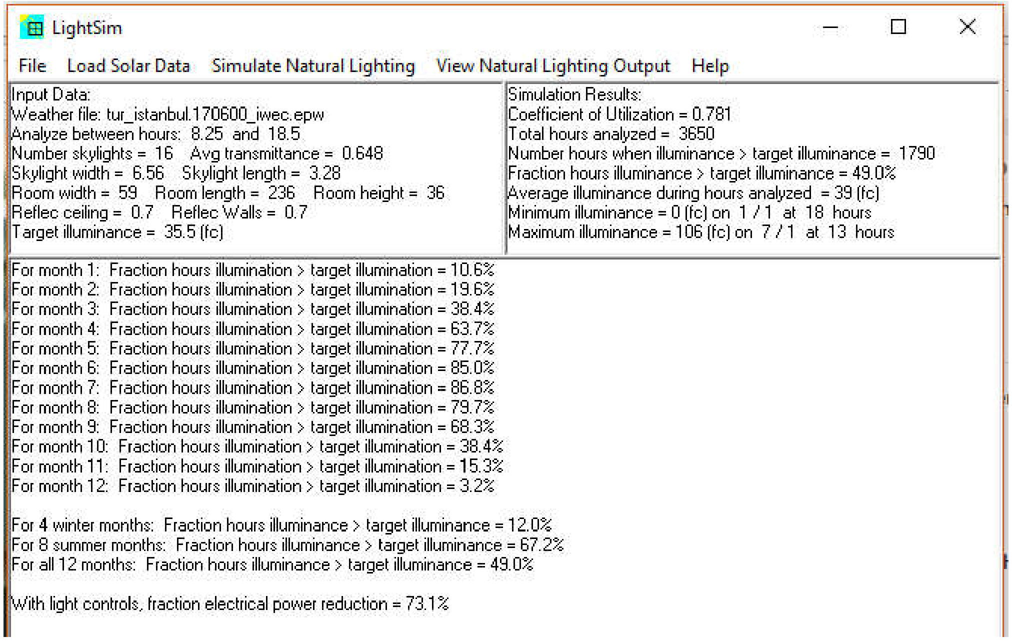
LightSim simulation software utilizes the Hay, Davies, Klucher, Reindle (HDKR) method to calculate the total solar radiation on a tilted surface (Kissock, 2004). The HDKR method estimates the solar radiation based on location, time and measured total solar radiation and can use typical meteorological data sets (e.g. EPW, TMY2, IWEC) as input to account for a typical cloud conditions at a given locations (Kissock, 2004). By this means, the sky conditions such as clear, partly cloudy, or overcast are taken into account and more accurate solar radiation estimation is executed. LightSim then calculates the solar illuminance from the total solar radiation by using a solar luminous efficiency of 94.2 lm/W (Kissock, 2004). From these solar illumination values, LightSim estimates the interior lighting levels by using the IES Lumen Method (Kissock, 2004). LightSim simulates hour-by-hour lighting levels on a work floor from daylighting using EPW (energy plus whether) meteorological data Based on the simulated lighting levels, LightSim can estimate the fraction of time that the specified daylighting design can meet or exceed a target lighting level on a work floor (Kleinhenz et al., 2007). As an input to the LightSim, EPW meteorological data for Istanbul downloaded from www.eren.doe.gov is used. Other data required by the software are given in Table 6-54.

Table 6-54: Data input to Lightsim

Plant length	72 m (236 ft)
Plant width	18 m (59 ft)
Height above work plane	11 m (36 ft)
Ceiling reflectivity	0.7 (Kleinhenz et al., 2007)
Wall reflectivity	0.7 (Kleinhenz et al., 2007)
Skylight dimensions (w, h)	1 m, 2 m (3.28 ft, 6.56 ft)
Skylight solar transmittance	0.72 (supplier)
Simulation hours	From 08:15 to 18:30
TLFX_meltingshopsection	382.5 Lm/m2 (35.5 fc)
TLFX_finishingsection	297.5 Lm/m2 (27. 6 fc)

6.5.2.4.3 ESP by using hybrid daylighting system

The lighting potential through skylights should be estimated throughout the day and year and determine how many lights can be turned off for how long. The fraction of time that the specified daylighting system meet or exceed a target lighting level on the work floor has to be estimated. To do this, LightSim daylighting analysis software has been used. Because the foundry floor consists of two sections and the required illumination levels of these sections are different as indicated in Table 6-54, they have been analysed separately. The data presented in Table 6-54 were entered to LightSim and the simulation was run two times (i.e. one for Melting Shop Section with a target illumination of 35.5 fc and one for Finishing Section with 27.6 fc). The simulation results for Melting Shop Section can be seen in Figure 6-62 whereas Figure 6-63 shows the results for Finishing Section. Figure 6-64 shows the average hourly lighting output (foot-candle, fc) values on a monthly basis for the 4 winter months and 8 summer months. Daytime production shift in the subject plant begins at 08:15 am and ends around 18:30. This period is shown in green colour bordered rectangular in Figure 6-64. The target lighting output 35.5 fc for melting section and 27.6 fc for finishing section are indicated by vertical red line.



```
Input Data:
Weather file: tur_istanbul.170600_iwec.epw
Analyze between hours:  8.25  and  18.5
Number skylights =  16    Avg transmittance =  0.648
Skylight width =  6.56    Skylight length =  3.28
Room width =  59    Room length =  236    Room height =  36
Reflec ceiling =  0.7    Reflec Walls =  0.7
Target illuminance =  35.5 (fc)
```

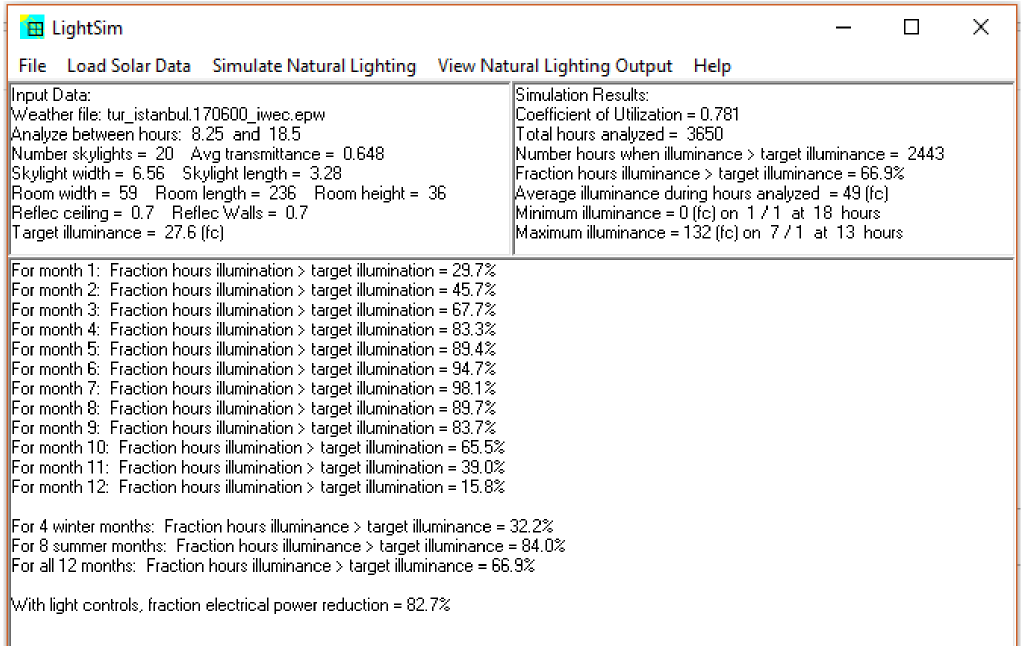
```
Simulation Results:
Coefficient of Utilization = 0.781
Total hours analyzed =  3650
Number hours when illuminance > target illuminance =  1790
Fraction hours illuminance > target illuminance = 49.0%
Average illuminance during hours analyzed  = 39 (fc)
Minimum illuminance = 0 (fc) on  1 / 1  at  18  hours
Maximum illuminance = 106 (fc) on  7 / 1  at  13  hours
```

```
For month 1:  Fraction hours illumination > target illumination = 10.6%
For month 2:  Fraction hours illumination > target illumination = 19.6%
For month 3:  Fraction hours illumination > target illumination = 38.4%
For month 4:  Fraction hours illumination > target illumination = 63.7%
For month 5:  Fraction hours illumination > target illumination = 77.7%
For month 6:  Fraction hours illumination > target illumination = 85.0%
For month 7:  Fraction hours illumination > target illumination = 86.8%
For month 8:  Fraction hours illumination > target illumination = 79.7%
For month 9:  Fraction hours illumination > target illumination = 68.3%
For month 10:  Fraction hours illumination > target illumination = 38.4%
For month 11:  Fraction hours illumination > target illumination = 15.3%
For month 12:  Fraction hours illumination > target illumination = 3.2%

For 4 winter months:  Fraction hours illuminance > target illuminance = 12.0%
For 8 summer months:  Fraction hours illuminance > target illuminance = 67.2%
For all 12 months:  Fraction hours illuminance > target illuminance = 49.0%

With light controls, fraction electrical power reduction = 73.1%
```

Figure 6-62 LightSim Simulation Output for Melting Section



```
Input Data:
Weather file: tur_istanbul.170600_iwec.epw
Analyze between hours:  8.25  and  18.5
Number skylights =  20    Avg transmittance =  0.648
Skylight width =  6.56    Skylight length =  3.28
Room width =  59    Room length =  236    Room height =  36
Reflec ceiling =  0.7    Reflec Walls =  0.7
Target illuminance =  27.6 (fc)
```

```
Simulation Results:
Coefficient of Utilization = 0.781
Total hours analyzed =  3650
Number hours when illuminance > target illuminance =  2443
Fraction hours illuminance > target illuminance = 66.9%
Average illuminance during hours analyzed  = 49 (fc)
Minimum illuminance = 0 (fc) on  1 / 1  at  18  hours
Maximum illuminance = 132 (fc) on  7 / 1  at  13  hours
```

```
For month 1:  Fraction hours illumination > target illumination = 29.7%
For month 2:  Fraction hours illumination > target illumination = 45.7%
For month 3:  Fraction hours illumination > target illumination = 67.7%
For month 4:  Fraction hours illumination > target illumination = 83.3%
For month 5:  Fraction hours illumination > target illumination = 89.4%
For month 6:  Fraction hours illumination > target illumination = 94.7%
For month 7:  Fraction hours illumination > target illumination = 98.1%
For month 8:  Fraction hours illumination > target illumination = 89.7%
For month 9:  Fraction hours illumination > target illumination = 83.7%
For month 10:  Fraction hours illumination > target illumination = 65.5%
For month 11:  Fraction hours illumination > target illumination = 39.0%
For month 12:  Fraction hours illumination > target illumination = 15.8%

For 4 winter months:  Fraction hours illuminance > target illuminance = 32.2%
For 8 summer months:  Fraction hours illuminance > target illuminance = 84.0%
For all 12 months:  Fraction hours illuminance > target illuminance = 66.9%

With light controls, fraction electrical power reduction = 82.7%
```

Figure 6-63: LightSim Simulation Output for Finishing Section

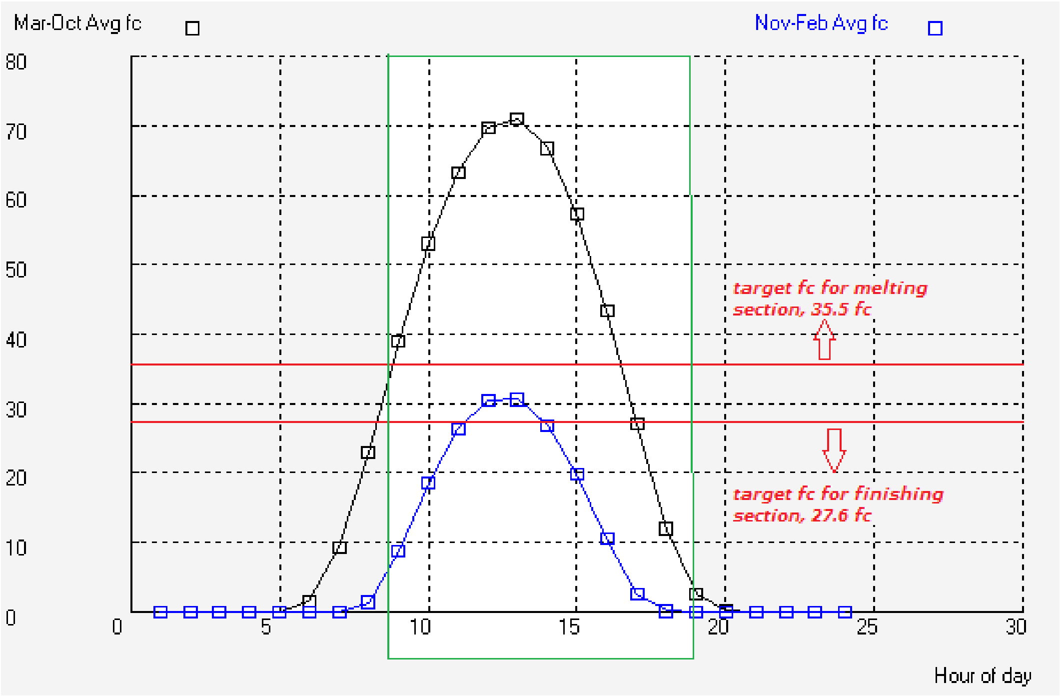


Figure 6-64 Average lighting output profile from daylighting panels during 24 hours a day in summer (March-October) and in winter (November-February)

As seen in Figure 6-62 and Figure 6-63, the fraction of electricity consumption by using the daylighting skylights for for Melting Shop Section and Finishing Section are 73.1% and 82.7%, respectively. In those times when the daylighting cannot meet the target illumination level, the electric lighting bulbs can be turned on to cover the lagging illumination inside the plant sections. This requires a photo sensor-based lighting control system. The purpose of using a lighting control system is to adjust the light with respects to the light levels measured by means of deploying photo-sensors. In a hybrid daylighting system, the photo-sensors measure the lighting level in an interior space to be lit and sends signals to a control module which interprets the signals. The control module dims the electric lightings to automatically maintain the desired lighting levels when required (Brambley et al., 2005). Such a system requires an investment for photo-sensors, control module, programming, and other associated costs. This must be taken into account in terms of the cost effectiveness of the investment.

This ESP is designated as "**ESP 6-15, ESP by Using Hybrid Daylighting**" and the associated annual ESP, PESP, ECSP, and CO_2 ERP are summarised in Table 6-55. As seen in Table 6-55, ESP in foundry floor lighting system by using daylighting system is 84% and the corresponding annual ESP, ECSP, and CO_2 ERP are 40,974.8 kWh/year, 2,683.85, 20,036.6 kg-CO_2, respectively.

Table 6-55: Calculations for ESP 6-15: annual ESP, ESP, ESCP, and CO_2 ERP

		Source/calculation/equation
ESP for Melting Section (a)	82.70%	
ESP for Finishing Section (b)	73.10%	
Daily energy use of Melting Shop Section (c)	89.092 kWh	Table 6-53
Daily energy use of Finishing Section (d)	75.39 kWh	Table 6-53
Daily ESP of Melting Shop Section (e)	73.68 kWh	e=c*a
Daily ESP of Finishing Section (f)	65.13 kWh	f=e*b
Total Daily ESP of Foundry Floor (g)	133.8 kWh	g=f+e
Annual ESP in Foundry Floor (h)	40,974.8 kWh	h=g*295
Annual anergy consumption of Foundry Floor Lighting System (i)	48,522.2 kWh	Table 6-53
ESP %(j)	84%	j=h/i%
Annual PESP (k)	101,207.75 kWh	Equation 3-1
Annual ECSP (l)	€ 2,683.85	Equation 3-2
Annual CO_2 ERP (m)	20,036.6 kg-CO_2	Equation 3-3

6.5.2.5 MACHINE SHOP LIGHTING SYSTEM

As mentioned before , the machine shop is the most occupied area in the basement floor whereas storages and model making room are used very rarely. The plant uses fluorescent tubes as a lighting bulb in the machine shop lighting (Figure 6-65). The main specifications for the fluorescent lamp used in this premise are given in Table 6-56.

Figure 6-65: Machine shop in the basement floor of the subject plant

Table 6-56: Specifications for the current fluorescent tubes used in the machine shop (source: manufacturer`s data)

Brand	Philips
Product Code	TL-D 36W/54-765 1SL
Power Rating	36 W
Cap-Base	G13
Bulb Shape	T8 [26]
Luminous Flux	2500 Lm
Energy Efficiency Label	B
Rated Life Time	13,000 hr
Rated Beam Angle	360°

6.5.2.5.1 Flourescent Lighting Basics

Fluorescent tubes are not the only element in a fluorescent lighting system although they are the most important for energy efficiency. Other components are ballasts and fixtures. A fluorescent lamp cannot be connected directly to the main voltage. The current flowing through the fluorescent must be limited which can be achieved by a device called as ballast. Ballast is a device which controls the voltage and current and provides the necessary circuit conditions to the fluorescent lamps. While doing this, a ballast also consumes energy. The type of the present ballast used in the plant is electronic ballast, which is the most efficient type. The alternative ballast type is magnetic ballast. But, the electronic ballasts are superior to the magnetic ballasts because they are typically 30% more energy efficient than the magnetic ballasts. In addition, they produce less lamp flicker, ballast noise, and waste heat (Turner and Doty, 2008). For instance, ballast loss for a 34 W fluorescent lighting circuit is 24 W in the case of magnetic ballast whereas it is 6W when electronic ballast is used (Kwok-tin, n.d.)

Light output of a fluorescent lamp depends on the current supplied to the lamp which is controlled by the ballast (NLPIP, 2002). Ballast factor (BF) is the measured ability of particular ballast to produce the light from the lamp and it determines the actual light output of the lamp. Therefore, a fluorescent lighting system actual light output (SLO) can be expressed as:

$$SLO = RLO \ x \ NL \ x \ BF$$

Eq.6-25

where:

RLO is rated light output specified by the manufacturer,
NL is number of lamps used in the system.

Thus, system efficacy (SE) can be expressed as:

$$SE = \frac{SLO}{Pin} = \frac{RLO \ x \ NL \ x \ BF}{Pin} \qquad ({}^{lm}/_{W})$$

Eq.6-26

As seen in the product specifications in Table 6-56 the energy efficiency class for the fluorescent bulbs used in the plant is *class B* which is a less efficient class as seen in Table 6-51. Hence, energy can be saved by using lamps of more energy efficient class. For this purpose, LED tubes with higher efficiency rating will be proposed as energy saving measure in the following.

In addition to the above, an obvious unnecessary use of lighting was observed during the audit. 3 fluorescent fixtures (6 fluorescent bulbs in total) over a group of 3 machines were kept on throughout the measurement periods and on the other days of the energy audit (Figure 6-66). Although these machines are used very rarely, lights are kept on all the time. This is an obvious waste of energy. By keeping these lights off when there is no need, energy can be saved.

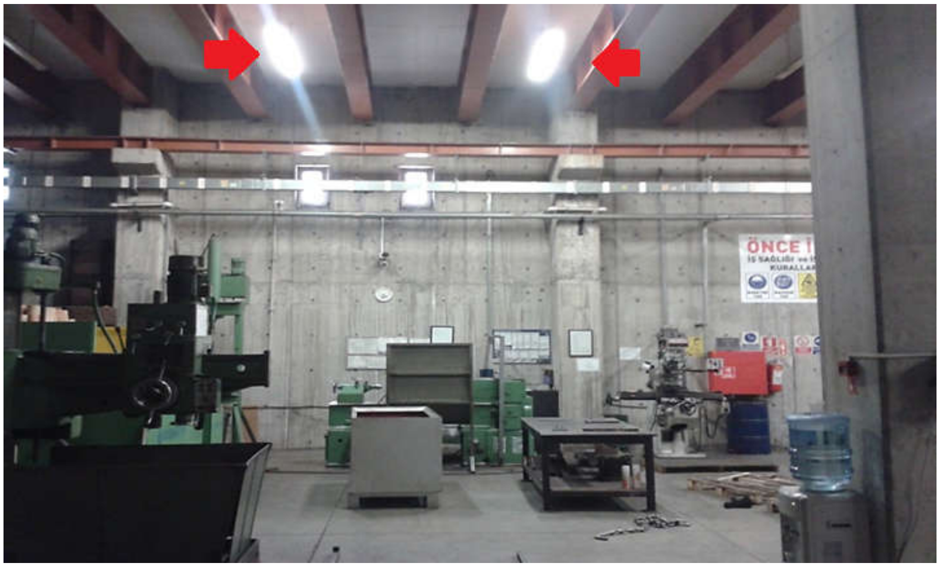


Figure 6-66: Unnecessary use of lighting in the machine shop

6.5.2.5.2 ESPS by Using Led Tubes

In this study, LED tube with energy efficiency label A+ will be proposed. The details of the LED are given in Table 6-57. As seen in Table 6-57, the power rating for the proposed LED tube is 21 W whereas it was 36 kW for the existing fluorescent tubes. Also, energy efficiency label for LED tube is A+ which means it is more energy efficient than the fluorescent tubes with energy efficiency label of B. Moreover, LED tubes do not require any ballast and there are no associated losses related to it. For comparison, the lamp efficacy can be used. Hence, the system efficacy for the existing fluorescent lights in the machine shop can be estimated as presented in Table 6-58 below. As seen, the system efficacy for the existing fluorescent lighting in the machine shop is 68.44 Lm/W.

Table 6-57: Specifications of the LED tube proposed for energy saving (Source: manufacturer`s data)

Brand	Philips
Product Code	MASTER LED tube PERF 1200mm 21W865 T8 C
Application	Industrial
Power Rating	21 W
Cap-Base	G13
Bulb Shape	T8 [26]
Luminous Flux	2100 Lm
Energy Efficiency Label	A+
Rated Life Time	50,000 hr
LLMF-end nominal lifetime	70%
Beam Angle	140°

Table 6-58: and comparison of system efficacies for the existing fluorescent lighting and LED tubes

Fluorescent Lighting		
Rated light output of the existing lamps	2500 lm	Table 6-56
Rated power input	36 W	Table 6-56
Number of lambs operating	22	average number based on the observations in a typical prod. shift
Ballast Factor	1	
SE for fluorescent lighting	69.44 lm/W	Equation 6-26
LED Lighting		
Rated light output of the proposed LED tubes	2100 lm	Table 6-57
Rated power input	21W	Table 6-57
Number of lamps	22	
SE for LED tubes	100 lm/W	Equation 6-26

As seen, the SE for the LED tubes is greater than the existing fluorescent used in the machine shop. However, an important point is the lighting output. For health and safety reasons, the lighting level in the machine shop should satisfy certain values. When the light output (luminous flux) is into account the, it is 2100 lm for the LED tubes while 2500 lm for the fluorescent lights. Put it differently, the LED tube provides a little less output than the fluorescent. However, it should be borne in mind that that an LED tube emits all the light through a 140° window, rather than the full circumference (360°), so it is unlikely to notice any reduction in the light level (Wynne, 2014). Also, based on the results of a recent environmental audit carried out in the plant in a typical production shift, the machine shop lighting levels are found to be quite higher than the lowest permissible levels. The measurement values and measurement points in the machine shop can be seen in Table 6-59 and Figure 6-67. As mentioned, only machine shop lighting systems have been considered since the machine shop is occupied more frequently than the other areas in the basement floor.

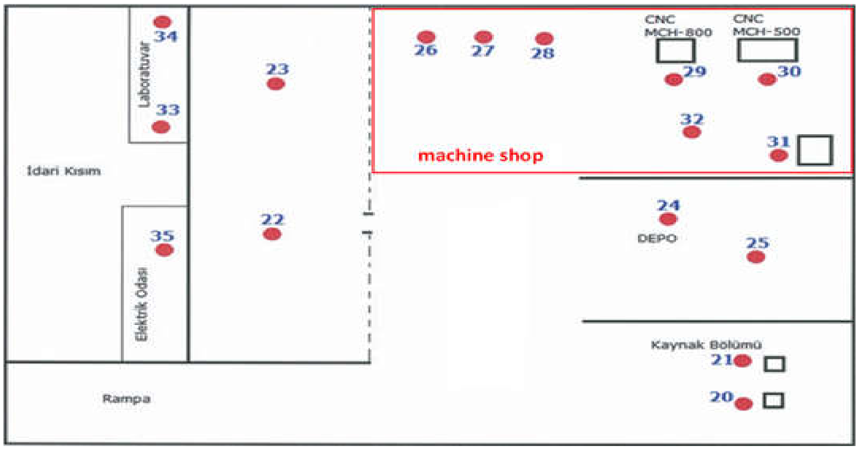


Figure 6-67: Lighting level measurement points in the machine shop

Table 6-59: Lighting measurement levels and measurement points

Measurement Point	Measured Value (Lux)	Lowest Allowed Level (Lux)
26	245	100
27	311	200
28	282	200
29	324	100
30	314	100
31	265	200
32	256	50

As such, in light of the above discussions, it can be suggested that the LED tubes satisfy the lighting level requirements and can be used instead of the current fluorescent tubes used in the plant for energy saving purposes. Hence annual ESP as well as the associated annual PESP, ECSP and CO_2 ERP can be estimated as presented in Table 6-60. This ESP is designated as "**ESP 6-16, ESP by Using LED Tubes".**

As seen, ESP 6-16, ESP by replacing the existing fluorescent with energy efficient LED tubes is 53% and the corresponding annual ESP, PESP, ECSP, and CO_2 ERP are 2,725.8 kWh, 6,732.73 kWh, €178.54, and 1,332.9 kg-CO_2, respectively.

Table 6-60: Calculations for ESP 6-16: annual ESP, PESP, ECSP, and CO_2 ERP

		Source/calculation/ equation
Daily operation hours of lighting system in machine shop (a)	17.5 hours	
Annual working days (b)	295	
Pflourescent (c)	45 W (fluorescent + gear/ballast losses)	(Wynne, 2014)
Pledtubes (d)	21 W	
Reduction in power demand per lamp (e)	24 W	e=c-d
Average number of lamps operating in a day (f)	22	
Annual ESP (g)	2,725.8 kWh	g=e*a*b*f
ESP%	53%	
Annual PESP (h)	6,732.73 kWh	Equation 3-1
Annual ECSP (i)	€ 178.54	Equation 3-2
Annual CO_2 ERP (j)	1,332.9 kg-CO_2	Equation 3-3

6.5.2.5.3 EPS by Turning the Unnecessary Lightings Off

As mentioned previously, 3 lighting fixtures (6 fluorescent bulbs) are kept on although there is no need. From the plant machine shop personnel, average load factor (i.e. utilisation of the machines over a production shift) for these machines were learnt to be about 20%, which makes 17.5 hours * 0.20= 3.5 hours/day. Therefore, these lights should be kept off at (other) 80% of the production shift (12.25 hours). Based on this, the corresponding ESP can be estimated as calculated in Table 6-61. This ESP is designated as "**ESP 6-17, ESP by Keeping the Unnecessary Lightings Off**".

Table 6-61: Calculations for ESP 6-17: annual ESP, PESP, ESCP and CO_2 ERP

		Source/ calculation /equation
Number of unnecessary light bulbs (a)	6	
Average Power demand (b)	0.045W	
Running hours in a day (c)	17.5 hours	
Unnecessary running hours in a day (d)	12.25 hours	
Annual working days (e)	295 days	
Annual energy use of 6 light bulbs (f)	1,393.8 kWh	f=a*b*c*e
Annual ESP by keeping the unnecessary lights off (g)	975.7 kWh	g=a*b*d*e
ESP% (h)	69%	h=g/f %
Annual PESP (i)	2410 kWh	Equation 3-1
Annual ECSP (j)	€ 64	Equation 3-3
Annual CO_2 ERP (k)	477.1 kg-CO_2	Equation 3-2

As presented in Table 6-61 , ESP 6-17, ESP by Keeping the Unnecessary Lights Off in the machine shop is 69% and the corresponding annual ESP, PESP, ECSP, and CO_2 ERP are 975.7 kWh, 2410 kWh, €64, and 477.1 kg-CO_2, respectively.

6.5.3 OVERALL REVIEW OF THE IDENTIFIED ESPS IN THE LIGHTING SYSTEM

Three ESPs have been identified in this chapter:

- ESP 6-15, ESP by using Hybrid Daylighting System
- ESP 6-16, ESP by using LED tubes
- ESP 6-17, ESP by Turning the Unnecessary Lightings Off

These ESPs together with the total ESP in the overall lighting systems are summarised and documented in Table 6-62.

Table 6-62: Summary of ESPs identified in Lighting System

ESP No:	Measure	EPS (%)	Annual ESP (kWh/year)	Annual PESP (kWh/year)	Annual ESCP (€)	Annual CO_2 reductions (kg-CO_2)
6-15	ESP by using Hybrid Daylighting System	84%	40,974.8	101,207.75	2,683.85	20,036.6
6-16	ESP by using LED tubes	53%	2,725.8	6,732.7	178.54	1,332.9
6-17	ESP by keeping the unnecessary lightings off	69%	975.7	2,410	64	477.1
Overall $ESP_{Lighting}$		83.3%	44,676.3	110,350.4	2,926.3	21,846.6

Overall, the total ESP in the lighting systems, $ESP_{lighting}$ is the sum of all the identified ESP in the lighting systems. Thus,

$$ESP_{lighting} = ESP\ 6\text{-}15 + ESP\ 6\text{-}16 + ESP\ 6\text{-}17$$

$$ESP_{sandreclamation} = 40{,}974.8 + 2{,}725.8 + 975.7 = 44{,}676.3\ kWh$$

If all the identified ESPs materialized, the overall annual ESP in the lighting systems will be 44,676.3 kWh which about 83.3% of the overall annual lighting systems energy consumption. Using Equation 3-1, Equation 3-2, and Equation 3-3, the associated annual PESP, ECSP, and CO_2 emissions release will be 110,350.4 kWh, kWh, €2,926.3, and 21,846.6 kg-CO_2, respectively.

6.6 PLANT OFFICES

Figure 6-68 shows the power demand profile of the subject plant offices. The office power consumers consist of computers, lights, various office equipment, lift, domestic hot water boilers (i.e. their pumps are powered by electricity), kitchen appliances, a spectrometer, and a 24-hour-running data centre. Based on the power measurement, average energy consumption of the plant offices per day is 142 kWh. Thus, the annual energy consumption is 41,890 kWh. The corresponding annual primary energy consumption, energy cost and CO_2 emissions are €2,743.8 and 2,0484.2 kg-CO2, respectively.

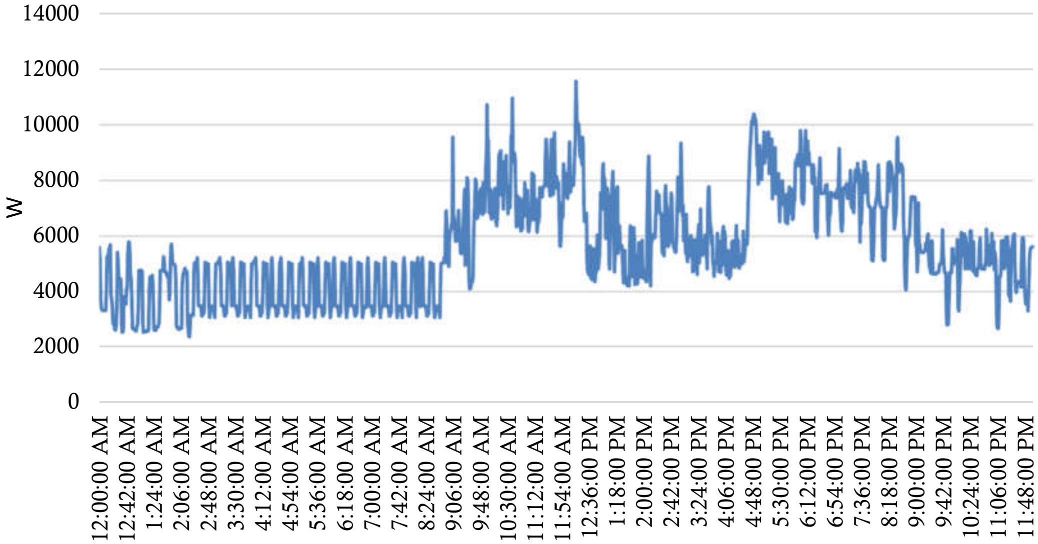


Figure 6-68 Plant offices power demand in a 24-hours period

As seen in Figure 6-68, the power demand is very fluctuating. Particularly, it has a highly varying nature during day time shift when the plant offices are most busy. During non-production hours (between 01:30 am and 08:30 am on Figure 6-68), there is a constantly fluctuating power demand. The only working energy consumer during those hours in the subject plant is the data centre; therefore, considering that it is working continuously for 24-hours, the data-centre creates a background power demand and accounts for a major part of the overall plant offices electricity consumption. Other partners of the office energy consumption are DHW boilers and office device and appliances such as computers.

Evaluating the data centre energy efficiency as well as the other energy consumers of the subject plant offices is beyond the scope of this study. However, considering the low level of awareness of the subject plant in energy efficiency issues, the following recommendations can be done:

- Taking its contribution to the overall energy use, the data centre energy efficiency can be given priority to cut the energy consumption of the subject plant offices.
- The office devices such as computer and screens can be replaced with more energy efficient ones. Today, many office equipment and devices are labelled for their energy efficiency level. Replacement can be done in the event of an unrecoverable breakdown or end of life.
- Stand-by power consumption of computers and similar devices should be avoided.
- Two natural gas-fired combi boilers are used to produce domestic hot water used for heating of the offices as well as the shower needs of the workers. The pumps of the boilers consume considerable amounts of electricity particularly during winter periods when they continuously operate to circulate hot water for office heating. Regular maintenance of these boilers is essential for efficient operation. Also, the efficiency level of the boilers pumps should be evaluated to explore any improvement gap.

6.7 CHAPTER SUMMARY AND CONCLUSIONS

The steps 1 and 2 of PHASE-2 of the Energy Auditing Methodology of the proposed holistic framework in the thesis requires the detailed study and analysis of the collected data on the target energy consuming systems in order to identify ESPs of which application will reduce energy consumption and improve the energy efficiency of the plant. As a requirement of the energy auditing methodology, the objective of this chapter was to present the energy auditing analyses conducted on the target energy consuming systems of the production support systems which included the Ventilation System, the Compressed Air System, the Cooling Tower Systems, Lighting Systems, and the Plant Offices. This was done through detailly studying and analysing the data collected through the energy audit conducted in the subject plant.

The following major conclusions can be drawn from this chapter:

- The Ventilation System of the subject plant was found to be operating without no regard to the plant ventilation need. If the existing ventilation system is converted to a DCV system (ESP 6-1), considerable amount of energy can be saved (%14.4). Further energy reduction can be realized by replacing the existing fan electric motor with a premium efficient one (ESP 6-2). In total, the energy consumption of the ventilation system can be reduced by 15.5%

- The capacity of one of the air compressors in the subject plant was found to be significantly oversized resulting in considerably excessive energy consumption than the actual requirement. It was found that a 55% of energy reduction can be achieved in the Compressed Air System if the oversized compressor is replaced with a right-sized one (ESP 6-4, ESP 6-9). Also, 3.3% of further reduction can be achieved by fixing the air leaks on the compressed air system.

- The circulation pumps in Cooling Tower Systems of the subject plant were found to be either oversized or inefficient or both and driven by inefficient electric motors resulting in excessive energy consumption than the actual requirement. Also, the air fan in Cooling Tower 1 was operating at a constant speed with no regard to the actual cooling need of the induction furnaces which varies throughout a day. It was found that a considerable energy reduction of 39.6% can be realized if the required energy efficiency retrofits and replacements are applied (ESP 6-10, ESP 6-11, ESP 6-12, ESP 6-13, ESP 6-14).

- It was found that a significant energy saving of 84% in the foundry floor lighting systems of the subject plant can be realized through the application of a Hybrid Daylighting System (ESP 6-15). 53% of the machine shop lighting sytem energy consumption can be reduced by replacing the existing flourescent tubes with energy efficient LED tubes (ESP 6-16). About 19% of the energy consumption of the machine shop lighting system can be saved by simply turning the unnessary lights off (ESP 6-17).

- The production support systems included in the energy audit accounts for about 32.3% of the total plant energy consumption. The results of the energy audit conducted on the production support clearly presents that there exist considerable energy efficiency gaps in each system. The application of the ESPs identified in the production support systems can provide a collective ESP of 324,082.34kWh per year. This provides a reduction of 33.8% in the overall production support systems energy consumption and a reduction of about 11% in the total plant annual energy consumption. These reduction potentials are technically feasible potentials. Their economic feasibilities are evaluated in Chapter 7.

7

Cumulative Sum of ESPs, LCC, Ranking and Prioritisation of ESPs, and Decision Making

7.1 INTRODUCTION

Chapter 5 and Chapter 6 have presented auditing of target energy consuming systems in the subject plant and a number of ESPs together with associated PESPs, ECSPs and CO_2 ERPs for each target energy consuming systems have been identified and quantified. Implementation of these ESPs will provide "improved energy performance" to the subject plant. To see the collective effect of the identified ESPs and to what extent it is "technically" possible to reduce the energy consumption of the subject plant, the cumulative sum of the ESPs must be determined. As explained in the Step 3 of the energy audit methodology in Chapter 3, some of the identified ESPs require an initial investment which will lead to future ESCPs. The cost-effectiveness of the investment should be assessed to see whether it will justify the initial expenditure or not. Regarding the real-time implementation of these ESPs, they must be prioritised with regards to various decision criteria and energy management action plan which will guide the subject plant can be prepared.

Bearing the above paragraph in mind, the objectives of this chapter and the chapter structure can be listed as outlined in the following:

- to determine the cumulative sum of the ESPs (Section 7.2),
- to present the economic assessments, evaluation, and prioritisation of the ESPs (Section 7.3).

In addition to the above a sensitivity analysis is conducted in Section 7.4 to see the effect some economic parameters on the economic feasibility of the ESPs. Finally, Section 7.5 gives the concluding remarks of the chapter with a short summary of the chapter.

7.2 CUMULATIVE SUM OF THE IDENTIFIED ESPS

The cumulative sum of the all annual ESPs identified in the audited energy consuming systems of the subject plant is shown in Figure 7-1. The sum of the all annual ESPs is 530,298 kWh. This is about 17.8 % of overall plant annual energy consumption. The associated annual PESP, annual ECSP, and annual CO_2 ERPs are 1,283,321.16 kWh, €34,755.73, and 259,846.02 kg-CO_2, respectively.

It should be noted that the total annual ESP can be higher than 534,187 kWh. This is because ESP 5-2 in Section 5.2 of Chapter 5 was estimated based on the assumption that the subject plant could approach to 50% of Europe Best Practise value. If the plant can approach to 100% of Europe Best Value, the corresponding ESP in melting process would be 29%, which means that 297.57 MWh of electricity can be saved in a year. Therefore, given that ESP 5-1 is estimated based on the full achievement of 100% of Europe Best Value, the overall plant annual ESP will be 681,655.06 kWh which corresponds to an overall ESP of 22.9%. Similarly, ESP 5-2 was estimated based on the assumption that the subject plant would achieve a 50% reduction of the base case casting defect rate. If ESP 5-2 is estimated based on the scenario of 100% reduction of the base case casting defect rate, the corresponding annual ESP will be 14,901 kWh and the overall plant annual ESP will be 696,556.06 kWh which corresponds to an overall ESP % of 23.4%. **Therefore, it is technically possible to reduce the energy consumption of the subject plant by 23.4%**

As Table 7-2 lists, there are 32 identified ESPs as a consequence of the detailed energy audit conducted in the subject plant. Figure 7-2 shows a Pareto chart which shows the individual values of the identified ESPs and the cumulative percentage of the sum of the ESPs. As can be observed in Figure 7-2, ESP 5-1, which is ESP by Improving Melting Practice, is the most favourable ESP as it has the highest energy saving value amongst all other energy consuming units. The percent of ESP 5-1 in the melting process is 14.25% which can be considered as low compared to some ESPs identified in other energy consuming systems such as ESP 6-15 and ESP 5-9 of which % ESP are 84% and 45%, respectively. However, its contribution to overall plant wide ESP is high as seen in Figure 7-2 because the melting process is the most energy intensive system in the subject plant as noted before. Other important ESPs in terms of the magnitude of energy savings are ESP 6-4, ESP 6-12, ESP 6-15, ESP 6-1, and ESP 6-11.

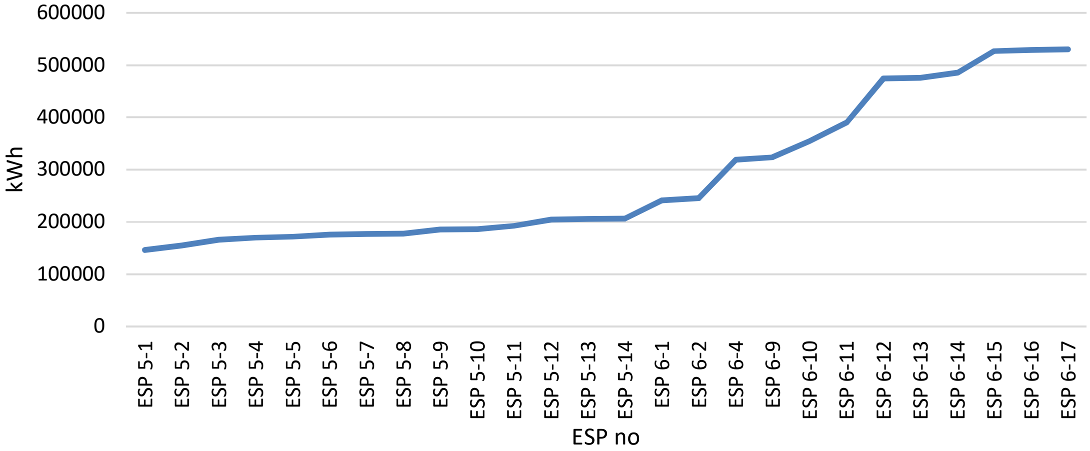


Figure 7-1: Cumulative sum of the identified ESPs

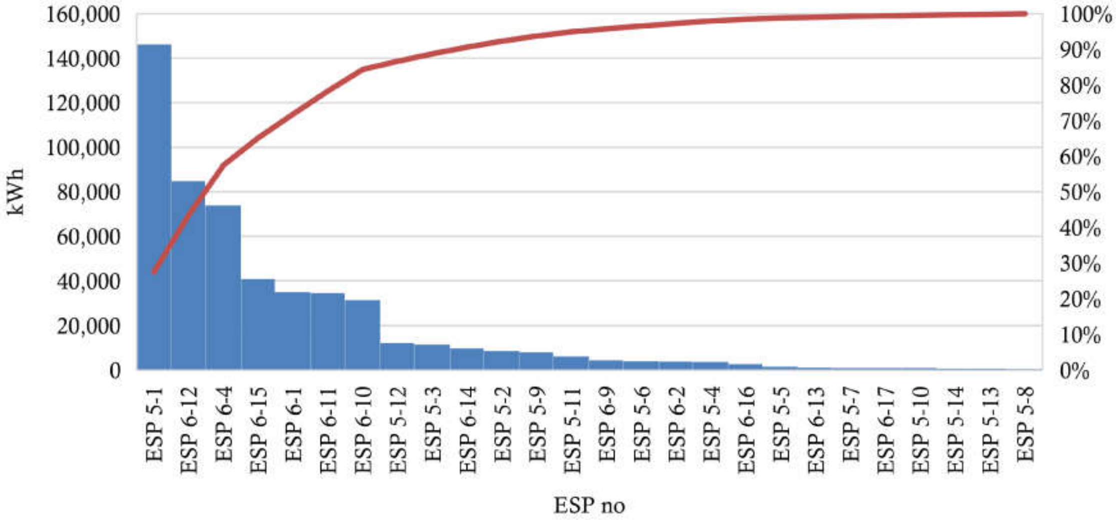


Figure 7-2: Pareto Chart of EPSs

Table 7-1: List of ESPs identified in the subject plant

system group	**ESP no**	**Energy Consuming Systems**	**Measure**	**ESP (%)**	**Annual ESP (kWh/year)**	**Annual PESP (kWh/year)**	**Annual ECSP (€/kWh)**	**Annual CO_2 ERP (kg-CO_2/year)**
Production Process Systems	ESP 5-1	Melting Furnaces	ESP by improving melting practice	14.25%	146,220	361,163.70	9,577.41	70,523.58
	ESP 5-2	Melting Furnaces	ESP by reducing reject rate	0.82%	8,642.60	21,347.20	566.10	4,168.42
	ESP 5-3	Grinding Systems	ESP by keeping the idle machines off	15%	11,397	28,150.60	746.50	5,573.13
	ESP 5-4	Grinding Systems	ESP by using premium efficient electric motor	4.9%	3,770	9,312	247.1	1,847.3
	ESP 5-5	Grinding Systems	ESP by using notched V belts	2%	1,582.9	3909.7	103.68	774.03
	ESP 5-6	Abrasive Blasting System	ESP by keeping the idle fans off	12%	3,976.05	9,820.84	260.43	1944.3
	ESP 5-7	Abrasive Blasting System	ESP by using premium efficient electric motor	3%	1,039.4	2,567.3	67.50	508.6
	ESP 5-8	Abrasive Blasting System	ESP by using more efficient transmission belts	2%	662.67	1,635.3	43.40	324
	ESP 5-9	Machine Shop	ESP by replacing old lathe with a new one	45%	8,025	19,741.50	525.60	3,924.22
	ESP 5-10	Machine Shop	ESP by turning the unnecessary working machine off	6.50%	964.7	2,373.16	63.20	472.7
	ESP 5-11	Sand Reclamation System	ESP by avoiding the unnecessary operation of sand reclamation system	9%	6,188	15,222.48	405.30	3,026
	ESP 5-12	Sand Reclamation System	ESPs by using more efficient electric motor for the sand reclamation system air fan	10%	12,219	30,058.74	800	5,975.10
	ESP 5-13	Heat Treatment Furnace	ESP by using more efficient electric motor for the air fan in the heat treatment furnace	5.40%	746.4	1,836.14	49	374.5
	ESP 5-14	Quenching Pool	ESP by using higher efficiency electric motor for the agitator	4.40%	782	1,923.72	52	382.3

Production Support Systems	ESP 6-1	Ventilation System	ESP by DCV system	14.38%	35,109.64	86,720.89	€ 2,299.66	17,168.60
	ESP 6-2	Ventilation System	ESP by using more energy efficient electric motor	2.23%	3,843.30	9,492.95	€ 251.70	1,879.37
	ESP 6-3*	Compressed Air System	ESP by converting the existing 55kW compressor to a VSD one (Scenario 1)	33.70%	33,650.65	83,117.11	2,205.50	16,387.90
	ESP 6-4	Compressed Air System	ESP by using a multiple compressor system (Scenario 2)	74.10%	74,015.50	182,818.30	4,851.00	36,045.50
	ESP 6-5*	Compressed Air System	ESP by using a multiple compressor system (Scenario 3)	73.10%	73,065.60	180,472.00	4,788.70	35,582.90
	ESP 6-6*	Compressed Air System	ESP by using a multiple compressor system (Scenario 4)	73.00%	72,924.00	180,122.30	4,779.40	35,514.00
	ESP 6-7*	Compressed Air System	ESP by using a multiple compressor system (Scenario 5)	60.10%	60,115.10	148,484.30	3,939.90	29,276.10
	ESP 6-8*	Compressed Air System	ESP by using a multiple compressor system (Scenario 6)	66.70%	66,681.80	164,704.00	4,370.30	32,474.00
	ESP 6-9	Compressed Air System	ESP by fixing air leaks	3.30%	4,361	10,771.70	€ 285.60	2,132.40
	ESP 6-10	Cooling Tower 1	ESP by using VFD for the cooling tower air fan Cooling Tower 1	53%	31,478.50	77,751.90	€ 2,063	15,424.45
	ESP 6-11	Cooling Tower 1	ESP by replacing Pump 2 with an efficient pump and premium efficiency electric motor Cooling Tower 1	22%	34,692	85,689.24	€ 2,273.71	16,999.08
	ESP 6-12	Cooling Tower 1	ESP by replacing Pump 1 with an efficient and right size pump and premium efficiency electric motor Cooling Tower 1	45%	84,903.70	209,712.14	€ 5,564.59	41,602.81
	ESP 6-13	Cooling Tower 2	ESP by replacing the existing electric motor of Pump 1 with a premium efficient electric motor in Cooling Tower 2	3.55%	1,196.40	2955.108	€ 78.41	586.236
	ESP 6-14	Cooling Tower 2	ESP by replacing Pump 2 with an efficient and right size pump and electric motor in Cooling Tower 2	42%	9,806	24,220.57	€ 643	4,804.89
	ESP 6-15	Lighting Systems	ESP by using a hybrid daylighting system	84%	40,974.80	101,207.75	€ 2,683.85	20,036.60
	ESP 6-16	Lighting Systems	ESP by using LED tubes	53%	2,725.80	6,732.70	€ 178.54	1,332.90
	ESP 6-17	Lighting Systems	ESP by turning the unnecessary lights off	69%	975.7	2,410	€ 64	477.1
	TOTAL			18%	**530,298**	**1,283,321.16**	**34,755.73**	**259,846.02**
	*Because these ESPS are alternative to ESP 6-4, they are not included in total ESP (%), total annual ESP, annual PESP, annual ECSP, and annual CO_2 ERP.							

7.3 ECONOMIC ASSESSMENTS AND PRIORISATION OF THE ESPS

ESPs can be categorised into two groups with respect to whether they need investment or not:

- Cost-free (or relatively low cost) ESPs which do not require any investments.
- ESPs requiring initial investment cost.

7.3.1 COST-FREE ESPS

Table 7-3 lists the ESPs which do not require any capital investment. As seen in Table 7-3, there are cost-free 7 ESPs. Among them, ESP 5-1 and ESP 5-2 may require the subject plant to improve their casting skills. Improving casting skills may require the subject plant to have consultancy service from an expert or a university; or they can improve their skills themselves by conducting in-house research and development. Depending on which way they will follow to improve their casting skills, there might and might not involve costs for these ESPs (i.e. ESP 5-1 and ESP 5-2). Considering that the subject plant has experience of long years in casting techniques, it is assumed that the subject plant can improve their casting skills through in-house resources; and thus, that there will be no cost allocation for this. The total annual ESP sums up to 178,364 kWh which accounts for an attractive 35% of the total annual ESP (i.e. 523,594 kWh) as a result of the cost-free ESPs. The subject plant immediately can take action to apply the cost-free ESPs leading to saving energy and money.

As for other cost-free ESPs, ESP 6-17, ESP 5-3, ESP 5-6, ESP 5-10, and ESP 5-11, these emanate from the ignorance of the **labours (i.e. human factor).** The sum of their annual ESPs is 23,501.45 kWh/year, which is greater than the annual ESPs provided by some ESPs with initial capital cost. What is more, they can be easily materialised by "simply keeping the unnecessary working energy consumers off". These ESPs also shows the lack of awareness of the energy issues in the subject plant. Bearing this in mind, the subject plant can consider conducting energy awareness training across the plant.

Table 7-2: ESP% and annual ESP values for Cost-Free ESPs

ESP measures	ESP %	Annual ESP (kWh)
ESP 5-1, ESP by improving melting practice in Melting Process	14.25%	146,220
ESP 5-2, ESP by reducing casting defect rate in Melting Process	0.82%	8,642.6
ESP 6-17, ESP by turning the unnecessary lights off in Lighting System	69%	975.7
ESP 5-3, ESP keeping the idle machines off in Grinding System	15%	11,397
ESP 5-6, ESP by keeping the idle fans off in A.Blasting System	12%	3,976.05
ESP 5-10, ESP by turning the unnecessarily working machine off in Machine Shop	6.50%	964.7
ESP 5-11, ESP by avoiding the unnecessary operation in Sand Reclamation System	9%	6,188
	TOTAL	178,364

7.3.2 EVALUATION OF THE ESPS REQUIRING INITIAL INVESTMENT

The cost-effectiveness of ESPs which require an investment should be assessed to see whether it will justify the initial expenditure or not. To do this, all the costs and benefits which occur throughout thune project life must be identified and added together (i.e. LCC). APPENDIX E presents the cost components for each ESP. Further, the NPVs and B/C ratios for each ESP have been calculated and presented in Appendix E. Table 7-3 lists the values of economic parameters calculated for the base case energy price scenario for the ESPs together with their annual ESPs and initial capital costs.

7.3.2.1 ECONOMIC APPRAISAL OF ESPS

Economically non-feasible ESPs

As stated earlier, a project must have a positive NPV to be economically feasible. The LCC analyses results show that there are six ESPs which show negative NPVs amongst all. Therefore, these are deemed to be economically not feasible. The economically non-feasible ESPs and their NPVs are shown in Table 7-4. These are ESP 6-5, ESP 6-6, ESP 6-7, ESP 6-8, ESP 5-8, and ESP 5-9.

As explained in Chapter 6, ESP 6-3, ESP 6-4, ESP 6-5, ESP 6-6, ESP 6-7, and ESP 6-8, which have been identified in the compressed air system, are alternatives to each other and cannot be applied together. Amongst them, ESP 6-5 ESP 6-6, ESP 6-7, and ESP 6-8 are found to be non-feasible. Instead of these, ESP 6-3 or ESP 6-4 can be applied based on their prioritisation with regards to the decision criteria presented in the forthcoming subsection.

Regarding ESP 5-8 (ESP by using more efficient transmission belts), which is found to be economically non feasible, its annual ESP can be considered as dispensable because it is just 662.67 kWh/year. Instead of applying this economically non-feasible ESP, efficient notched V-belts can be employed when the existing standard belts used in the abrasive blasting system are torn or worn off.

Table 7-3: Economic parameters for the ESPs requiring IPC

	Initial Purchasing Cost (€)	Annual ESP (kWh)	Net PV of the benefits (€)	Net PV of the costs (€)	NPV (€)	B/C	Economically Feasible
ESP 5-4	1,126	3,770.00	4,274.6	1,126	3,148.6	3.79	Yes
ESP 5-5	258	1,582.90	1,854	1,406.2	447.9	1.31	Yes
ESP 5-7	2,060	1,039.40	2,631.4	2,060	571.4	1.27	Yes
ESP 5-8	172	662.7	888.5	937.4	**-48.9**	0.94	No
ESP 5-9	100,000	8,025	25,325	100,000	**-74,675**	0.25	No
ESP 5-12	1,284	12,219	11,893.8	1,284	10,609.8	9.26	Yes
ESP 5-13	375	746.4	691.7	375	316.7	1.84	Yes
ESP 5-14	1,284	782	1,758.8	1,284	474.8	1.37	Yes
ESP 6-1	9,050	35,109.6	31,192.2	5065,7	26,126.5	6.15	Yes
ESP 6-2	1,890	3,843.3	4,961.2	1,890	3,071.2	2.62	Yes
ESP 6-3	8,000	33,650.65	29,900.7	18,822.23	11,078.52	1.59	Yes
ESP 6-4	8,000	74,015.5	65,688.22	18,822.23	46,866	3.49	Yes
ESP 6-5	50,000	73,065.6	68,296.5	117,638.92	**-49,342.4**	0.58	No
ESP 6-6	122,000	72.924	178,330.2	287,038.96	**-108,708.75**	0.62	No
ESP 6-7	108,000	60,115.1	165,823.7	254,100.06	**-88,276.36**	0.65	No
ESP 6-8	123,000	66.681.8	172,878	289,391.74	**-116,513.78**	0.59	No
ESP 6-9	100	4361	3864.2	1452.8	2,411.4	1.66	Yes
ESP 6-10	6,150	31,478.5	27,934.5	13,116.8	14,817.6	2.13	Yes
ESP 6-11	2,266	84,903.7	77,557.2	2,266	75,291.2	34.22	Yes
ESP 6-12	2,018	34,692	33,491.2	2,018	31,473.2	16.59	Yes
ESP 6-13	1,615	1,196.4	2,401.4	1,615	786.4	1.48	Yes
ESP 6-14	1,263	9,806	10,384.5	1,263	9,121.5	8.22	Yes
ESP 6-15	8,700.6	40,974.8	50,246.7	14,585.2	35,661.5	3.44	Yes
ESP 6-16	1,364	2,725.8	4,632.8	1,364	3,268.8	3.39	Yes

As for another economically non-feasible ESP 5-9, ESP by replacing the old lathe with a new one, the initial purchasing cost and NPV of the costs for ESP are very high compared to the energy saving and monetary benefits it provides. Therefore, rather than replacing this machine with a new one, which is economically non-feasible, using the existing old machine tool efficiently with optimal process parameters and avoiding the idle workings can be aimed. Further, the newer machine tool should be preferred as much as possible and the old one can be used for overtime works where the work cannot be finished in a certain lead time only with the newer one (as described in Chapter 5, there is a newer machine tool of the size and capacity with the older one).

Economically feasible ESPs

The economically feasible ESPs are those which have positive NPVs. There are 18 economically feasible ESPs. These are shown in Table 7-4. Their annual ESP (excluding ESP 6-3 because it cannot be applied together with ESP 6-4) sum up to 343,246.3 kWh. As seen, the most favourable three options in terms of the NPV are ESP 6-11, ESP 6-4, and ESP 6-15. The NPV for them are €75,291.1, €46,866, and €35,661.4, respectively.

The NPV analysis presented above shows the economic justification for each ESPs. NPV is an important indicator which shows the profitability of an investment project itself. However, it does not show that a project (i.e. investment in an ESP) is superior to another in terms of cost-effectiveness. In other words, it is not a useful parameter to compare different ESPs and using NPV to compare the cost-effectiveness of ESPs with different project costs can give misleading results. For instance, the NPVs for ESP 6-11 and ESP 6-15 are €75,291.2 and €35,661.5, respectively. As seen, ESP 6-11 has a higher NPV than ESP 6-15. If NPV is used as a benchmarking indicator, NPV suggests ESP 6-11 provides better economic outcomes than ESP 6-15 because €75,291.2 is greater than €35,661.5. However, this approach does not evaluate the NPV of a project in relation to the project costs. A project with a smaller NPV can be more profitable than a project with a greater NPV by virtue of its lower project costs. It can produce higher benefits compared its costs. Therefore, B/C ratio which provides a ratio value by diving the sum of the discounted benefits by the sum of the discounted costs, can be used to benchmark the alternatives.

NPV and B/C ratio are useful parameters for economic justification of projects and compare their cost-effectiveness. However, a plant cannot be able to implement all these ESPs because of various factors such as limited sources or there might be additional factors that are important to the plant. For instance, a company might want to reduce the energy intensity of its plant regardless of the project costs. Conversely, initial purchasing costs can be a major issue for the company. Therefore, ESPs can be ranked and prioritized with regards to the criteria which are important to the subject plant.

7.3.3 PRIORITISING ESPS AND DECISION MAKING

In this study, the weighted sum model (WSM) is used to evaluate the ESPs in terms of various criteria. This approach is the simplest and most widely used multi-criteria decision making method which involves a basic concept of evaluating a number of options according to a number of decision criteria (Triantaphyllou, 2000). The following decision criteria are used to evaluate the ESPs:

1. Annual ESP
2. NPV
3. B/C
4. Initial purchasing cost (IPC)

Table 7-4 shows the rating values and conditions to rate the criteria. Points from 1 to 4 are given to the ESPs for four criteria depending on the conditions defined in Table 7-4. For instance, if the NPV of an ESP is equal to or greater than 20,000, it is given 4 points. Similarly, the ESP is given point for other criterion depending on the conditions. One should note that the expected time required for implementation of an ESP could be taken into accounte as an additional criterion to the above. Similarly, easiness/simplicity of implementation of an ESP could be considered. These criteria were not taken into account in this study because most ESPs listed in Table 7-2 are retrofit measures such as installing a VFD or replacement measures such as replacing an electric motor with a more efficient one. These measures are very straightforward and can be implemented in a short time by the plant maintenance team as noted in economic assessments in Appendix E.

Table 7-5 presents the scoring of each ESP for each criterion with respects to conditions shown in Table 7-4 and their performance values for each criterion shown in Table 7-4.

Table 7-4: Rating values and conditions for criteria used to evaluate the ESPs

Criterion	**Rating values and conditions**			
	1	**2**	**3**	**4**
NPV (€)	0<NPV<=5000	5000<NPV<=10,000	10,000<=NPV<20,000	20,000<=NPV
B/C	0<B/C<=2	2<B/C<=5	5<B/C<=10	10<B/C
ESP (kWh)	ESP<1,000	1000<=ESP<10,000	10,000<=ESP<20,000	ESP=>20,000
IPC (€)	IPC>6000	6000=>IPC>4000	4000=>IPC>2000	2000=>IPC>0

Table 7-5: Scoring of ESPs for each criterion

	NPV	B/C	ESP	IPC
ESP 5-4	1	2	2	4
ESP 5-5	1	1	2	4
ESP 5-7	1	1	2	3
ESP 5-12	3	3	3	4
ESP 5-13	1	1	1	4
ESP 5-14	1	1	1	4
ESP 6-1	4	3	4	1
ESP 6-2	1	2	2	4
ESP 6-3	2	1	4	1
ESP 6-4	4	2	4	1
ESP 6-9	1	1	2	4
ESP 6-10	3	2	4	1
ESP 6-11	4	4	4	2
ESP 6-12	4	4	4	2
ESP 6-13	1	1	2	4
ESP 6-14	2	3	2	4
ESP 6-15	4	2	4	1
ESP 6-16	1	2	2	1

Decision Weights

The criteria defined above must be assigned weights of importance which are normalized to add up to one. For this purpose, 5 scenarios are defined as presented in Table 7-6. Table 7-7 shows the relative weights assigned to the criteria according to the scenarios. Scenario 1 assumes that all criterion is equally important. In other scenarios, one criterion is assigned more importance while the rest is equally less important. For instance, in Scenario 2 where annual ESP is the most important criterion among others, the relative weight of the criterion ESP is equal to 0.55 and the relative weight for other criteria is 0.15. It should be noted that these weights are defined by the Author for demonstration purpose and the subject plant can define other weightage values depending on their preferences on the criteria.

Table 7-6: Scenarios for importance of decision criteria to evaluate ESPs

Scenario 1	All criteria are equally important
Scenario 2	Annual ESP is more important while others are equal: the plant wants to reduce its energy consumption, energy cost, and CO_2 emissions with less consideration to the investment costs. Therefore, the ESPs with higher annual ESP are preferred.
Scenario 3	IPC is more important while others are equal: The plant gives priority to the IPC of the ESPs. ESPs with lower IPC are preferred.
Scenario 4	B/C is more important while other are equal: The plant gives priority to the ESPs which are more cost-effective.
Scenario 5	NPV is more important while others are equal: The plant gives priority to the ESPs which creates higher economic value.

Table 7-7: Assigning weights to the criteria according to the scenarios

	relative weightage				
Criterion	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
NPV	0.25	0.15	0.15	0.15	0.55
B/C	0.25	0.15	0.15	0.55	0.15
ESP	0.25	0.55	0.15	0.15	0.15
IPC	0.25	0.15	0.55	0.15	0.15

The ranking and the scores that the ESP are assigned in Scenario 1, Scenario 2, Scenario 3, Scenario 4, and Scenario 5 can be seen in Figure 7-3, Figure 7-3, Figure 7-4, Figure 7-5, Figure 7-6, and Figure 7-7.

Scenario 1: All criteria have equal importance:

This scenario assumes the plant does not have a priority for the decision criteria. Thus, the equal relative weightage of 0.25 are given to each criterion. As seen Figure 7-3, the top five winners of this scenario are ESP 6-11, ESP 6-12, ESP 5-12, ESP 6-1, and ESP 6-4. The sum of their annual ESP and IPC are 240,940 kWh and €22,618, respectively.

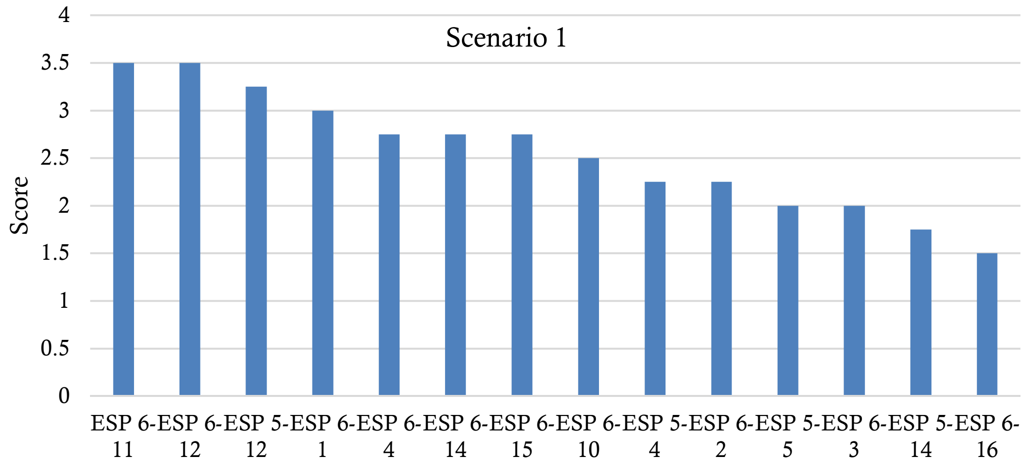


Figure 7-3: Ranking of the ESPs in Scenario 1

Scenario 2: ESP is the most important while others are equal:

In this scenario, it is assumed that the plant wants to reduce its energy consumption, energy cost, and CO_2 emissions with less consideration to the investment costs and economic performances. Reduced energy consumption is the ultimate aim in this scenario. Therefore, the relative weightage given to the ESP criteria is 0.55 while others are 0.15. As seen in Figure 7-4, the top five winners of Scenario 2 are ESP 6-11, ESP 6-12, ESP 6-1, ESP 6-4, and ESP 5-4. The sum of their annual ESP and IPC are 269,695 kWh and € 30,035 , respectively.

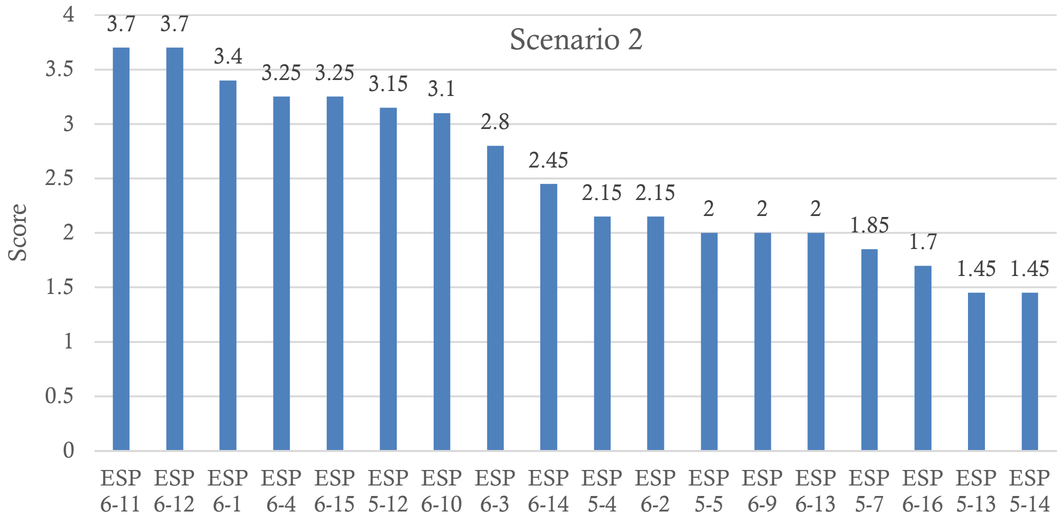


Figure 7-4: Ranking of the ESPs in Scenario 2

Scenario 3: IPC is the most important while others are equal:

This scenario assumes that the plant gives priority to the IPC of the ESPs. ESPs with lower IPC are preferred due to the low capital budget. Therefore, the relative weightage given to the IPC criteria is 0.55 while others are 0.15. As seen Figure 7-5, the top five winners of Scenario 1 are ESP 5-12, ESP 6-14, ESP 5-4, ESP 6-2, and ESP 5-11, respectively. The annual sum of their ESPs is 114,542 kWh whereas the total IPC is €7,829.

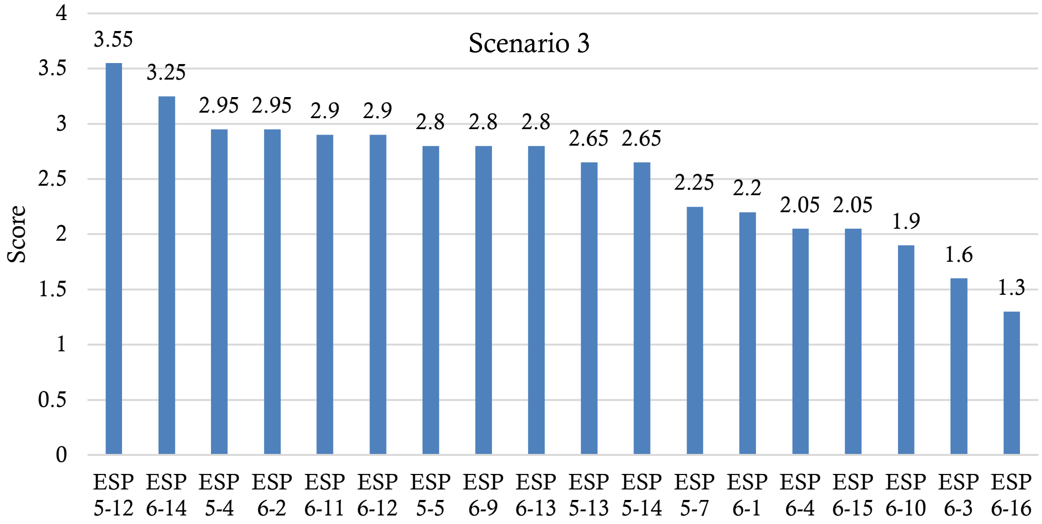


Figure 7-5: Ranking of the ESPs in Scenario 3

<u>Scenario 4: BC is the most important while others are equal:</u>

In this scenario, the plant gives priority to the ESPs which have higher B/C ratios. The ESPs with higher B/C ratios are more cost-effective. As seen in Figure 7-6, the top five in Scenario 4 are ESP 6-11, ESP 6-12, ESP 5-12, ESP 6-1, and ESP 6-14. The B/C ratios for these ESPs are 34.2, 16.6, 9.26, 8.22 and 6.15, respectively. These ESPs provides higher net benefits compared to net costs occurring throughout the project lives. The sum of their annual ESP and IPC are 176,730.3 kWh and €15,881, respectively.

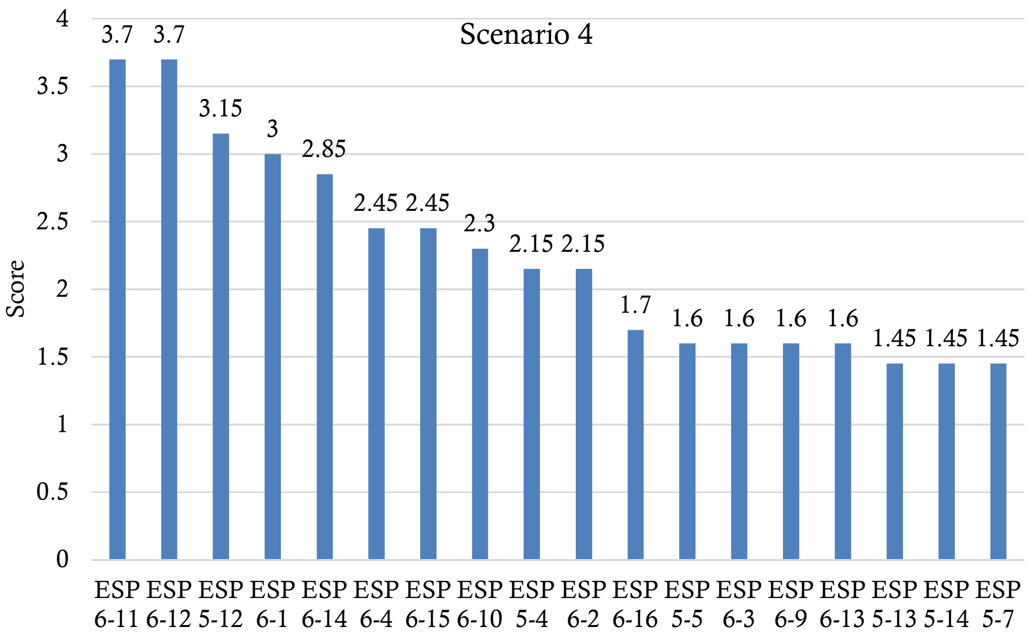


Figure 7-6: Ranking of the ESPs in Scenario 4

Scenario 5: NPV is the most important while others are equal:

In this scenario, it is assumed the plant gives priority to the ESPs which creates higher economic value. As seen in Figure 7-7, the top five are ESP 6-11, ESP 6-12, ESP 6-1, ESP 6-4, and ESP 6-15. The sum of their annual ESP and IPC are 269,695 kWh and € 39,305, respectively.

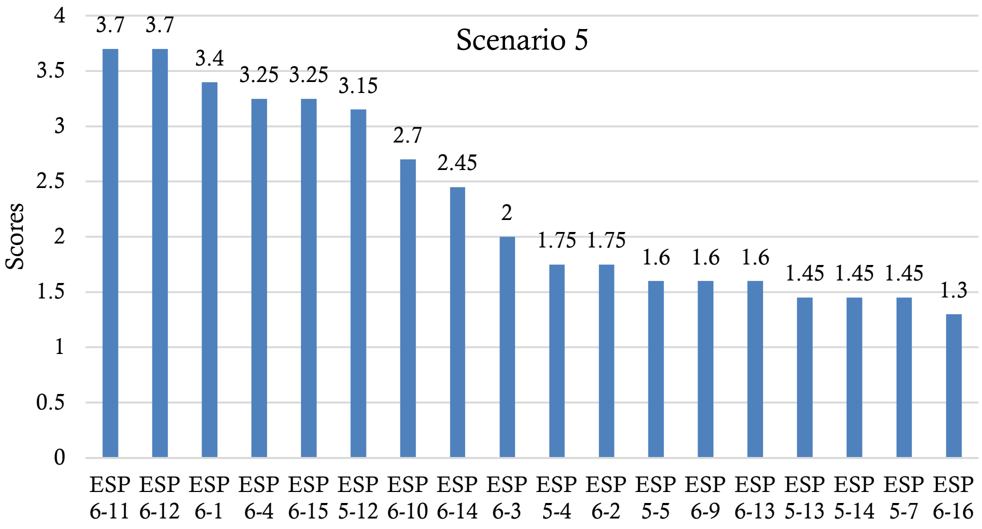


Figure 7-7: Ranking of the ESPs in Scenario 5

Regarding the ESPs in the compressed air system, as presented in the succeeding section, ESP 6-5, ESP 6-6, ESP 6-7, and ESP 6-8 were found to be non-feasible, thus they were eliminated. As for ESP 6-3 and ESP 6-4, one of them must be chosen because they are alternatives of each other. As one can see in the above scenario analyses, ESP 6-4 outstrips ESP 6-3 in each scenario. Therefore, it is obvious that ESP 6-4 is more feasible than ESP 6-3 in terms of all decision criteria.

7.4 SENSITIVITY ANALYSIS

7.4.1 DISCOUNT RATE

While calculating the LCCs of the ESPs, the discount rate was assumed to be constant throughout the project life. Therefore, a sensitivity analysis has been done on the real discount rate to see how it effects the economic performance of the ESPs. For this purpose, the nominal discount rate and the expected inflation rates are defined as seen in Table 7-8 such that 5%, 10%, 15% increases and decreases in the real discount rate are obtained. The resulting real discount rates are can be seen in Figure 7-8. ESP 6-15 has been chosen to see the effect of changing real discount rate on the NPV.

Table 7-8: Scenarios for increase in real discount rate for sensitivity analysis

Nominal Discount Rate %	**Expected Inflation Rate %**	**Real Discount Rate %**	**Increase in Real Discount Rate %**
8.82	7.40	1.32	-
8.38	7.03	1.26	5%
7.85	6.59	1.19	10%
7.41	6.22	1.12	15%
9.26	7.77	1.38	-5%
9.79	8.21	1.46	-10%
10.23	8.58	1.52	-15%

From Figure 7-8, it is clear that increasing discount rate increases the NPV of the project and vice versa.

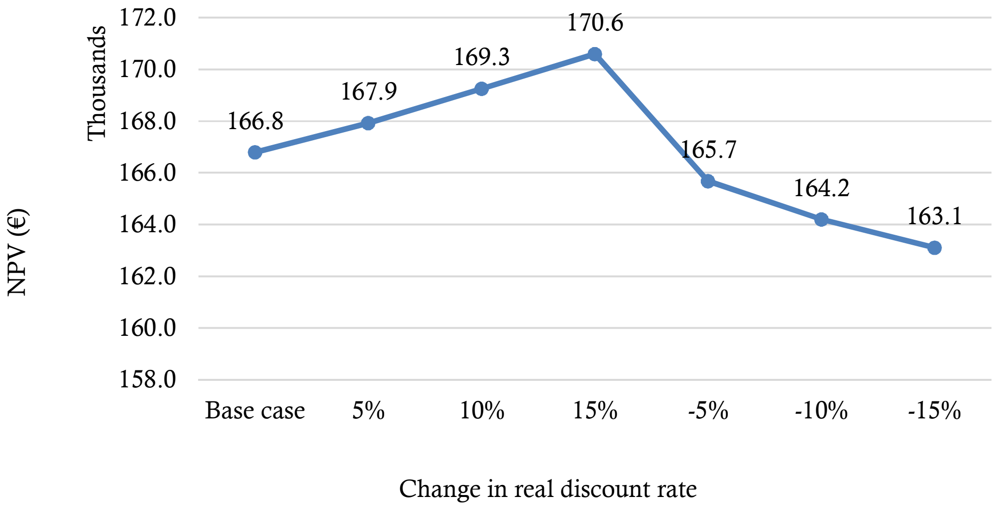


Figure 7-8: Effect of changing real discount rate on the NPV of ESP 6-15

7.4.2 ELECTRICITY PRICES

Four energy price scenarios are arbitrarily established to use in the NPV s. The yearly increase scenarios are increases of 5%, 10%, 15%, and 20%. These increases are additional increases to the increase due to the inflation. The sensitivity analysis with these energy prices scenarios are applied to ESP 16-5 to see the effect of the increasing electricity unit cost rates.

From Figure 7-9, it is obvious that increasing energy prices strongly increases the NPV of the ESP. In other words, increasing energy prices increase the cost-effectiveness of the ESPs. This is quite expected because annual ESCP, which is a major component of the net benefits, increases with increased energy unit cost. This in turn increases the NPV of a project. As explained in Chapter 3, the base case energy cost scenario which assumes 0% energy price increase throughout the project life was defined assuming that the energy increase will be only due to the inflation. However, as frequently mentioned before, Turkey is an energy dependent country located in a region where political conflicts and unrests are major issues. As such, energy prices show volatilities and sudden increases in Turkey. Bearing these in mind, it is likely that real-time investments in the ESPs will be more profitable than the 0% energy price increase scenario.

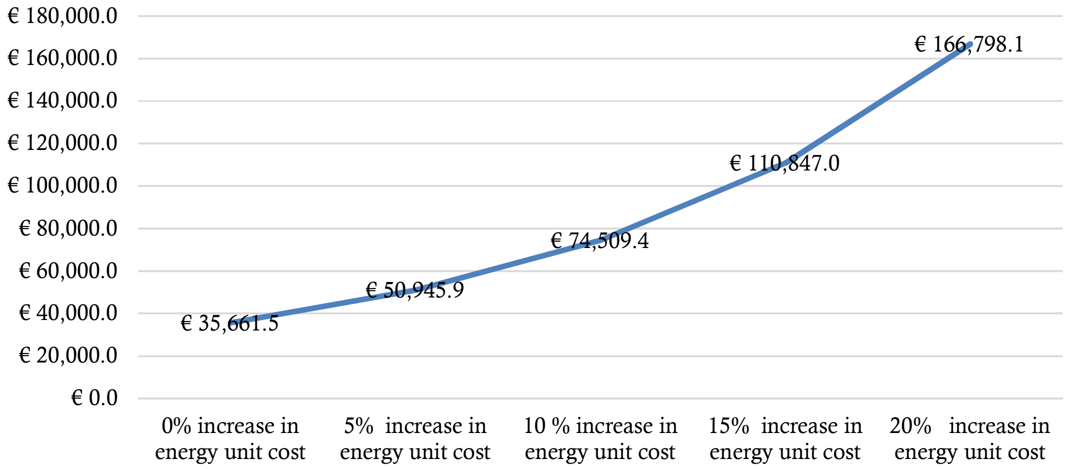


Figure 7-9: NPV for ESP 6-15 for different energy price scenarios

7.5 CHAPTER SUMMARY AND CONCLUDING REMARKS

The objective of this chapter was to present the LCC assessments of the identified ESPs based on the NPV method and evaluation and prioritization of them with regards to various decision criteria. Initially, the cumulative sum of the all identified ESPs was presented to see their overall energy reduction impact over the total energy consumption of the subject plant. The ESPs were categorised into two main groups: cost-free ESPs and ESPs requiring initial investment. The results of the economic assessments conducted on the ESPs requiring initial investment were presented. The ESPs requiring initial investment were ranked and prioritised with regards to four decision criteria, which are annual ESP, NPV, B/C. and IPC. The ESPs were evaluated based on a scenario analysis which assigns relative weights to each criterion depending on their importance defined in each scenario. Finally, a sensitivity analysis was performed to see the effect of changes in discount rate and energy unit cost rate on the economic feasibility of the ESPs. Thus, the thesis objective 6 was completed.

The following conclusions can be deduced from this chapter:

- As a result of the energy audit conducted on the target energy consuming systems of the subject plant, there have been identified 31 ESPs with various technical, economic, and environmental benefits. The cumulative sum of the all annual ESPs (that can be applied together) is 534,187 kWh. This is about 18% of overall plant annual energy consumption implying that the subject plant can be technically 17.8% energy efficient in comparison the baseline energy consumption. What is more, it is technically possible to reduce the energy consumption of the subject plant by 23.4% through a best-case-scenario in when the subject plant performs best melting process practices which are more energy efficient and productive.

- Of 32 ESPs, the application of 7 ESPs do not require any capital investment. The sum of these cost-free ESPs is 178,364 kWh/year which accounts for an attractive 35% of the total annual ESP (i.e. 534,187 kWh). Because there involves no cost to implement these ESPs, the subject plant can immediately act to materialise the cost-free ESPs.

- Of cost-free ESPs, 5 ESP (ESP 6-17, ESP 5-3, ESP 5-6, ESP 5-10, and ESP 5-11) are related to human factors. This clearly shows the lack of awareness of the energy issues in the subject plant. Bearing these in mind, the subject plant can consider conducting an energy awareness training within the plant. The sum of their annual ESPs is 23,501.45 kWh greater than the annual ESPs provided by some technicalities-related ESPs which require an initial capital cost to implement. Besides, materialisation of these ESPs is very straightforward: simply "keeping the unnecessarily working energy consumers off". Thus, the analysis in the energy audit has revealed the importance of human factors for energy efficiency.

- Of 32 ESPs, 6 ESPs (ESP 6-5, ESP 6-6, ESP 6-7, ESP 6-8, ESP 5-8, and ESP 5-9) were found to be economically non-feasible because their LCC analysis revealed negative NPVs. However, because ESP 6-5, ESP 6-6, ESP 6-7, and ESP 6-8 are alternatives to ESP 6-4 or ESP 6-5 to be applied in the compressed air system, only one ESP could be applied to the compressed air system and others would be eliminated even if they were economically feasible having a positive NPV. Regarding economically non-feasible ESP 5-8, its annual ESP can be considered as dispensable because it is just 662.67 kWh/year. Instead of applying this economically non-feasible ESP, efficient notched V-belts can be employed when the existing standard belts used in the abrasive blasting system are torn or worn off. ESP 5-9, ESP by replacing the old lathe with a new one, can by no means applied in terms of economic considerations since it requires a significant investment costs and does not pay itself off. This machine tool has a twin with the same size and capacity but new. Instead of replacing this machine with a new one which is economically non-feasible, the newer machine tool should be preferred as much as possible and the old one can be used for overtime works where the work cannot be finished in a certain lead time only with the newer one. If the older one is required to be use, it should be used with optimal process parameters and the idle workings should be avoided

- Increasing the discount rate increases the NPV of the ESPs and vice versa. Considering that the energy inflation is likely to be higher than the normal inflation, it is likely that the real-time investments in the identified ESPs will be more profitable than the 0% energy price increase scenario which assumes that energy priced are only affected by the normal inflation.

8

Feasibility of Microgrid Application with Renewables and Demand Response

8.1 INTRODUCTION

This chapter explores the techno-economic feasibility of the application of a hybrid microgrid with renewables and demand response for the subject plant. The methodology followed in this chapter was given Section 3.3.2 in Chapter 3. Following the steps in the microgrid application methodology presented in Chapter 3, this chapter is comprised of the following sections:

- Section 8.2 presents microgrid modelling steps for microgrid feasibility analysis. This includes the plant electricity consumption modeling (Section 8.2.1), modelling of energy supply options and of microgrid components (Section 8.2.2), energy efficiency (Section 8.2.3), and sensitity analysis (Section 8.2.4),
- Section 8.3 presents the simulation results which shows the results of the microgrid feasibility analysis,
- Section 8.4 presents the demand response modelling,
- Section 8.5 presents the result of demand response simulations,
- Finally, Section 8.6 concludes the chapter with a summary of the chapter and concluding remarks.

8.2 PLANT ELECTRICITY CONSUMPTION MODELLING (STEP 1)

To produce a typical daily electricity load curve which represents the entire manufacturing plant power demand, all specific load curves of individual users were augmented together, and a high resolution aggregated electric load was generated. The accuracy of power demand data both in terms of magnitude and distribution is of very important as this will directly affect the feasibility of the project. The generated secondly power demand was averaged to one-minute interval values to use as input to the equipment database of the HOMER. During the energy audit, few of the energy consuming systems were not be able to be measured for their consumption. Their power demand values were estimated based on the power ratings, operating periods and system characteristics. The load profiles of individual energy consuming systems can be seen in Figure F-1 and F-18 in Appendix F. Plant power demand and consumption for a typical production day over a 24-hours period can be seen in Figure 8-1.

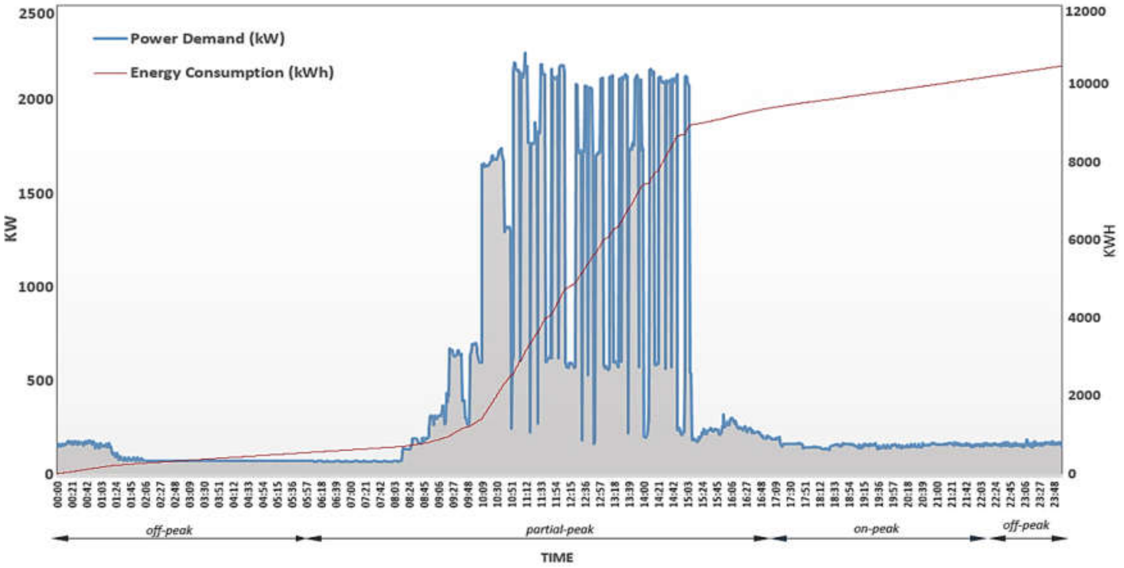


Figure 8-1: Plant power demand and consumption for a typical production day over a 24 hours period

The one-minute interval power demand values presented in Appendix F entered to the HOMER data base. HOMER produced the representative daily load profile of the subject manufacturing plant shown in Figure 8-1. The average daily power load profile of the plant shows more or less the same shape each day across a year because the major power users (i.e. induction furnaces of 1500 kW and 350 kW) operates in day time shift and the same operation patterns for these furnaces are followed as it was described in Chapter 5. But there can be minor variability for the time that furnaces are on and off. This also applies to other power using systems. HOMER allows a user to model this variability by adding randomness to the load data to make it more realistic. For this reason, 5% for day-to-day variability and 13% for timestep variability have been entered to HOMER. Based on these values, HOMER calculated the load factor as to be 17% which is equal to the real load factor value of the subject plant which was calculated and presented in Section 8.5.1.

8.3 MODELLING MICROGRID COMPONENTS AND ENERGY SUPPLY OPTIONS (STEP 2)

8.3.1 WIND POWER AND WIND TURBINE

8.3.1.1 PLANT LOCATION WIND POTENTIAL

Figure 8-2 shows the wind speed map at 50 m for the province where the plant is located. According to Manwell et al. (2009), locations with average annual speed of more than 5.6 m/s are suited for wind power generation. As seen in the wind speed map in Figure 8-2, the average annual wind speed at 50m for the plant location is around 6-6.5 m/s. Measured hour-to-hour average wind speed data at 10 m for the region where the plant located (Figure 8-3) have been obtained from Turkish State Meteorological Service in order to use as input for HOMER.

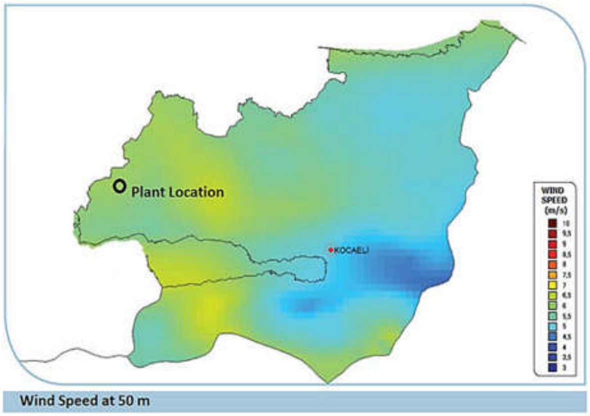


Figure 8-2: Wind speed map at 50 m for the province the plant is located (REGD, 2015)

Figure 8-3 illustrates the measured hour-to-hour average wind speed data at 10 m for the region where the plant located based on the data obtained from Turkish State Meteorological Service (TSMS) (TSMS, 2015).

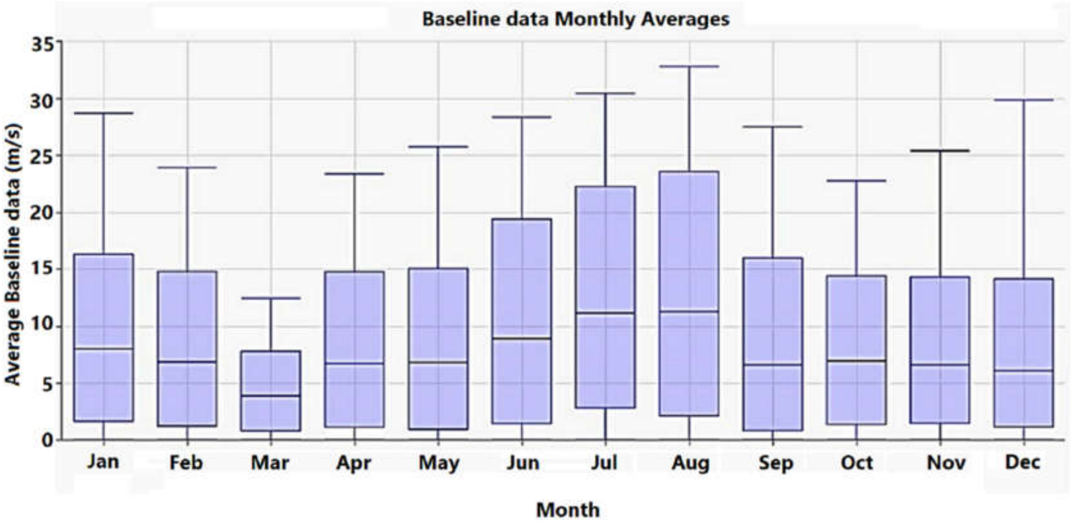


Figure 8-3: Wind speed monthly averages in the case plant region at a height of 10 m

8.3.1.2 WIND TURBINE SPECIFICATIONS

Five wind turbines with different power ratings will be modelled in this study. They are Vesta V90/2.0, Vesta V90/1.8, GE 1.5s, Nordex N60/1.3, and E44/0.9. Their technical specifications can be seen in Table 8-1. Their power ratings are 2.0MW, 1.8MW, 1.5MW, 1.3MW, and 0.9MW, respectively. These wind turbines are not modelled in HOMER to work in parallel. This is because the plant can only accommodate 1 wind turbine. To see which wind turbine size can contribute to the optimal micro-grid configuration, simulations for grid-connected and standalone microgrid configurations are run separately for five different turbines. The data in Table 8-1 are entered as the wind turbine input specifications to HOMER.

Table 8-1: Technical specifications for the wind turbines

Parameters	V90/2.0	V90-1.8	GE1.5s	N60/1.3	E44/0.9
Power rating	2.0MW	1.8MW	1.5MW	1.3MW	0.9MW
Cut in speed	4m/s	4m/s	4m/s	4m/s	3m/s
Cut-out speed	25m/s	25m/s	25m/s	25m/s	25m/s
Rotor diameter	90m	90m	70.5m	60m	44m
Hub height	105m	105m	85m	69m	65m
Swept area	n/a	6,362m^2	n/a	2,828m^2	1,521m^2
No. of rotor blades	3	3	3	3	3
Lifetime	20 years	20 years	20 years	20 years	20 years

One may regard the size of wind turbines as enormous. The induction melting furnaces of 1500 kW and 350 kW has a dramatic impact on the wind turbines size and capacities. Their power ratings (e.g. 1500 kW) are very significant compared to other energy consuming systems of which power and have a significant share in the power demand profile of the subject plant. Because of this, very big wind turbines size is needed as the simulation results will have shown in the forthcoming sections. For a less energy intensive manufacturing plant, for example if the induction furnaces are removed from the system, smaller wind turbines could be enough. In such a case, even a PV system could have had a considerable share on the overall power generation depending on the available plant roof area and power demand of the plant.

8.3.1.3 WIND SPEED ADJUSTMENT

As explained in Section 3.4.2.5.2.1 in Chapter 3, the wind speeds at 10m need to be correlated to the wind speeds at the hub heights of the selected wind turbines. HOMER uses Equation 3-17 for wind speed adjustment between two different heights (Lambert, 2009a). Following this, HOMER calculates the power output of the wind turbine referring to its power curve using Equation 3-18.

8.3.1.4 WIND TURBINE COSTS

Besides the technical specifications, economic figures of the wind turbines are needed for economic simulations. Bloomberg NEF (NEF, 2014) reports global average pricing for the most-recent contracts of approximately $1300 (€1040)/kW in 2013 for newer turbine models that feature larger rotors. The wind turbine prices are expected to drop by 1%-6% per year in the near term (Lantz et al, 2012). In 2015, capital cost for a new wind turbine is assumed to be €968/kW based on average cost reduction of 3.55% per year. Because the life time of a wind turbine is assumed to be 20 years and the project life time is 25 years, there will be a replacement cost 20 years later. The replacement cost per kW after 20 years is assumed to be €774/kW based on a conservative 20% cost reduction in 20 years ((Lantz, 2014)). Table 8-2 summaries the cost assumptions used for wind turbine economic modelling in HOMER.

Table 8-2: Cost assumptions for wind turbine

Capital Cost	968 €/kW
Replacement Cost	774 €/kW
Annual O & M	2% of initial capital cost

8.3.2 SOLAR PV SYSTEM

8.3.2.1 GLOBAL SOLAR IRRADIATION POTENTIAL

Figure 8-4 shows the average solar radiation at the plant coordinates (40.862713, 29.416021). This data is provided by HOMER based on the specified subject plant coordinates and HOMER uses it as an input to use in Equation 3-19 and Equation 3-20.

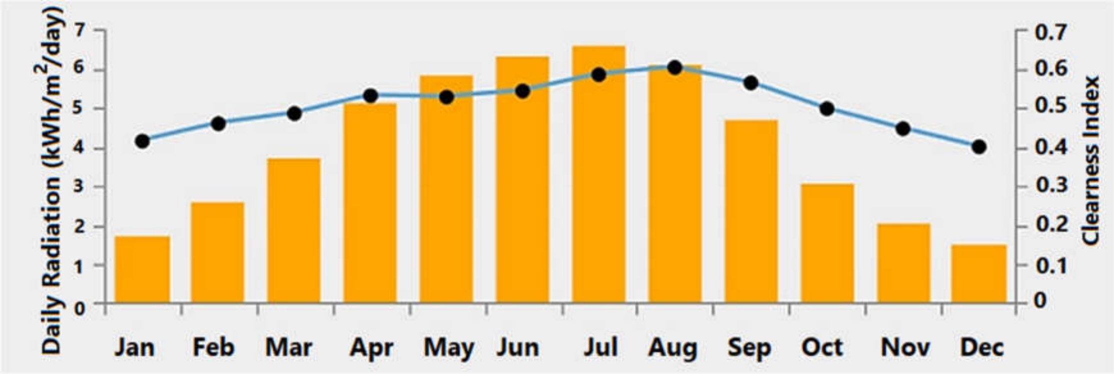


Figure 8-4: Average solar radiation and clearness index at plant location

8.3.2.2 PV PANELS ORIENTATION

Figure 8-5 shows an overview and orientation of the case plant. The plant roof has two extensive zones very exploitable for PV panel installation. Therefore, the PV system for the plant will be a roof-top system. The orientation of PV arrays has a significant importance as this will influence the incoming radiation on the module surfaces. The PV arrays orientation in such a rooftop PV system can be set in two ways. The first way is the same orientation as the roof by mounting the PV modules parallel to the roof surface, which is in the same azimuth and tilt angle of the roof zones. The second way is in an ideal orientation in which a PV module receives the maximum solar radiation throughout a year, by using rack mounts to tilt up the PV panels on the roof and facing due south. The ideal tilt angle of the PV panels should be equal to the latitude of the location plus 15° in winter and minus 15° in summer (REC, 2014). These will be 55.86° in winter and 25.86° in summer for the subject plant and the optimum tilt angle which receives the maximum solar radiation can be sought between these two angles. However, when the PV panels are tilted, there has to be some gap between PV arrays in order to prevent mutual shading of PV modules as it reduces the module performance. In this case PV modules number per available space will decrease. Further, tilting the PV modules at an optimum angle and facing due south over a sloped roof surface will require a complex mounting task. Mounting racks for tilting the PV modules in this option are relatively more expensive per PV module as they require extra structural material and more strength against wind forces whereas the mounting materials in the first option are relatively straight forward and less costly. Therefore, PV modules for the subject plant in this study have the same orientation of the roof zones.

The area of each zone is about 1140 m^2 and the total PV suitable roof area is 2228 m^2. The total number of PV modules that can be installed on two roof zones is 1176 which makes a total installed power of 329.28 kWp with the selected PV module when a walking area is deducted in two zones. As seen in Figure 8-5, roof zones face different directions due to the roof shape. While zone 1 faces North West, zone 2 faces South East and has an advantage of having more sunlight. As a result of this, the performance of the PV modules in zone 2 and zone 1 are different from each other and they need to be handled separately. Therefore, they were modelled as two different PV power generation systems in HOMER. Table 8-3 summaries the orientations of roof zones which are used as PV modules orientation in HOMER.

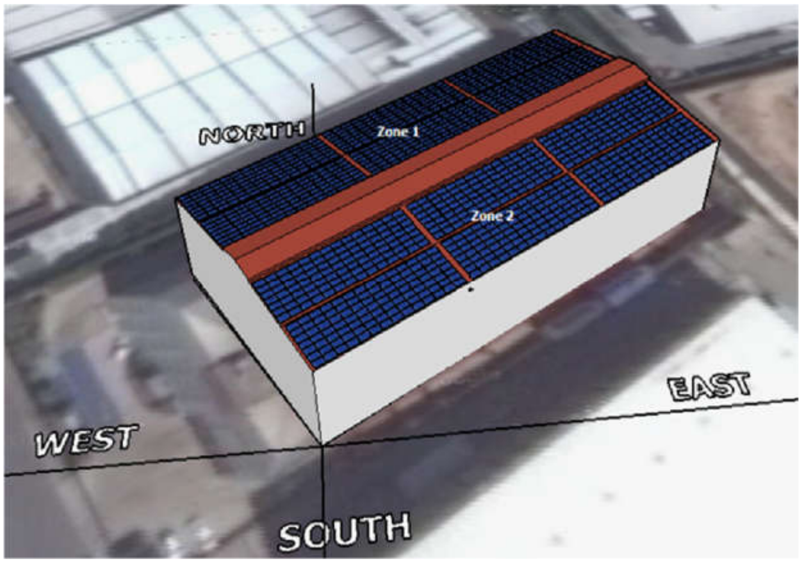


Figure 8-5: The plant orientation

Table 8-3: Roof zones azimuth and slope angles

	Azimuth angle	Slope angle
Roof zone 1	122°	9 °
Roof zone 2	-32 °	9°

In this point, a valuable implication can be referred to initial factory building designs. In order to maximally benefit from the PV panels installed on the factory roof, as long as the area where a plant is to be settled allows, the optimal plant orientation and roof angles which will produce the best PV performance should be taken into account and designed accordingly. In other words, PV system design should be factored into the initial factory building design.

8.3.2.3 PV SYSTEM COST ASSUMPTIONS

In order to model cost components of the PV system, the latest cost structure for the chosen PV module and other cost elements were obtained from a vendor in Turkey (Edites, 2015). As the PV panel life is the same with project life cycle which is 25 years, replacement cost is irrelevant, and it is not taken into account. Table 8-4 presents the PV system cost assumptions.

Table 8-4: PV system cost assumptions

Item	Capital Cost (€/kW)	O & M Cost (€/kW.year)
Monocrystalline PV panel	678.5	
Mounting racks and assembly kits	118.78	
DC cables	23.32	
AC cables	20	
Transportation	6.07	
Static grounding	9	
Breaker and switch panel	43.32	
Labour cost	26.64	
Others	6.67	
Total PV system	932	16.65

8.3.3 DIESEL GENERATOR

A variable speed diesel generator is used and modelled in this study based on the technical specifications of a typical generator Innovus Power which is already provided in the database of HOMER Pro. As regards the generator size, the sizes of 0 kW, 100 kW, 300 kW, 600 kW, 900 kW, and 1200 kW were taken into account and entered to the search space of HOMER in order to find the optimum system. 0 kW is considered so as to see the performance of the micro grid without a generator.

8.3.3.1 DIESEL GENERATOR COST ASSUMPTIONS

Although conventional fixed speed diesel generators are very well-established and mature technology and available in the market, generators with variable-speed, constant-frequency technology are comparatively new. Also, variable speed diesel generators will have higher investment costs because of the additional cost of power controller technology. The latest cost figures for conventional generator sets of various sizes and brands have been obtained from a vendor in Turkey (Emsa, 2015) and a cost increase factor by 1.3 based on (Dengler et al. 2011) have been applied to these values to estimate the capital cost for the same size of variable speed diesel generator. Normally, an additional cost to account for the installation of the generator should be integrated into the initial capital cost. In this respect, 10% of the initial cost of each generator can be assumed for it based on (Adaramola et al., 2014). However, the installation cost will not be taken into account for the subject plant in this study because it is assumed that, as reported by the plant management, the installation of the generator set will be carried out by the plant maintenance team. Replacement costs will be assumed to be 90% of the present investment costs based on (Soshinskaya et al., 2014). Additionally, O & M costs for variable speed generators will be assumed not to exceed those of the conventional generators based on (Dengler et al. 2011). A good rule of thumb is that O & M costs for a power delivery system should run between 1/8 and 1/30 of capital cost on an annual basis (Karhammar et al., 2006). The cost assumptions for the diesel generators and fuel price (Doviz, 2015) are summarised in Table 8-5. These values were entered to the HOMER search space so that HOMER simulates all combinations of these values to find out the most efficient configuration.

Table 8-5: Cost assumptions for VS diesel generators

Capacity (kW)	**Capital Cost (€)**	**Replacement Cost (€)**	**O & M Cost (€/hr)**	**Diesel fuel price (€/l)**
390	64,500	58,050	2.38	1.377
600	78,484	70,635.60	2.9	1.377
730	101,976	91,778.40	3.77	1.377
1090	152,606	137,345.40	5.65	1.377

8.3.4 CONVERTER

In this study, ZBB EnerSection ® converters were chosen from HOMER database and modelled. The cost figures for converters are €150/kW for capital cost and €100/kW for the replacement cost at the end of 20 years of life cycle. These cost figures were obtained from the market survey (Edites, 2015). The HOMER optimizer was used to find the optimum converter capacity.

8.3.5 ENERGY STORAGE

8.3.5.1 FLOW BATTERY BANK COST ASSUMPTIONS

Cost ranges for flow batteries significantly vary based on the size and design of the system. The initial investment cost of a flow battery system consists of the cost of cell stack and cost of the electrolyte with storage tanks ((De Boer and Raadschelders, 2007). Based on (Viswanathan et al., 2014) the initial capital cost for the cell stack of a vanadium flow battery range from 458-1066 $ kW^{-1} with corresponding cost ranges for the electrolyte being 81-204$ kWh^{-1}. Estimates of (762) 458 $ kW^{-1} and (142) 81 $ kWh^{-1} for cell stack and electrolyte, respectively, were used in this study. A €1.1 Euro per USD conversion was used for Euro-USD conversion. At the end of their useful life, cell stack has to be a replaced so that there will occur a replacement cost. Flow batteries is not yet very completely mature technology; therefore, their capital costs are expected to decrease to lower levels in the future (de Boer and Raadschelders, 2007). While cost estimates for 2007 vary from 750-2750 € kW^{-1} for cell stack based on (de Boer and Raadschelders, 2007), present values are between 458-1066 $ kW^{-1} as mentioned. For this reason, their replacement cost after 20 years of life cycle is assumed to be around 400 € kW^{-1}. As for O & M cost, it is assumed to be 44 € kW-year $^{-1}$ based on (Viswanathan et al., 2014). There is no replacement cost associated with the electrolyte as it has an indefinite life. Table 8-6 summaries the cost assumptions for VRB ESS storage system.

Table 8-6: Cost assumptions for VRB ESS storage system (Viswanathan et al., 2014).

	Capital	**Replacement**	**O & M**
Cell Stacks	503.8 €/kW	450 €/kW	44 €/kW.year
Electrolyte	89.1 €/kWh	-	-

Regarding the capacity of the battery bank power (i.e. cell stacks) and storage capacity (i.e. electrolyte), the values presented in Table 8-7 were entered to HOMER Search Space for capacity optimisation. HOMER simulates all combinations of these values to identify the optimum capacity.

Table 8-7: Cell stacks and electrolyte capacities entered to HOMER search space

	Capacity
Cell Stacks (kW)	100; 300; 600; 900; 1200; 1500; 1800
Electrolyte (kWh)	100; 300; 600; 900; 1200; 1500; 1800

8.3.6 GRID

Grid power price (€/kWh) and demand rate (€/kW) were entered to HOMER based on the plant bill values as summarized in Table 8-11. In addition to the cost rates, the grid CO_2 emission factor was assumed as to be 0.49 kg-CO_2/kWh as given in Chapter 3 and entered to HOMER. Grid sellback unit price was entered to HOMER to be as 0.0905€/kWh. Besides, there is an extra support price for the use of domestically manufactured renewable generators. If domestic renewable generators are used in the project, the sellback rate becomes 0.137 €/kWh which corresponds to an increase of 50% from the current sellback rate 0.09043 €/kWh. This is considered in the sensitivity analysis in Section 8.9.

8.3.7 MICROGRID CONTROLLER

The capital cost of microgrid controller in this thesis is assumed to be €103,200 based on a case study carried out by Soshinskaya (2013). This cost includes all controllers, communication devices, and disconnect switches. The O & M cost is assumed to be 5% of the capital cost. The lifetime is 25 years. These values were defined in HOMER. Therefore, there is no replacement cost because the lifetimes of the controller and project life time are the same (Soshinskaya, 2013).

8.4 MICROGRID FEASIBILITY SIMULATION RESULTS

The simulation results for the techno-economic feasibility of the microgrid application for the subject plant based on the modelling are presented. First, the performance of renewable energy generators, i.e. wind turbines and PV system, are presented and discussed. Thereafter, technical, and economic potentials for various feasible GC and SA microgrid configurations are presented followed by the presentation of optimal microgrid configuration.

8.4.1 PERFORMANCE OF RENEWABLE GENERATORS

Energy generation systems are non-dispactable and the micro-grid has not a direct control on power generation from these systems. Their electricity generation performance and output will be the same in each microgrid configuration. On the contrary, other dispactable generators such as grid and diesel generator and other components such as energy storage operation can be controlled by the micro-grid depending on the microgrid configuration and economic factors and they will show different performance characteristics in each microgrid configuration. Therefore, the performance of renewable energy generators will be presented in the following parts.

8.4.1.1 WIND TURBINE PERFORMANCE RESULTS

Figure 8-6 shows the total energy productions in a year and capacity factors (C_f) of the wind turbines used in the microgrid simulations. C_f shows the field performance of a power generator and defined as the ratio of the energy actually produced by the generator to the energy which could have been generated if it would have operated at its rated power throughout the operation period (Mathews, 2006). As seen in Figure 8-6, the best C_f has been achieved as 36.1% for the wind turbine V90-1.8 MW with a power rating of 1800kW. The C_fs for other turbines are 35.36%, 29.68 %, 24.19%, and 22.73% for V100-2.0MW with a power rating of 2000kW, for GE1.5s with 1500 kW, N60/1.3 with 1300kW, and E44/0.9MW with 900kW, respectively.

As seen in Figure 8-6, although V90-1.8 MW has a lower rated capacity and produces less energy in comparison to the Vesta V100-2.0 MW, it has a higher C_f. This is because they have the same tower height (i.e.105m) and hence subject to the same wind speeds. This makes the V90-1.8MW generate electricity close to its rated capacity and it achieves a higher C_f. This relation can also be seen between wind turbines E44/0.9MW and N60/1.3. The C_f for the wind turbine E44/0.9MW (i.e. 22.73%) is just slightly less than the C_f for the wind turbine N60/1.3 (i.e. 24.19%) despite the considerable difference between their rated capacities. This is again due to the tower height factor. The tower heights for E44/0.9MW and N60/1.3 are 69m and 65m, respectively. This makes E44/0.9MW be exposed to similar wind speeds and approach to its rated capacity compared to N60/1.3.

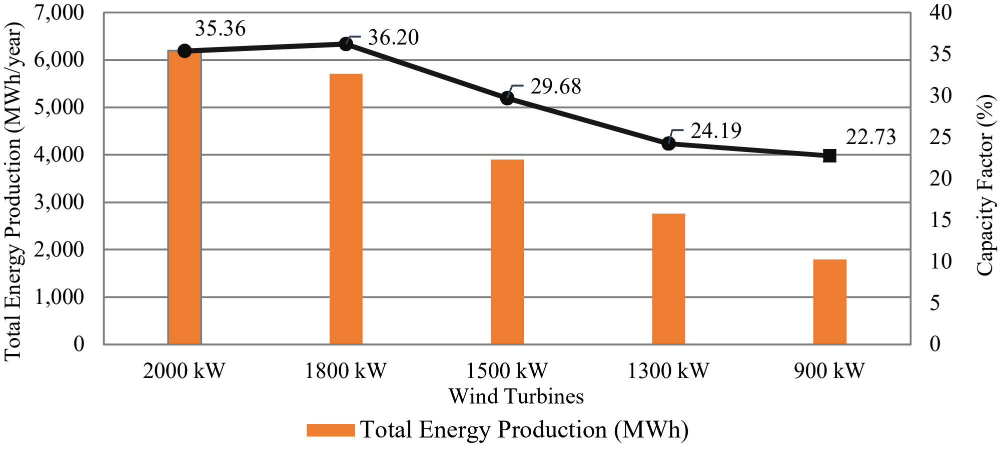


Figure 8-6: Annual total energy production and C_f for the wind turbines modelled and used in the microgrid

Figure 8-7 shows the LCOE values for the wind turbines. As seen, the lowest LCOE was achieved as €0.023423 per kWh by V90-1.8 MW. LCOE for other turbines are €0.024129, €0.028747, €0.03602, and €0.03754 for V100-2.0M, GE1.5s, N60/1.3, and E44/0.9MW, respectively.

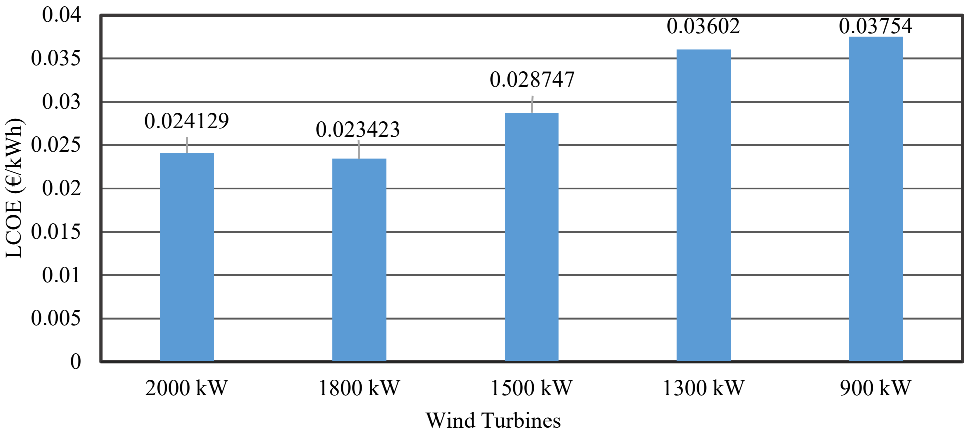


Figure 8-7: LCOE values of wind turbines modelled and used in the microgrid

8.4.1.2 PV SYSTEM PERFORMANCE RESULTS

Figure 8-8 and Figure 8-9 illustrate the power generation distribution over a year for PV2 and PV1, respectively. As seen in these figures, there is a significant difference in power output from the PV systems between summer days and winter days as well as between daytime and night-time. This significant difference is quite as anticipated since the higher incoming solar radiation, through the increasing solar altitude during summer days, leads to greater power production in comparison to the winter days. Accordingly, the average hourly power output from PV2 and PV1 during winter months (from 1st December to 28th February) are 11.63 kW and 9.25 kW, respectively. Summer figures of average hourly power output are 33.60 kW for PV2 and 32.72 kW for PV1, which leads to an increase of around 65-70% compared to the winter figures. Similarly, power output from PV systems peaks in the afternoon of each day, as illustrated Figure 8-8 and Figure 8-9. This is because the sun reaches its highest point at noon during a day as it is evident from Figure 8-10, which shows the solar altitude change at the plant location throughout a year.

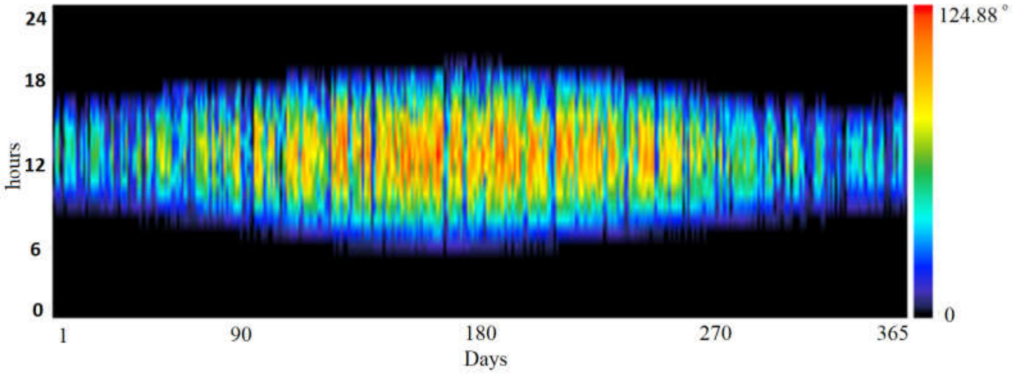


Figure 8-8: PV1 power generation (kW) over a year

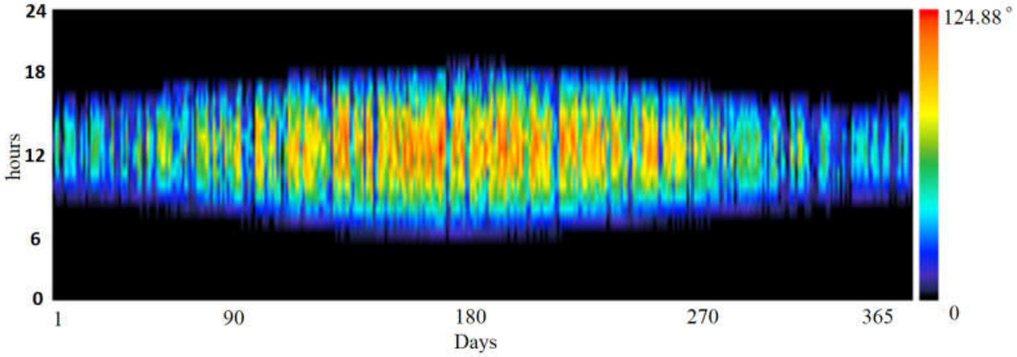


Figure 8-9: PV2 power generation (kW) over a year

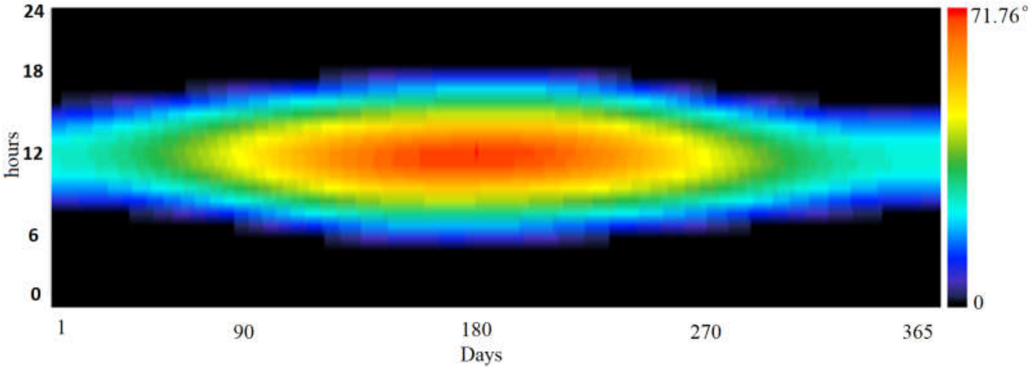


Figure 8-10: Solar altitude(°) change at the plant location throughout a *year*

Figure 8-11 compares the total annual energy generation by PV1 and PV2 and their capacity factors. The electricity generated annually is 197,669 kWh by PV2 and 181,035 kWh by PV1. This leads to an overall electricity generation of 378,704 kWh per year from the PV system in the microgrid. Also, the capacity factor for PV2 was 13.7% whereas it was 12.5% for PV1. Despite these slight differences, the LCOE for both PV2 and PV1 was calculated to be €0.026861 per kWh by HOMER.

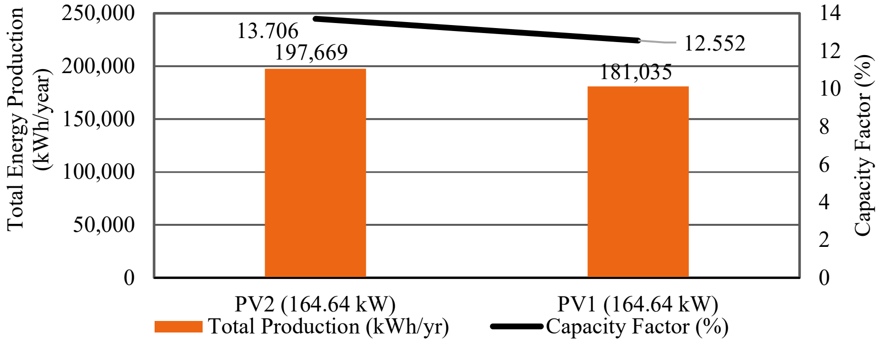


Figure 8-11: Total annual energy production and capacity factors for PV systems modelled and used in the microgrid

Although their installed powers are the same (i.e. 164.64kW) and made up of the PV modules of the same technical specifications, the energy yields and capacity factors for PV1 and PV2 are slightly different. PV2 has a higher energy production and capacity factor. This is because the solar panels of PV2 receive more solar radiation than the panels of PV1 due to the roof zone orientations. PV2 panels faces the South East through its tilt angle and receives more solar radiation whereas PV1 faces the North West as previously shown in Figure 8-5. The advantage of PV2 over PV1 is clearly seen in, which show the angle of incidence (°) over a year for PV1 and PV2, respectively. Angle of incidence is defined as the angle between a vertical line to the PV module surface and a line to the sun (Lambert, 2009a). As the angle of incidence approaches zero, the sun radiation strikes to the PV surfaces more vertically and the power yield is maximized. As indicated in Figure 8-12 and Figure 8-13, for the same hour and day of the year, PV2 has a smaller angle of incidence than that of PV1. As a result of this, PV2 produces more power in a year than PV1.

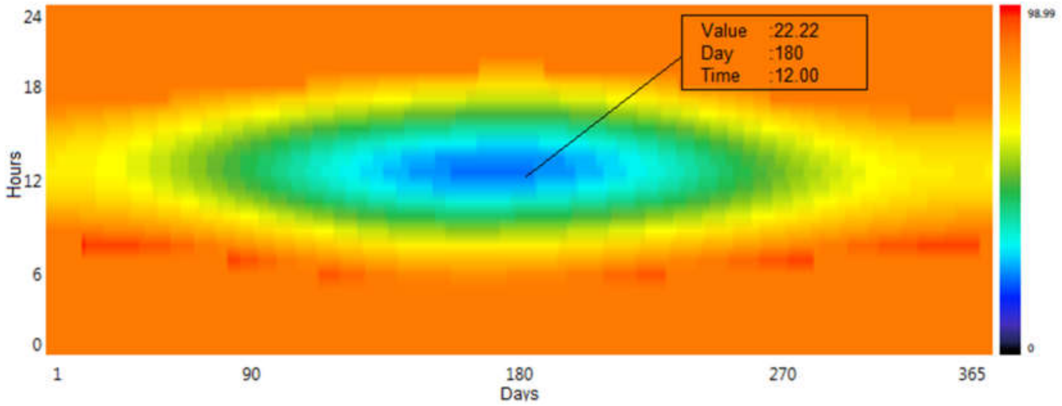


Figure 8-12**:** Angle of incidence for PV1

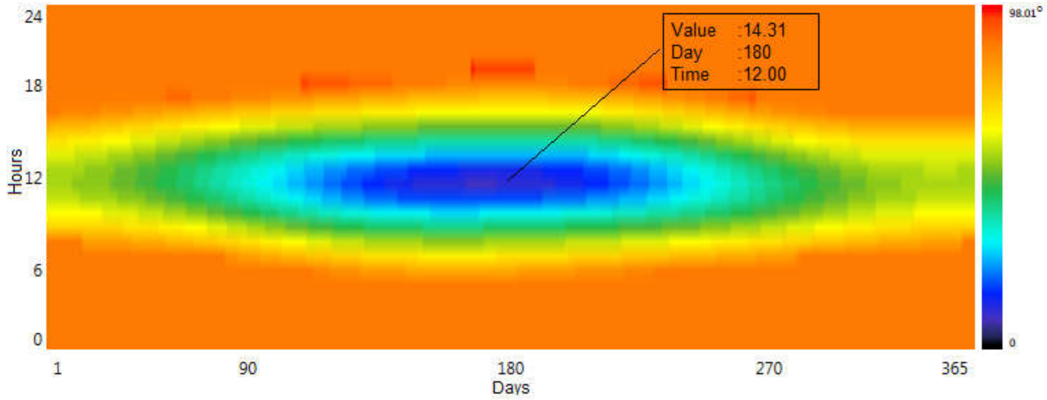


Figure 8-13: Angle of incidence for PV2

8.4.2 MICROGRID CONFIGURATIONS TECHNO-ECONOMIC POTENTIAL RESULTS

Having run HOMER for grid-connected and standalone scenarios, this section will be explaining the technical and economic potentials of various optimal microgrid configurations. Each optimal microgrid configuration are described in these tables by three major parameters groups:

- Microgrid configuration parameters
- Economic potentials parameters
- Technical potentials parameters

All parameters used to describe Microgrid Configurations, Economic Potentials, and Technical Potentials are presented in Table 8-8.

Table 8-8: Parameters used in microgrid optimisation result tables

Microgrid Configuration Parameters	**Economic Parameters**	**Technical Parameters**
· PV(kW)	· COE (€/kWh)	· Power generation (kWh/year) by power generators: diesel generator, PV system, and wind turbine
· WT(MW)	· NPV (€)	· Battery throughput (kWh/year)
· DG(kW)	· Operating Cost (€)	· Grid purchase (kWh/year)
· BB (kW) (power)	· Initial Capital (€)	· Grid sold (kWh/year)
· BB(kWh) (size)	· Cost/Benefit Ratio	· Total renewable energy generation (kWh /year)
· Converter(kW) · PS (whether peak shaving applied (Y) or not (N))		· Total energy generation (kWh/year) · RE fraction of total energy generation (%)
		· Plant energy use (kWh/year)
		· CO_2 emissions (kg-CO_2/year)

Before moving on to the simulation results, it should be noted that the wind turbine is the primary generator of microgrid configurations. Because there are 5 wind turbines with different power ratings, there can be defined 5 different microgrid configuration groups. In the following sections, "a WT-microgrid group" refers to one of these microgrid configuration group. For instance, 1.8MW-WT-microgrid group refers to the group which have microgrid configurations with a 1.8MW wind turbine and other microgrid components with varying capacities. There are 5 different WT-microgrid groups and each WT-microgrid group can have thousands of microgrid configurations. Also, the terms microgrid configuration and microgrid design will be used interchangeably in the following subsections.

8.4.2.1 STANDALONE SYSTEMS OPTIMISATION RESULTS

The feasibility of a SA microgrid shows whether a plant can be entirely self-sufficient in terms of power generation or not because the plant will be independent from the main utility grid power supply. To model a SA microgrid in HOMER in this study, the grid power supply was set to 0 kW. Thus, the HOMER controller never imports power from the grid. But, the grid sell back is activated so that the microgrid can sell power back to the grid promoting the economic feasibility.

As mentioned earlier, normally, the number of WT and capacity of PV system for the subject plant have to be limited to 1 and 329 kW, respectively, on the grounds of the plant space constraints which cannot accommodate more than the specified values. However, an initial simulation run by the Author showed that microgrid designs with these limited WT number and PV system capacity did not return any feasible results. Therefore, one can say that the subject plant cannot be completely independent from the main grid. Thus, in order to find out the optimal system type and capacity for 100% power self-sufficiency for the subject plant, the number and space constraints for WT and PV system are removed and HOMER quantity (i.e. for WT) and capacity (i.e. for PV) optimisations are enabled. HOMER will decide for the optimal number of WT and capacity of PV system without any constraints.

8.4.2.1.1 Highest NPV standalone microgrid configurations

HOMER produced hundreds of feasible SA microgrid design configurations. The highest NPV design configuration for each WT-microgrid group have been extracted from the overall simulation results and presented in Table 8-9.

As seen in Table 8-9, Microgrid Configuration SA_1.8 has the highest NPV (i.e. €20,751,630) which means that it is economically the most feasible option. Microgrid Configuration SA_1.8 consists of 5 1.8MW WTs, a 135 kW PV system, a 390 DG, a battery system of 100 kW/kWh, and a converter of 90kW. The RE % of total energy generation in this microgrid configuration is 98.6%. This microgrid configuration requires the smallest initial capital investment and provides the highest NPV among all. Hence, it has the greater B/C ratio which is 1.974. The subject plant can be self-sufficient most economically by deploying Microgrid Configuration SA_1.8. To be supplied by 100% renewable power, then, Microgrid Configurations SA_1.5, SA_1.3, and SA_0.9 can be deployed.

However, the capacity of PV systems and the number of WTs in each SA microgrid configurations are enormous in comparison to what size and capacity the subject plant can accommodate. This is as anticipated because the energy intensity of the subject plant is very high and, as such, without the presence of the grid supply, large power capacities of renewable generators are inevitable. Because of the space constraints of the subject plant, materialisations of these microgrid configurations are impossible. Therefore, the potentials for GC microgrid configurations will be explored in the following section.

Table 8-9: Extracted highest NPV SA Microgrid configurations for each WT-microgrid groups

Config No	MICROGRID CONFIGURATIONS						ECONOMIC POTENTIALS					TECHNICAL POTENTIALS										
	PV (kW)	WT (#*MW)	DG (kW)	BB (kW)	BB (kWh)	Converter (kW)	COE (€)/kWh	NPV (€)	Operating cost (€)	Initial capital (€)	B/C	DG (kWh)	PV (kWh)	WT (kWh)	BB Ann.Throughput (kWh)	Grid Purchase (kWh)	Grid Sold (kWh)	Total Ren Generation (kWh)	Total Energy Generation (kWh)	RE Frac of Total E. Generation (%)	Plant Use (kWh)	CO2 (kg/yr)
SA_18	135	5x1.8	390	100	400	90	-0.04363	20751630	1410190	9102621	1.974	296056	160649.8	28537730	157477.6	0	19699090	28698380	48693526	98.6	2920000	-9432455
SA_2	2253	4x2	390	200	400	1542	-0.04146	19465300	1409618	10376840	1.651	176089	2680710	24780010	202058.6	0	19286730	27460720	46923539	99.2	2920000	-9313015
SA_1.5	3959	5x1.5	0	150	1600	2361	-0.03679	15546430	1283422	11624100	1.204	0	4711017	19499330	445879.6	0	17292490	24210347	41502837	100	2920000	-8456028
SA_1.3	2330	6x1.3	0	100	800	1484	-0.03121	11106180	1012518	10329220	0.979	0	2772528	16531930	289629.8	0	14104590	19304458	33409048	100	2920000	-6897143
SA_0.9	4939	8x0.9	0	100	800	3001	-0.02668	9823065	1042444	12245880	0.739	0	5877356	14334960	289493.5	0	14713900	20212316	34926216	100	2920000	-7195099

8.4.2.2 GRID-CONNECTED SYSTEM OPTIMISATION RESULTS

This section explains the techno-economic potentials of optimal GC microgrid systems. Normally, HOMER produces hundreds of technically and economically feasible microgrid configurations. The microgrid configurations with the highest NPV ones in each WT-microgrid group are extracted and presented in the following subsection.

8.4.2.2.1 Highest NPV grid-connected microgrid configurations and the optimised system

Table 8-10 lists the highest NPV microgrid configurations from each WT-microgrid groups (i.e. 2MW-WT-microgrid, 1.8MW-WT-microgrid, 1.5MW-WT-microgrid, 1.3MW-WT-microgrid, and 0.9MW-WT-microgrid). The highest NPVs for 2MW-WT-microgrid, 1.8MW-WT-microgrid, 1.5MW-WT-microgrid, 1.3MW-WT-microgrid, and 0.9MW-WT-microgrid groups are GC2_1, GC1.8_1, GC1.5_1, GC1.3_1, and GC0.9_1, respectively. As one can see in Table 8-10, GC2_1 and GC1.8_ 1 show positive NPVs while GC1.5_1, GC1.3_1, and GC0.9_1 have negative values. Therefore, GC2_1 and GC1.8_1 are technically and economically most feasible options in their WT-microgrid groups.

Although GC1.5_1, GC1.3_1, and GC0.9_1are technical feasible because they can meet the plant load demand, they are economically not feasible as they have negative NPVs. One can see that the COE values of GC1.5_1, GC1.3_1, and GC0.9_1 are lower than the plant base COE. Despite this, any investments in these microgrid design configurations cannot be considered as rational from an economic point of view because they will not pay-off themselves as the net project savings will be less than the sum of the initial cost and the operation costs in their project life cycles.

Hence, there are two economically most feasible options: GC2_1 from microgrid 2MW-WT-microgrid group and GC1.8_1 from 1.8MW-WT-microgrid group. Both are economically the most feasible configurations in their groups.

Table 8-10: The lowest cost (highest NPV) microgrid design configurations in each WT-microgrid groups

Config No	MICROGRID CONFIGURATIONS						ECONOMIC POTENTIALS					TECHNICAL POTENTIALS										
	PV (kW)	WT (MW)	DG (kW)	BB (kW)	BB (kWh)	Converter (kW)	COE (€)/kWh	NPV (€)	Operating cost (€)	Initial capital (€)	B/C	DG (kWh)	PV (kWh)	WT (kWh)	BB Ann.Throughput (kWh)	Grid Purchase (kWh)	Grid Sold (kWh)	Total Ren Generation (kWh)	Total Energy Generation (kWh)	RE Frac of Total E. Generation (%)	Plant Use (kWh)	CO2 (kg/yr)
Base Case							**0.06554**	**-4106105**												**0**	**2920000**	**1427880**
GC2_1	**329**	**2**	**0**	**100**	**200**	**252**	**-0.01957**	**3086240**	**261561**	**2451101**	**1.138**	**0**	**378704**	**6195003**	**369607**	**1011069**	**4530766**	**6573707**	**7584776**	**86.43**	**2920000**	**-1721132**
GC1.8_1	**329**	**1.8**	**0**	**100**	**200**	**300**	**-0.01669**	**2431658**	**221833**	**2264635**	**0.978**	**0**	**378704**	**5707545**	**374055**	**927370**	**3961791**	**6086249**	**7013619**	**86.52**	**2920000**	**-1483832**
GC1.5_1	**329**	**1.5**	**0**	**100**	**200**	**252**	**0.00363**	**-411847**	**73470**	**1967230**	**-0.202**	**0**	**378704**	**3899867**	**364045**	**1212711**	**2439234**	**4278571**	**5491282**	**77.37**	**2920000**	**-599769**
GC1.3_1	**329**	**1.3**	**0**	**100**	**200**	**220**	**0.02361**	**-2211199**	**-19614**	**1795960**	**-1.245**	**0**	**378704**	**2755322**	**336503**	**1416856**	**1503322**	**3134026**	**4550882**	**67.96**	**2920000**	**-42282**
GC0.9_1	**329**	**0.9**	**0**	**100**	**200**	**220**	**0.04033**	**-3211809**	**-86439**	**1381863**	**-2.479**	**0**	**378704**	**1791870**	**294248**	**1702073**	**841811**	**2170574**	**3872647**	**54.75**	**2920000**	**420667**

8.4.2.2.2 Comparison of GC2_1 and GC1.8_1

As explained earlier in Chapter 3, to compare the NPVs of investments with different initial investment costs, B/C ratio is used in the proposed framework methodology. The NPVs for GC2_1 and GC1.8_1 are € 3,086,240 and € 2,431,658, respectively, whereas initial investment cost values are € 2,451,101 for GC2_1 and € 2,264,635 for GC2_1. Thus, the B/C ratios for GC2_1 and GC1.8_1 are 1.138 and 0.978, respectively, which means that GC2_1 has a higher B/C ratio and is a more profitable option to invest.

As one can see comparing GC2_1 and GC1.8_1 in Table 8-10, the only major difference in terms of microgrid architecture between them is the capacity of the wind turbines. As seen, GC2_1 is equipped with a 2.0MW wind turbine while GC1.8_1 employs a 1.8MW one. The size and capacity of BB and PV array for both options are 100kW/200kWh and 329kWh, respectively. Both ones do not require a diesel generator. As for the optimal converter capacity, it is 253 kW for GC2_1 and 300 kW for GC1.8_1.

Because the rated capacity of the wind turbine in GC2_1 is greater than that of GC1.8_1, the total renewable energy generation and overall energy generation in GC2_1 outstrip those in GC1.8_1. The renewable electricity produced and sold to grid in GC2_1 provides more revenue per initial capital cost compared to GC1.8_1. Owing to this, GC2_1 has a higher B/C ratio. However, GC1.8_1 is also a technically and economically feasible microgrid configuration, taking the lower initial investment cost into account, the subject plant can opt to invest in GC1.8_1.

In this study, based on the above explanations and the simulation results from HOMER, **the optimal microgrid design configuration is accepted to be GC2_1. The following subsections will discuss GC2_1 in more detail.**

8.4.2.2.3 Detailed description of Microgrid Configuration GC2_1

GC2_1 consists of a 2MW WT, 329kW PV system, a battery bank of 100kW/200kWh, and a 252kW converter. A diesel generator is not required. Such as a system requires an initial capital cost of €2,451,101 and provides a NPV of €3,086,240. Thus, the B/C ratio for this configuration is 1.138 which is the lowest amongst all other alternatives and makes this microgrid configuration the best design choice. The other economic merits, that are COE and annual operating cost, are -0.01957 €/kWh and €-261,561, respectively.

The Total Energy Generation in GC2_1 is 7,584,776 kWh/year. This has two major components: Grid Purchase and Renewable Energy Generation which are 101,106,9 kWh/year and 6,573,707 kWh/year, respectively. Thus, the RE fraction of the Total Energy Generation is 86.43%. The annual battery throughput is 369,607 kWh. The amount of energy sold to the grid is 4,530,766 kWh/year.

Figure 8-14 illustrates the monthly average power generation in GC2_1. As seen, the power generation is not constant because of the intermittent nature of renewables. It varies over the months. The solar PV generation peaks during summer months while the wind power does not follow of a strict seasonal variation. Due to the monthly varying contribution from the renewable generators, the grid purchase also varies.

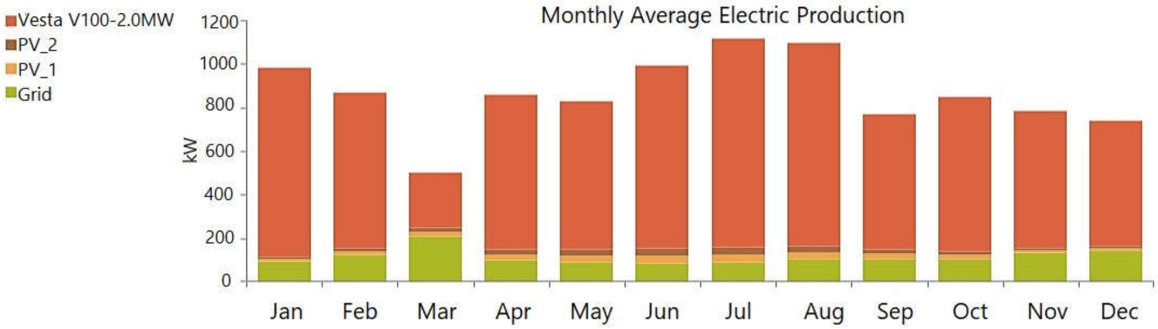


Figure 8-14: Monthly average electricity production in Microgrid GC2_1

Figure 8-15 shows the share of power generation by generators in GC2_1. As seen, the 2MW wind turbine is the major power producer among others accounting for about 83% of the overall electricity production. The other renewable generator, the 329 kW PV system, contributes to only 5% of the overall generation. It is obvious that the power contribution of the PV system is very limited because the available roof area where the PV modules are arrayed limits the PV power capacity. This can also be observed from Figure 8-16 which compares the total renewable power (total renewable energy output equals to sum of the wind turbine power output and solar PV system power output) and wind turbine power in a summer day where the PV system reaches to its maximum power production. As seen, the contribution of wind power to overall power generation is significant. Furthermore, during night hours when there is no sun, the wind turbine is the ultimate renewable energy generator in the system. This shows the importance of wind turbine for energy intensive manufacturing plants with a limited roof space which limits PV system capacity, provided that the plant location is rich in terms of the wind speed.

The grid purchase accounts for around 13% of the overall. This microgrid configuration does not need any diesel generator because the capacity of the other microgrid components can meet the subject plant power demand in a technically and economically viable way. In other words, there is no power generation shortage so that a diesel generator is not needed.

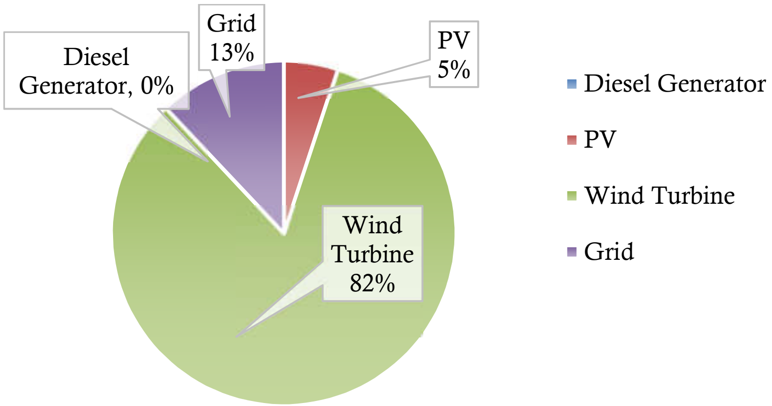


Figure 8-15: Share of power generation by generators Microgrid Configuration GC2_1

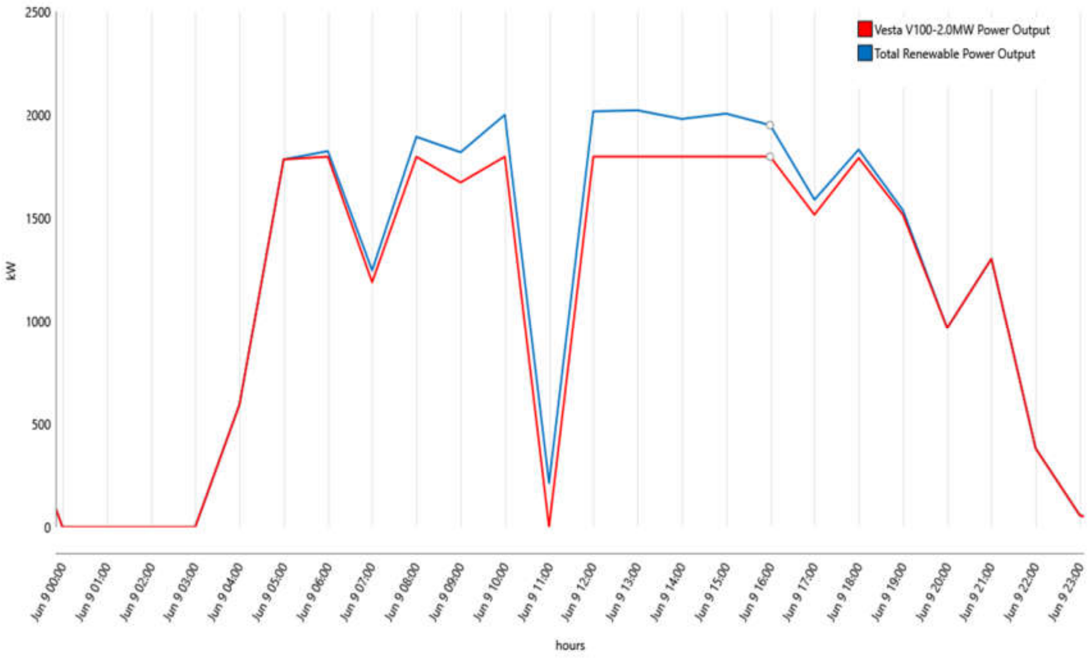


Figure 8-16: Comparison of total renewable energy generation and wind turbine output in a summer production day

As mentioned in the succeeding subsection, the maximum renewable energy generation capacity achieved in Microgrid Configuration GC2_1 can provide a RE faction of 87% of overall power generation (i.e. overall microgrid power generation equals to the generation from all generators plus the power purchased from the grid). The overall renewable generation (i.e. wind turbine +PV) is 6,573,707 kWh of electricity. The renewable electricity sold to the grid is 4,530,766 kWh. Thus, the difference between the overall renewable energy generation and renewable electricity sold to the grid is 2,213,806 kWh. Some of this power difference which is not sold to the grid is consumed by the plant. As one can see in Table 8-10, the plant annual electricity consumption is 2,920,000 kWh and the power purchased from the grid for the plant consumption is 898,099.8 kWh. The renewable electricity meets the remaining 2,021,900.2 kWh of the overall plant annual consumption. Based on this, one can say that the fraction of renewable energy directly consumed by the subject plant is 69% (i.e. 2,021,900.2 /2,920,00 0%). **Therefore, one can say that the subject plant can be partially self-sufficient at a maximum rate of 69%.** Although the total renewable energy generation is much more than the plant power consumption and it can cover the entire plant power need, the microgrid processor (i.e. the HOMER controller) sells most of the renewable based electricity back to the grid to create revenue and increase the cost effectiveness of the microgrid. Although the subject plant does not directly use the sold renewable electricity to the grid, it also increases the amount of renewable electricity on the main grid network, making it more **"low carbon"** in absolute terms. Indeed, while the electricity imported from the grid is 898,099.8 kWh, the exported electricity to the grid is 4,530,766 kWh. Thus, the net low carbon electricity gain of the main grid is 3,632,666,2 kWh. The resulting annual CO_2 emissions are – 1,721,132 kg-CO_2 whereas it is 1,427,880 kg-CO_2/year in the base case where the subject plant is powered only by the grid.

The distributions of energy purchased from the grid and energy sold to the grid throughout the day over the entire year in GC2_1 can be seen Figure 8-17. As seen, the energy purchasing from the grid takes place predominantly during working hours (i.e. between 10am-15pm) around 10am throughout the day when the plant load demand peaks which can be seen in Figure 8-18. This dramatic rise in power demand is due to the operation of induction furnaces which are the most energy intensive systems in the subject plant as explained before. On the other side, energy sells to the grid occur mainly during off-peak hours where the plant demand is very low as can be seen from Figure 8-17 and Figure 8-18.

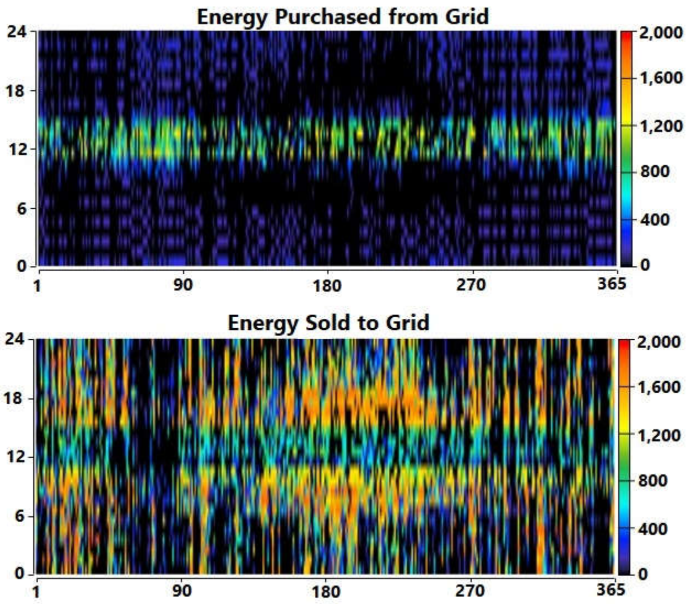


Figure 8-17: Distribution of grid energy sells and purchases throughout the day over a year for GC2_1

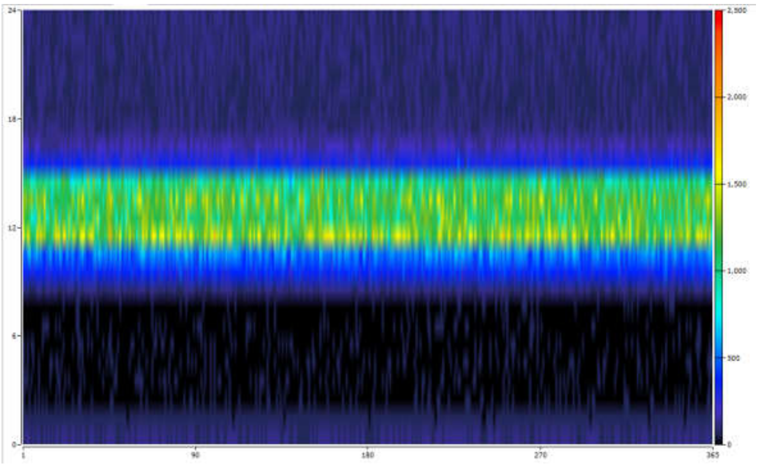


Figure 8-18: Plant load demand distribution throughout the days over a year for GC2_1

Without the PV system

If the PV system is removed from GC2_1, the NPV of the new microgrid design configuration, which can be named as GC2_2, becomes €2,335,986. The initial capital cost reduces to € 2,254,054. The B/C ratio becomes 1.036. COE and annual operating cost in GC2_2 are €-0.01574 and -216,814.2, respectively. The Total Energy Generation is 7,212,776 kWh/year. The Grid Purchase and Renewable Energy Generation are 1,017,773 kWh/year and 6,195,003 kWh/year, respectively. As seen, the total annual renewable energy generation equals to the annual energy generation of the 2MW wind turbine since the PV production is deduced from the system. As such, the RE fraction of total energy generation shows a slight reduction to 85.48%. The amount of energy sold to the grid is 4,091,429kWh/year. The resulting annual CO_2 emission is -1,503,018 kg-CO_2. Although GC2_1 has a better B/C ratio than GC2_2, there are not significant economic and technical potential differences. Considering the lower initial capital cost, GC2_2 can be a more attractive option to the subject plant management to invest. Overall, GC2_1 is the optimal microgrid configuration in this study.

8.5 DEMAND RESPONSE MODELLING (STEP 3)

8.5.1 PLANT ELECTRICITY BILLS ANALYSIS

There are two major cost components in the electricity bill of the case plant: consumption cost and demand charge cost. Consumption cost is charged based on the amount of active electricity consumed (kWh) in billing period and unit cost rate (€/kWh). The electricity consumption unit cost rates are established with regards to the tariff structure offered by the electricity provider. The electricity provider of the subject plant offers two types of tariff: 1) time-of-use (TOU) rate, 2) single flat rate. In TOU tariff, the customer is charged based on the time periods in which the electricity is consumed, so the unit cost rates per kWh will vary. In this tariff type, a day is divided to three main blocks: partial-peak, on-peak, and off-peak. The electricity provider of the case plant defines these periods as seen in Table 8-11. The unit cost rate for the electricity consumption is different for each period. The peak hours are the busiest hours of electricity consumption while off-peak periods are the least. The utility providers encourage the companies to shift their electricity consumption to the off-peak hours by offering lower unit cost rates for off-peak periods, so that less load will be imposed on their electricity infrastructure and less investment will be required. On the other hand, a single flat unit cost rate is charged regardless of the consumption period in single flat rate tariff. The subject manufacturing plant is currently charged according to the single flat rate for its electricity consumption. The latest unit cost rate figures for single flat and TOU tariffs and peak demand charge are shown in Table 8-11. As seen, electricity consumption unit cost is most expensive during peak periods 17:00-22:00 p.m. of time and cheapest during on off-peak periods.

As regards the demand charge, it is charged based on the peak (maximum) power demand of a plant during the billing period and unit cost rate (kW/€). Peak demands are measured based on the highest average power drawn by a consumer recorded over a short period (15 minutes for the subject plant) during one month (Morvay and Gvozdenac, 2008). Monthly peak power demands in a year for the subject plant can be seen in Figure 8-19.

Table 8-11: Electricity consumption and demand cost rates with regards to tariff types

Tariff	**Time period**	**Electricity consumption unit cost (€/kWh)**	**Demand charge unit cost (€/kW)**
Single Flat Rate	-	0.06554	0.80449
Time-of-Use (TOU)	partial-peak 06:00-17:00	0.06513	0.80449
	on-peak 17:00-22:00	0.11564	0.80449
	off-peak 22:00-06:00	0.0287	0.80449

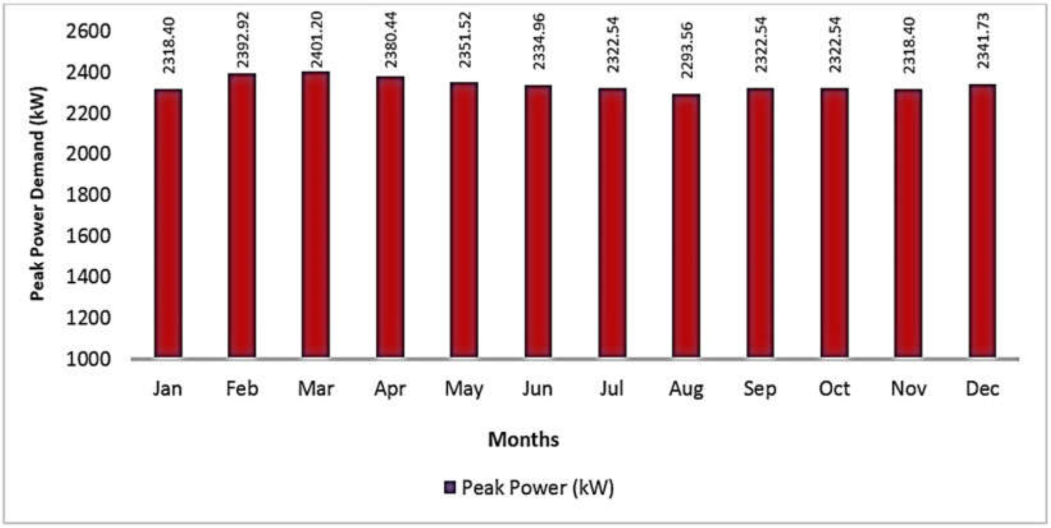


Figure 8-19: Monthly peak power demand for the subject manufacturing plant

The breakdown of monthly electricity consumption of the subject plant with regards to peak-on, partial-peak, and off-peak usage periods over a year can be seen in Figure 8-20 based on the plant electricity bills. As seen, significant amount of electricity consumption was in partial peak periods (06:00-17:00). This is because most of the production activities, particularly the melting processes, which has a dominant share on overall electricity demand, are carried out in day shift (08:15 a.m.-17:15 p.m.). Bearing these in mind, the potential of cost saving through shifting to TOU tariff for the subject plant should be explored.

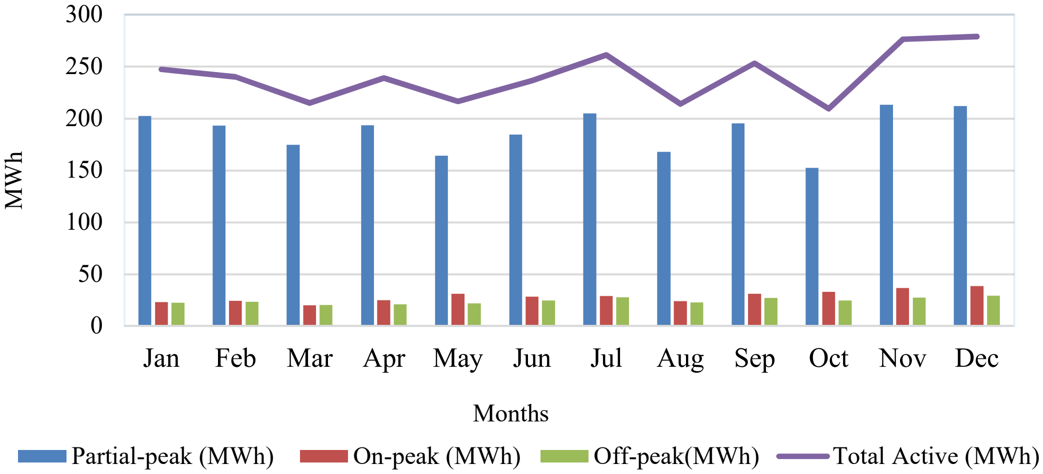


Figure 8-20: Breakdown of electricity consumption of the subject plant with respect to time of use

In addition to these, the power demand is also very erratic during the day shifts as can be seen in Figure F-19. This is due to the fact that there are numerous diverse energy consuming systems which operate independently in an intermittent manner. There are approximately 30 energy consuming systems with tremendously different power ratings. For example, induction furnaces for melting process with power ratings of 1500 kW and 350 kW have a tremendous impact over the peak power demand of the plant. This is because their power ratings are enormous compared to the other systems such as air compressor, cooling tower, ventilation fan with power ratings of 55 kW, 50 kW, and 45 kW, respectively. There are even smaller systems with 5-10 kW such as small fans, pumps, and lighting systems.

8.5.1.1 LF

Based on the electricity bills collected during the energy audit, the average monthly LF for the subject plant was found to be 17.24% which is dramatically low. This significant electricity consumption difference across the day and evening production shifts (Figure 8-1) and erratic nature of instant power demand leads to a lower LF and very high peak demands. This peak demand can be shaved by using an onsite generator which requires performing peak saving demand response measure.

8.5.2 PEAK SHAVING MODELLING

The peak shaving modelling method in Chapter 3 is applied to Microgrid Configuration GC2_1. The peak grid demand in GC2_1 is 1772kW based on the simulation results presented in the preceding subsection. This maximum grid demand will be lowered by peak shaving. To model this in HOMER, together with the peak demand in GC2_1 (i.e. 1772kW), maximum grid purchasing capacities between 1772 kW and 1300 kW at intervals of 50 kW (i.e. 1700 kW, 1650kW, 1600 kW, 1550 kW, 1500kW, 1450 kW, 1400 kW, 1350 kW) are introduced in Grid Purchase Capacity Search Space in HOMER.

To differentiate the microgrid configurations with a PS grid demand from the base case GC2_1, new abbreviations are defined suffixing PS_ "peak power demand" to GC2_1. For instance, GC2_1_PS1200 refers to microgrid configuration where peak shaving is applied by defining a maximum grid purchasing capacity of 1200kW to the base case microgrid configuration GC2_1.

8.5.3 GA USING ENERGY STORAGE MODELLING

The subject plant management is aware of the monetary benefits that shifting to the TOU tariff will provide. However, they state that furnace control and melting process is a potentially hazardous process which requires workers' attention and wakefulness so that performing these processes during late night hours might be dangerous. Furthermore, they state that shifting a part of work load will disturb their production planning and they can face various difficulties in terms of adapting to new planning. Hence, shifting the work load, particularly the energy intensive processes, is not a rational option for the subject plant due to the afore-said reasons. However, instead of shifting the work load off-peak hours which is a conventional way as a demand response measure, grid power can be purchased during low-cost off-peak hours and stored by a storage system and can be consumed during expensive on-peak hours or to cover peak demands.

GA using energy storage

The feasibility of implementing energy storage system in conjunction with TOU-based pricing is evaluated for the subject plant. For this purpose, the base case Microgrid Configuration G2_1 are modified. TOU-based energy consumption unit cost rates which are shown in Table 8-11 are defined in the grid component HOMER. Grid sellback rate and demand charge rate remain the same because they are the same in both tariffs.

The grid power will be purchased and stored in the microgrid batteries during off-peak periods when the grid power is cheapest and will be used on-peak periods. Do to this, HOMER provides some control parameters in each tariff period. By using these control parameters in the grid component in HOMER:

- grid is prohibited from charging the batteries above price of 0.0285 €/kWh
- battery is prohibited from discharging below price of 0.1156 €/kWh

By reason of these parameters, the HOMER microgrid controller allows the grid to charge batteries if the grid power unit cost rate is less than or equal to 0.0285 €/kWh. Similarly, the controller allows battery to be discharged if the grid power unit cost rate is greater than or equal to 0.1156 €/kWh. By this means, the controller will charge the batteries by using grid power between 22:00pm-07:00am and discharge it for the subject plant consumption between 17:00pm and 22:00pm when the grid electricity is the most expensive. To put simply, it will store cheap grid electricity and discharge it for the subject plant consumption instead of expensive grid electricity.

GA using energy storage + PS

The demand response measure GA using energy storage can be applied together with PS. To see the effect of this combination on the microgrid feasibility, the optimum microgrid configuration GC2_1 is chosen. The maximum grid purchasing capacities defined for PS modelling in Section 8.5.2 are used to model GA using energy storage + PS.

To differentiate the microgrid configurations with a GA DR measure, new abbreviations are defined suffixing "GA" to GC2_1. For instance, GC2_1_GA refers to a microgrid deseign configuration where the above defined GA is applied by shifting the grid tariff to TOU and purchasing and storing cheaper grid electricity during off-peak hours and discharging it for plant consumption during on-peak hours when the grid electricity is the most expensive. Further, if GA is applied with PS, then the suffix PS_ "peak power demand" is added to GC2_1_GA. For example, GC2_1_GA_PS1300 refers to the microgrid configuration where GA and PS at 1300 kW is applied to GC2_1.

8.6 DEMAND RESPONSE SIMULATION RESULTS

8.6.1 PS SIMULATION RESULTS

Table 8-12 shows the optimal microgrid component sizes for GC2_1 at each PS grid demand (i.e. maximum grid purchasing capacity). As seen in Table 8-12, the component sizes of PV, WT, and BB/BB are the same for all configurations. A DG of 390 kW is needed if PS1500, PS1450, PS1400, PS1350, and PS1300 are applied. This is because the grid maximum purchasing capacities are that low and renewable energy during peak periods are not enough to cover peak power demands so that HOMER microgrid controller decided to employ a DG to meet the load. As the grid purchasing capacity is lowered, the hours of operation for the DG increases. This can be observed comparing Figure 8-21 and Figure 8-22 which show the power generation of 350kW DG distribution throughout the days over a year when PS1200kW and PS1500kW is applied, respectively. As seen, there are more frequent power generations in Figure 8-21 in comparison to Figure 8-22. It is also clear that the power generation by the 350kW DG in both PS cases takes place between 10:00am and 15:00pm when the plant peak demand occurs. This implies that the DG is employed as a back-up generator to meet the plant peak demand.

Table 8-12: Optimal component sizes and maximum peak demands when PS is applied to GC2_1

Configuration No	PV (kW)	WT (MW)	DG (kW)	BB (kW)	BB (kWh)	PS Max Grid Demand (kW)	Converter (kW)
GC2_1_PS1350	329	1	390	100	200	1350	252
GC2_1_PS1400	329	1	390	100	200	1400	252
GC2_1_PS1450	329	1	390	100	200	1450	252
GC2_1_PS1500	329	1	390	100	200	1500	252
GC2_1_PS1550	329	1	0	100	200	1550	252
GC2_1_PS1600	329	1	0	100	200	1600	252
GC2_1_PS1650	329	1	0	100	200	1650	252
GC2_1_PS1700	329	1	0	100	200	1700	252
GC2_1_PS1750	329	1	0	100	200	1750	252
GC2_1	329	1	0	100	200	1772	252

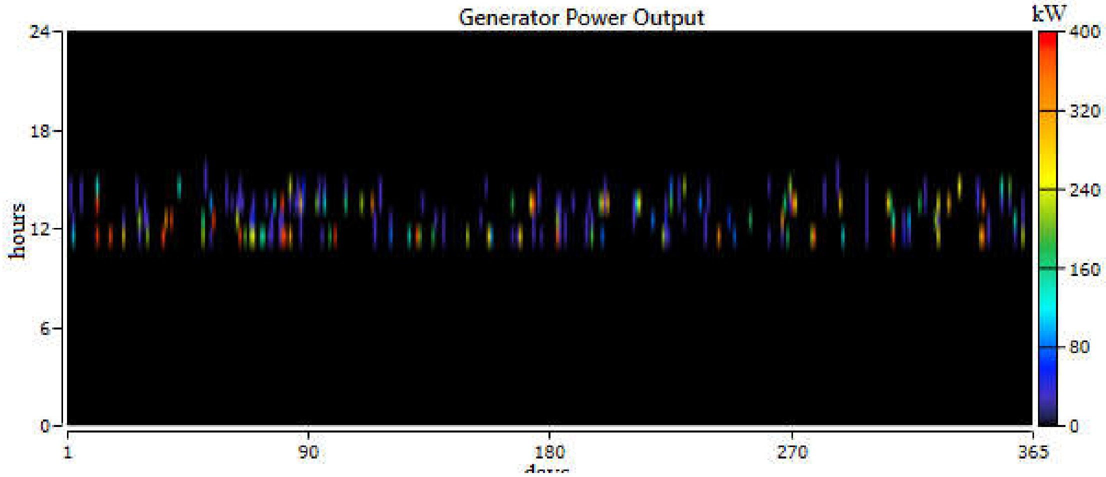


Figure 8-21: 350kW DG power generation distribution throughout the days over a year when PS1200kW is applied (GS2_1_PS1200)

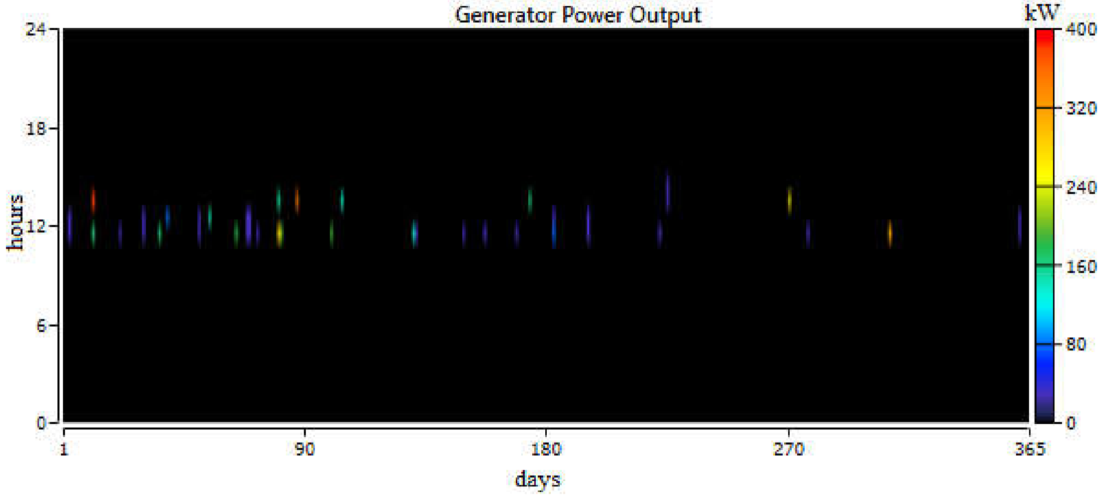


Figure 8-22: 350kW DG power generation distribution throughout the days over a year when PS1500kW is applied (GS2_1_PS1500)

All the microgrid configurations with PS options in Table 8-12 are technically feasible which means that they can meet the power demand of the plant with no shortage. However, their cost-effectiveness need to be taken into account to determine the optimal PS grid demand. Figure 8-23 shows the NPVs of each PS shaving option applied to Microgrid Configuration GC2_1 and the base case NPV. From Figure 8-23, it is clear that GC2_1_PS1550 has the highest NPV among all. From the base case GC2_1 to GC2_1_PS1550, the NPV shows a slightly increasing trend; while the base case NPV is €3,086,240, the NPV when PS1550 kW is applied is € 3,099,090 which is the highest among all. After 1550 kW, the NPV gradually decreases. Thus, the optimal peak shaving grid capacity is 1550 kW.

While the peak grid demand in GC2_1 is 1772 kW, it is reduced to 1550kW in GC2_1_PS1550 when by limiting the grid purchasing capacity to 1550kW. 222 kW is sort of shaved by using the renewable power instead of the grid power. Because the initial cost is the same for all peak shaving options, the B/C will be highest for the PS1550 since it has the highest NPV. The economic benefit provided by PS1550 kW can also be seen in Figure 8-24 which shows the COE of each PS shaving option and the base case. As seen, the lowest COE is achieved in PS1550 option. While the base case COE is €-0.0018, it decreases to €-0.0020 when the peak shaving with 1550kW is applied.

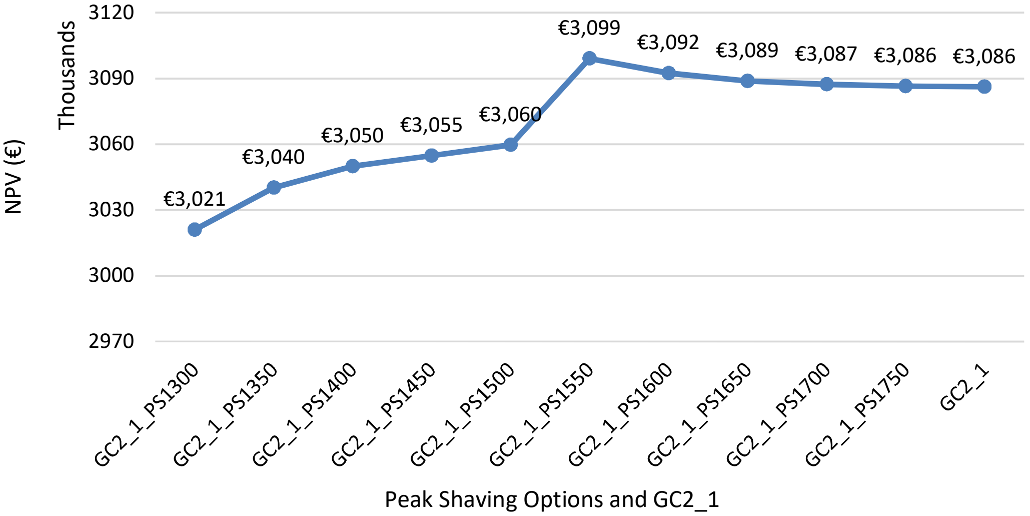


Figure 8-23: Effect of Peak Shaving on NPV in Microgrid Configuration GC2_1

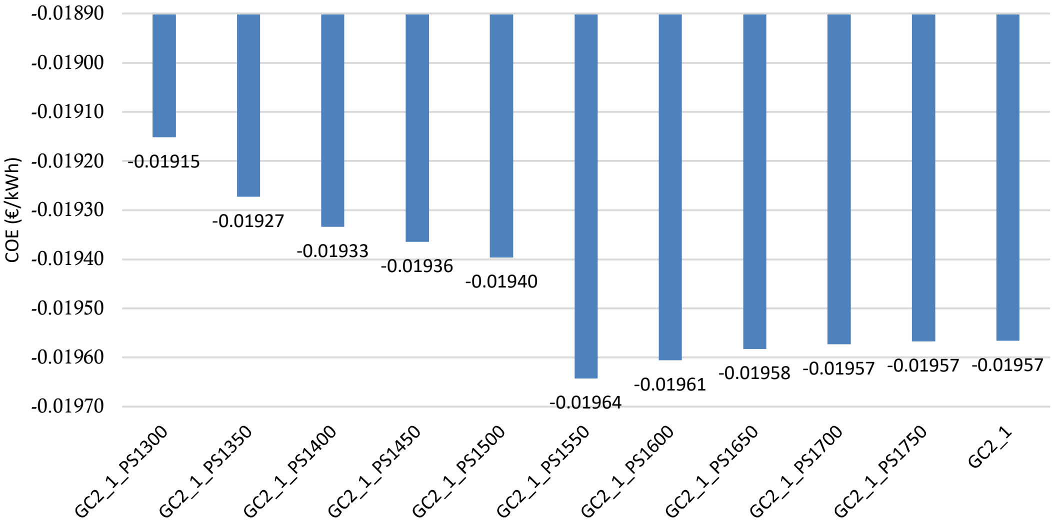


Figure 8-24: Effect of Peak Shaving on COE in Microgrid Configuration GC2_1

Overall, it is evident from the results that **the demand response measure Peak Shaving by limiting the grid purchasing capacity at 1550 kW** improves the cost-effectiveness of the microgrid configuration GC2_1. Since it does not require any further investment, it can be directly applied by the subject plant.

8.6.2 GA USING ENERGY STORAGE

Table 8-13 shows the optimal component sizes and maximum peak demands when GA and GA+PS are applied to GC2_1. As seen in Table 8-13, the peak power demand in GC2_1_GA becomes 1684 kW while it is 1772 kW in G2_1. This means that applying GA alone also performs PS to some extent by reducing the grid power demand of the plant. Also, while the converter size is 252kW in GC2_1, it decreases to 214 kW when GA is applied.

Table 8-13: Optimal component sizes and maximum peak demands when GC/GC+PS is applied to Microgrid Configuration GC2_1

Configuration No	PV (kW)	WT (MW)	DG (kW)	BB (kW)	BB (kWh)	PS Max Grid Demand (kW)	Converter (kW)
GC2_1_GA_PS1300	329	2	390	100	200	1300	220
GC2_1_GA_PS1350	329	2	390	100	200	1350	236
GC2_1_GA_PS1400	329	2	390	100	200	1400	220
GC2_1_GA_PS1450	329	2	390	100	200	1450	216
GC2_1_GA_PS1500	329	2	0	100	200	1500	236
GC2_1_GA_PS1550	329	2	0	100	200	1550	214
GC2_1_GA_PS1600	329	2	0	100	200	1600	214
GC2_1_GA_PS1650	329	2	0	100	200	1650	214
GC2_1_GA	329	2	0	100	200	1684	214
GC2_1	329	2	0	100	200	1772	253

The distributions of the state-of-the-charges (%) of the battery banks in GC2_1_GA and in GC2_1 for a year are shown Figure 8-25 and Figure 8-26, respectively. As seen, the charge/discharge behaviours of battery cycles are completely different in each microgrid configuration. The battery bank in GC2_1 is charged and discharged continuously throughout the days as seen in Figure 8-26. The state-of-the-charge (%) of the battery bank in GC2_1_GA is 100% full during non-on-peak hours (i.e. 17:00 pm – 22:00 pm) while it varies during on-peak hours as seen in Figure 8-25. This is because the battery discharging during non-on-peak hours is disabled; as a result, the state-of-charge remains 100%. The battery discharging during on-peak hours is enabled so that the power stored in the battery bank is discharged and used to meet the subject plant power demand instead of the expensive grid power supply.

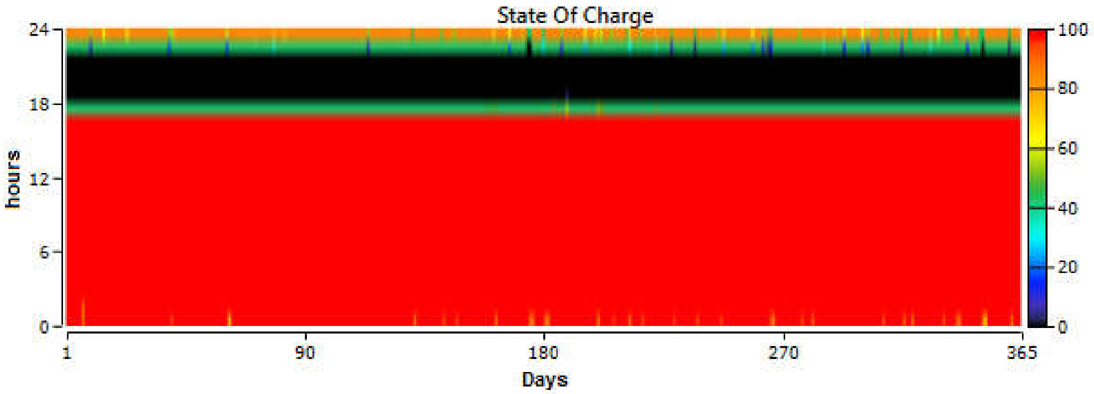


Figure 8-25: State of Charge of the battery system in GC2_1 when GA is applied

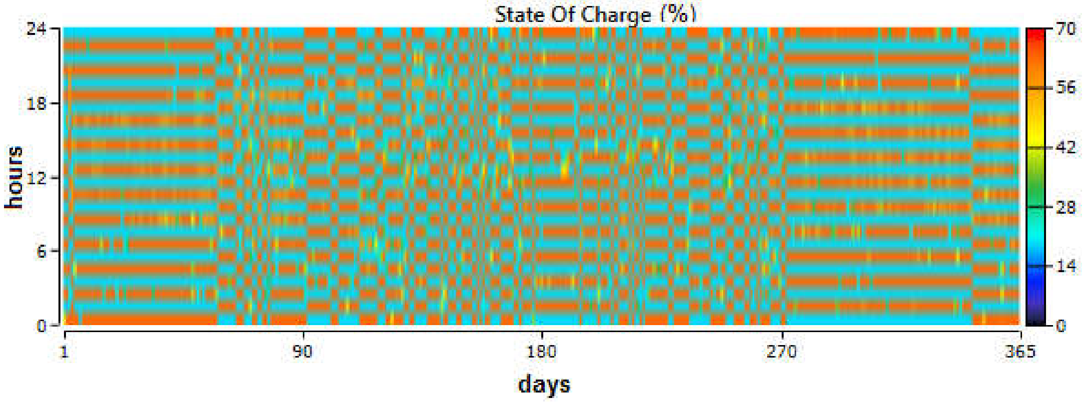


Figure 8-26: State of charge of the battery system in GC2_1 without any DRs

As for the economic benefits of GA, Figure 8-27 and Figure 8-28 show the effect of GA on NPV and COE in GC2_1, respectively. The NPV in GC2_1_GA is €3,368,076 whereas it is €3,086,240 in GC2_1. This means that if the subject plant performs the above defined GA in microgrid configuration GC2_1, the NPV of the investment increases by about 8.3%. Similarly, the COE decreases from -0.01957 €/kWh to -0.02120 €/kWh. Thus, it is obvious that the demand response measure GA positively contributes to the economic feasibility of the investment.

According to the simulation results, the economic merits can be further improved by applying the PS in addition to the GA. As one can see in Figure 8-27 and Figure 8-28 the optimal microgrid configuration with PS and GA is GC2_1_GA_PS1500 because the maximum NPV and minimum COE are achieved at GC2_1_GA_PS1500.

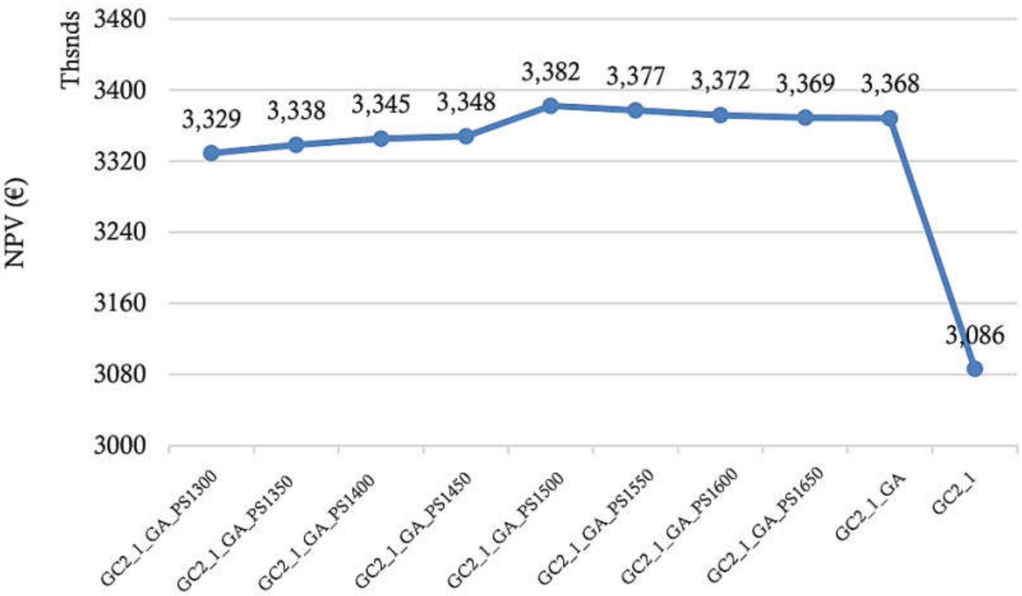


Figure 8-27: Effect of GA on NPV in Microgrid Configuration GC2_1

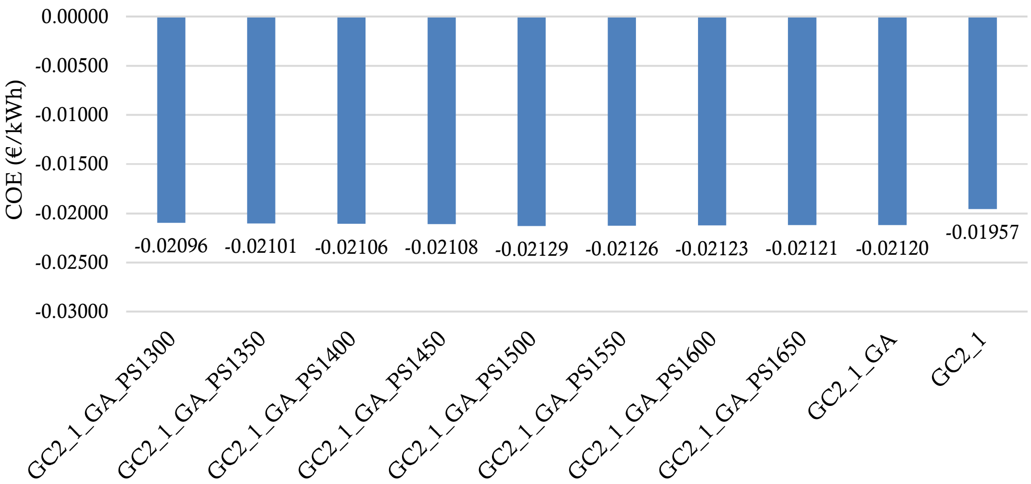


Figure 8-28: Effect of GA on COE in Microgrid Configuration GC2_1

Overall, it is evident from the above results and discussions that the demand response measure GA by shifting to TOU tariff improves the cost-effectiveness of GC2_1. Furthermore, GA can be applied together with PS. The optimal PS when applied together with the GA can be achieved by limiting the grid purchasing capacity at 1500kW.

8.7 EE MODELLING (STEP 4)

Using the efficiency options in HOMER, 4 main EE scenarios are defined and applied to the plant electric load to see the impact of EE on the microgrid technical and economic feasibility. HOMER reduces the plant power demand by these rates and repeates simulations for each EE options. The EE scenarios are as follows:

- 5% EE Scenario: This represents the plant load demand when 5% energy efficiency applied. HOMER calculated the annual plant electricity consumption in this EE scenario to be 2,774,000kWh.
- 10% EE Scenario: This represents the plant load demand when 10% energy efficiency applied. HOMER calculated the annual plant electricity consumption in this EE scenario to be 2,628,000 kWh.
- 15% EE Scenario: This represents the plant load demand when 20% energy efficiency applied. HOMER calculated the annual plant electricity consumption in this EE scenario to be 2,482,000 kWh.
- 20% EE Scenario: This represents the plant load demand when 20% energy efficiency applied. HOMER calculated the annual plant electricity consumption in this EE scenario to be 2,336,000 kWh.

8.8 EE SIMULATION RESULTS

HOMER was run for each EE option scenarios defined in Section 8.7. The highest NPV microgrid configuration results for each EE scenario have been extracted from the overall HOMER optimisation results. For each WT-microgrid group, the highest NPV base case and NPV EE case are compared in Figure 8-29 and Figure 8-30.

The results clearly show that EE improves the cost-effectiveness of any microgrid configuration. To set an example, GC2_1 can be looked through. As seen, while the NPV of GC2_1 with no EE is €3,086,240, a 5% EE improvement in the subject plant electric load increases the NPV to €3,357,374. Similarly, the NPV values when 10%, 15%, and 20% EE levels are applied are €3,613,505, €3,873,040, and €4,134,755, respectively. In parallel to these, the B/C ratio increases which indicates that the cost-effectiveness of the investments improves.

While EE improves the cost-effectiveness of the microgrid configurations, GC1.5_1, GC1.3_1, and GC0.9_1 are still not economically feasible because the NPV for them are still negative. In this point, GC1.5_1_EE20, GC1.5_1_EE15, and GC1.5_1_EE10 are exception since they have positive NPVs, but they also have very small B/C and less than 1 and cannot be considered as feasible options. Therefore, the microgrid configurations in 2MW-WT-microgrid group and 1.8MW-WT-microgrid group in all EE scenarios are still economically the most feasible design configurations.

An important implication that can be made from the above analysis is that, as seen in Table 8-14, an EE improvement of 5% in Microgrid GC1.8_1 results in a NPV of € 2,694,323 which is higher than that of GC2_1. Therefore, a 5% EE improvement in the subject plant energy consumption can result in a microgrid investment with less initial capital cost than the otherwise.

Overall, one can conclude that EE is of paramount importance in a renewable energy project and EE improvement potentials in an electric load should be investigated prior to undertaking a feasibility analysis such as the one presented in this thesis.

Table 8-14: Extracted HOMER optimisation results for Microgrid Configurations with EE

Config No	MICROGRID CONFIGURATIONS								ECONOMIC POTENTIALS					TECHNICAL POTENTIALS										
	PV (kW)	WT (MW)	DG (kW)	BB (kW)	BB (kWh)	PS Max Grid Demand	Converter (kW)	EE %	COE (€)/kWh	NPV (€)	Operating cost (€)	Initial Capital Cost (€)	B/C	DG (kWh)	PV (kWh)	WT (kWh)	BB Ann.Throughput (kWh)	Grid Purchase (kWh)	Grid Sold (kWh)	Total Renewable Generatio	Total Energy Generation	RE Frac of Total E. Generation (%)	Plant Use (kWh)	CO2 (kg/yr)
GC2_1	329	2	0	100	200	1772	252	0	-0.01957	3086240	261561	2451101	1.138	0	378704	6195003	369607.4	1011069	4530766	6573707	7584776	86.43	2920000	-1721132
GC2_1_EE5	329	2	0	100	200	1528	299	5%	-0.02147	3357374	274703	2458184	1.229	0	378704	6195003	372616.3	945554.1	4613939	6573707	7519261	87.20	2336000	-1793840
GC2_1_EE10	329	2	0	100	200	1538	283	10%	-0.02332	3613505	286690	2455823	1.318	0	378704	6195003	370498.1	878044	4692451	6573707	7451751	88.01	2482000	-1865245
GC2_1_EE15	329	2	0	100	200	1491	252	15%	-0.02522	3873040	298726	2451101	1.408	0	378704	6195003	367106.9	812921.5	4771332	6573707	7386629	88.79	2628000	-1935663
GC2_1_EE20	329	2	0	100	200	1342	300	20%	-0.02715	4134755	311423	2458184	1.493	0	378704	6195003	370262.7	749389.9	4856532	6573707	7323097	89.58	2774000	
GC1.8_1	329	1.8	0	100	200	1772	300	0	-0.01669	2431658	221833	2264635	0.978	0	378704	5707545	374055	927370	3961791	6086249	7013619	86.52	2920000	-1483832
GC1.8_1_EE5	329	1.8	0	100	200	1696	268	5%	-0.01868	2694323	234017	2259913	1.080	0	378704	5707545	371225.7	860859	4040161	6086249	6947108	87.37	2336000	-1554679
GC1.8_1_EE10	329	1.8	0	100	200	1538	268	10%	-0.02069	2957596	246453	2259913	1.180	0	378704	5707545	370999.1	797941	4123277	6086249	6884190	88.18	2482000	-1626089
GC1.8_1_EE15	329	1.8	0	100	200	1491	268	15%	-0.02275	3222867	258984	2259913	1.279	0	378704	5707545	370916.6	737711	4209108	6086249	6823960	88.97	2628000	-1697513
GC1.8_1_EE20	329	1.8	0	100	200	1342	268	20%	-0.02484	3486105	271418	2259913	1.377	0	378704	5707545	369116.7	676087	4294161	6086249	6762336	89.8	2774000	-1769238
GC1.5_1	329	1.5	0	100	200	1772	252	0	0.00363	-411847	73470	1967230	-0.202	0	378704	3899867	364045	1212711	2439234	4278571	5491282	77.37	2920000	-599769
GC1.5_1_EE5	329	1.5	0	100	200	1696	260	5%	0.00143	-160016	85421	1968410	-0.078	0	378704	3899867	367330.9	1134212	2506373	4278571	5412783	78.52	2336000	-670986.6
GC1.5_1_EE10	329	1.5	0	100	200	1538	252	10%	-0.00083	91300	97236	1967230	0.044	0	378704	3899867	365583.5	1051016	2568716	4278571	5329587	79.77	2482000	-742155.4
GC1.5_1_EE15	329	1.5	0	100	200	1491	252	15%	-0.00317	343832	109165	1967230	0.166	0	378704	3899867	364469.6	974014.6	2637818	4278571	5252586	80.97	2628000	-813599.8
GC1.5_1_EE20	329	1.5	0	100	200	1342	252	20%	-0.00568	606498	121572	1967230	0.290	0	378704	3899867	366473	900274	2709484	4278571	5178845	82.15	2774000	-884703.5
GC1.3_1	329	1.3	0	100	200	1772	220	0	0.02361	-2211199	-19614	1795960	-1.245	0	378704	2755322	336503	1416856	1503322	3134026	4550882	67.96	2920000	-42282
GC1.3_1_EE5	329	1.3	0	100	200	1696	268	5%	0.02129	-1958568	-7346	1803043	-1.091	0	378704	2755322	344161	1334822	1570894	3134026	4468848	69.27	2336000	-115439.3
GC1.3_1_EE10	329	1.3	0	100	200	1538	236	10%	0.01920	-1723487	3535	1798321	-0.957	0	378704	2755322	346853	1235192	1612822	3134026	4369218	70.87	2482000	-184661.2
GC1.3_1_EE15	329	1.3	0	100	200	1491	220	15%	0.01690	-1482168	14822	1795960	-0.819	0	378704	2755322	346452	1140553	1660442	3134026	4274579	72.47	2628000	-254226
GC1.3_1_EE20	329	1.3	0	100	200	1342	300	20%	0.01442	-1236029	27006	1807764	-0.674	0	378704	2755322	355270.6	1040766	1712863	3134026	4174792	74.29	2774000	-328655.3
GC0.9_1	329	0.9	0	100	200	1772	220	0	0.04033	-3211809	-86439	1381863	-2.479	0	378704	1791870	294248	1702073	841811	2170574	3872647	54.75	2920000	420667
GC0.9_1_EE5	329	0.9	0	100	200	1696	220	5%	0.03671	-2822234	-68037	1381863	-2.148	0	378704	1791870	2276	1475066	857123	2170574	3645640	59.37	2336000	302174
GC0.9_1_EE10	329	0.9	0	100	200	1538	220	10%	0.03483	-2588483	-56996	1381863	-1.954	0	378704	1791870	2342	1354366	882409	2170574	3524940	61.42	2482000	230787
GC0.9_1_EE15	329	0.9	0	100	200	1491	220	15%	0.03437	-2504214	-53015	1381863	-1.885	0	378704	1791870	302701	1384918	959137	2170574	3555492	59.75	2628000	208207
GC0.9_1_EE20	329	0.9	0	100	200	1342	268	20%	0.03251	-2283152	-42239	1388945	-1.695	0	378704	1791870	327310	1265084	981180	2170574	3435658	61.86	2774000	138829

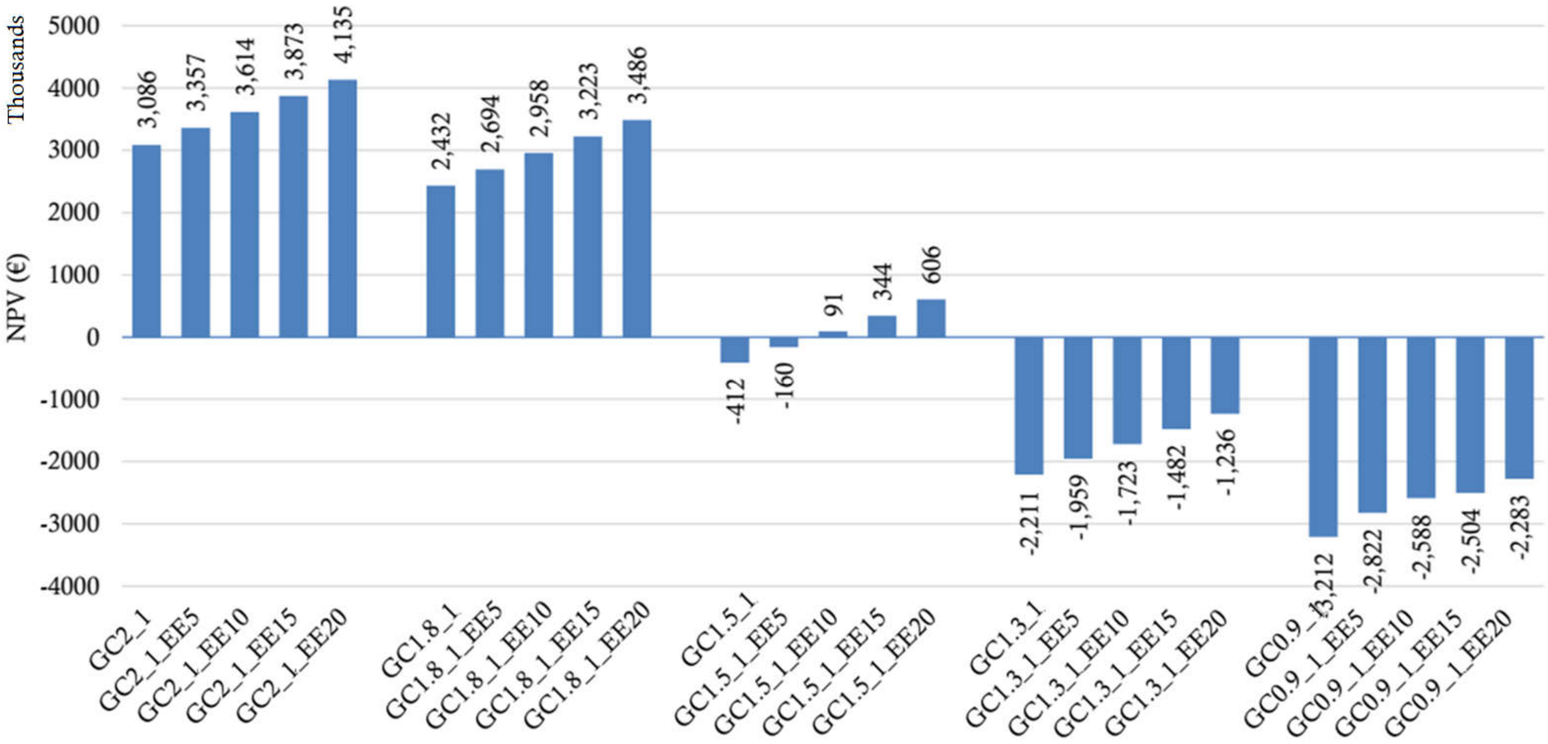


Figure 8-29: Effect of EE on NPVs for each WT-microgrid groups

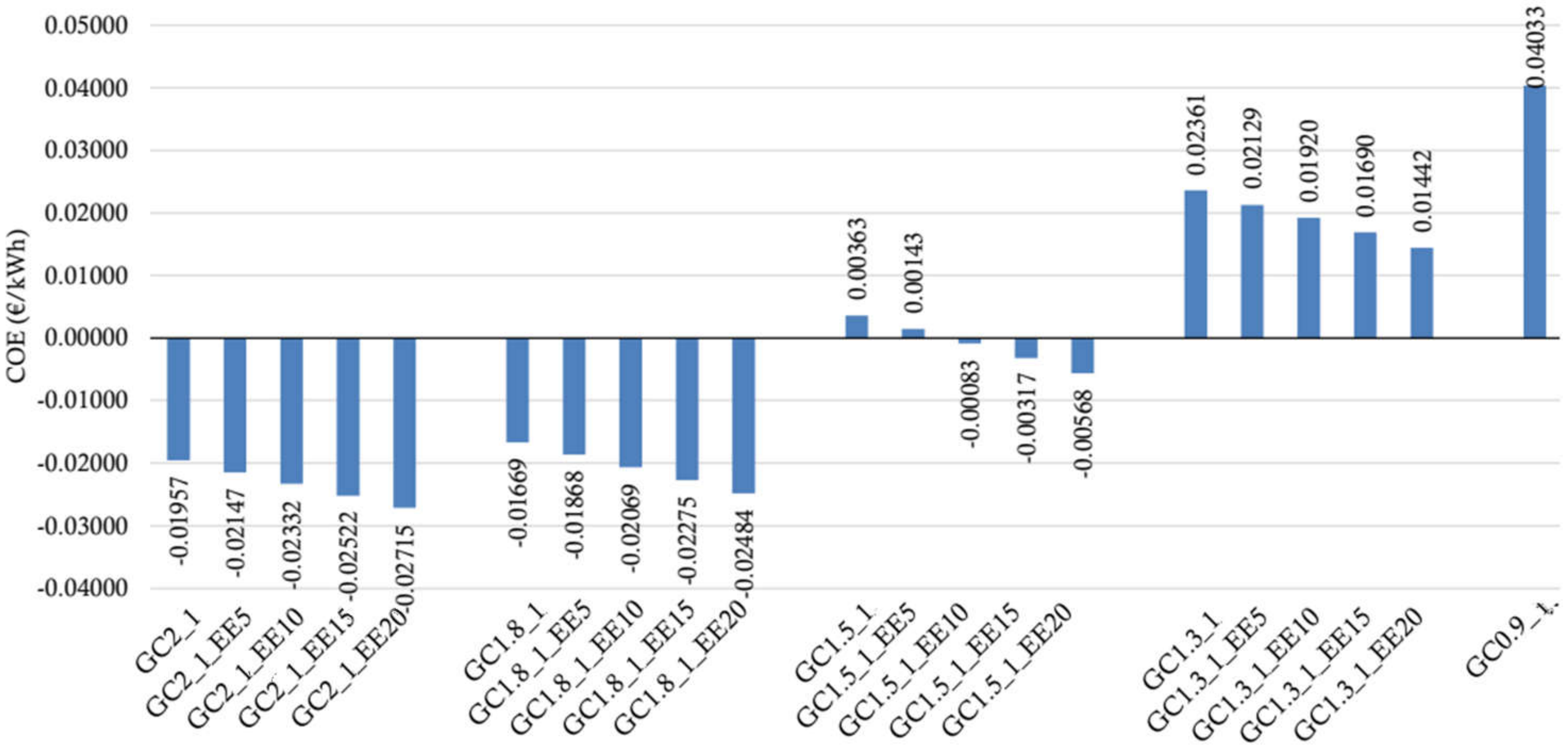


Figure 8-30: Effect of EE on COEs in each WT-microgrid groups

8.9 SENSITIVITY ANALYSIS (STEP 5)

As shown in Section 8.4, the 2MW wind turbine in GC2_1 accounts for about 78% of the overall net present cost and 82% of the total renewable energy generation. Therefore, it is the major component of the microgrid and any change in its lifespan can have a profound effect on the economic merits of the GC2_1. Bearing this in mind, the sensitivity analysis has been conducted for the wind turbine lifetime by adding and subtracting 5 years from the base model lifetime 20 years based on the wind turbine technology provider.

As explained earlier in Chapter 3, the nominal discount rate and expected inflation rate were assumed to be 8.82% and 7.50%, respectively. The real discount rate is nominal discount rate minus inflation rate as given in Chapter 3. Thus, the real discount rate was 1.32% in the above microgrid simulations. HOMER assumes that these parameters do not change throughout the project life. Therefore, a sensitivity analysis is done on the real discount rate to see how the NPV of GC2_1 is affected from the real discount rate. For this purpose, the values which were defined in Table 7-8 in Chapter 7 previously are entered in sensitivity values in HOMER Microgrid Project Economics.

8.9.1 DISCOUNT RATE

Figure 8-31 indicates the results of the sensitivity analysis on the effect of increasing and decreasing discount rate on the economic feasibility. As seen, increasing real discount rate increases the project NPV while vice versa decreases.

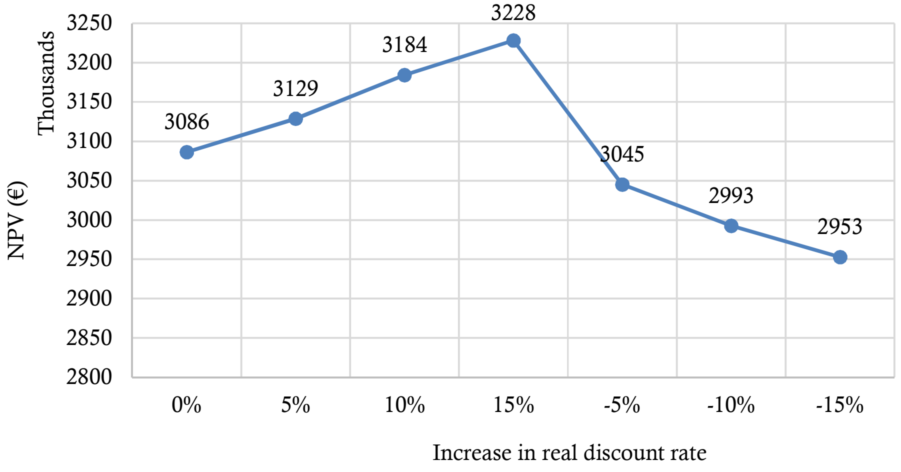


Figure 8-31: The effect of change in the real discount rate on NPV for microgrid configuration GC2_1

8.9.2 ELECTRICITY PRICES

Figure 8-32 shows the results of the sensitivity analysis. It indicates that for every 5% increase in electricity prices, the NPV of GC2_1declines by 3%. The reason for the declining trend is because 31% of the annual electricity consumption of the plant is met by grid electricity whereas 69% is met by the renewables. Keeping the generation cost of renewable and sellback rate constant, increasing electricity prices will inevitably reduce the NPV. Despite this, 3% decline in NPV can be considered as marginal and can be compensated by applying GA and PS demand response measures which provide more than 3% increase in NPV.

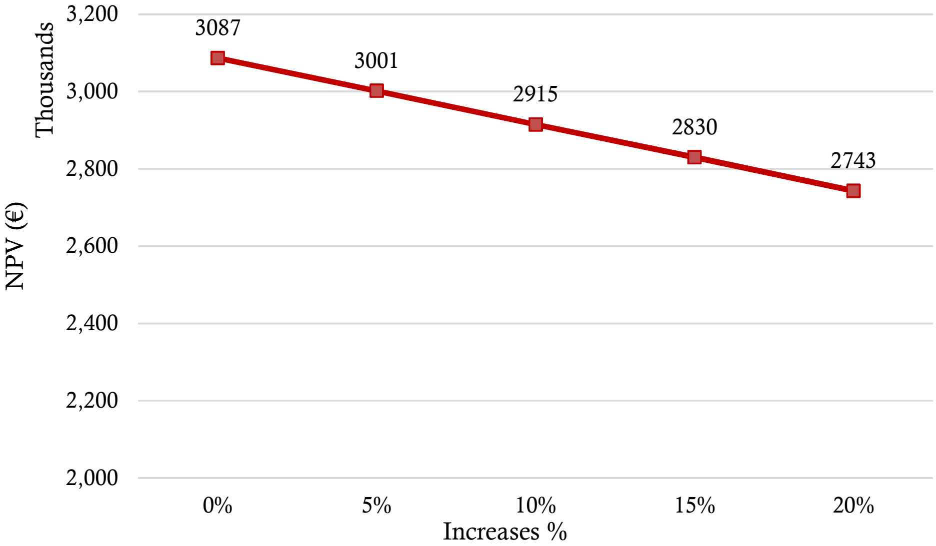


Figure 8-32: Effect of increasing electricity price on the NPV in microgrid Configuration GC2_1

8.9.3 SELLBACK RATE

The results can be seen in Figure 8-33. As seen, if the sellback rate decreases by 5% from the current sellback rate, the NPV declines to by about 14%. If the sellback rate decreases 10%, the NPV decreases to €2,652,411 from €3,086,546. This corresponds to a decrease of 14%. Similarly, 10% and 15% decreases in the sellback rate from the current value leads to approximately 28% and 42% decreases in the NPV, respectively. On the contrary, %5, 10%, and 15% increases in the sellback rate from the current value leads to 14%, 28%, and 42% increases in the NPV, respectively. As seen the economic potentials are highly sensitive to the changes in the sellback rate indicating the importance of the sellback for the economic feasibility.

As for the extra support when the domestic equipment for renewable generators are used, this significantly improves the economic feasibility. As seen in Figure 8-33, if the sellback rate is increased by 50%, the NPV increases by about 141%. This shows the economic importance of the using domestically produced renewable generators. However, it is not possible to find any renewable generators which are entirely manufactured in Turkey at present.

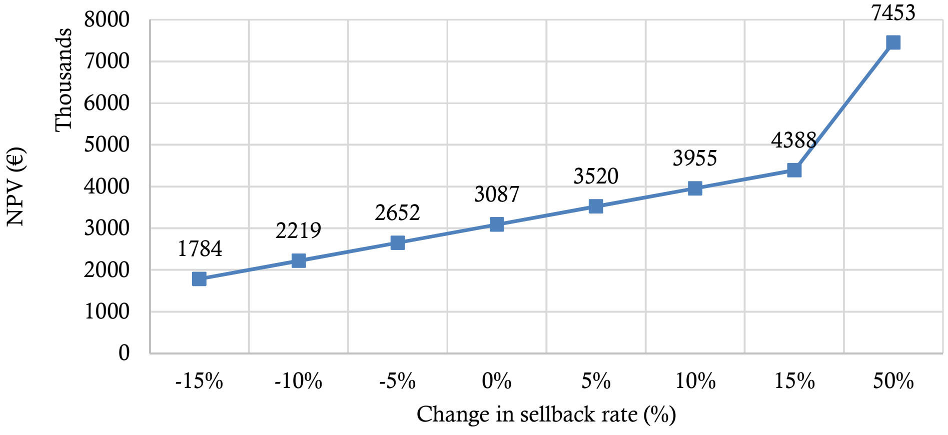


Figure 8-33 : Effect of changing sellback rates on the NPV in Microgrid Configuration GC2_1

8.9.4 TECHNOLOGY LIFETIME

Figure 8-34 shows the effect of shorter and longer lifetimes of the wind turbine on the NPV in Microgrid Configuration GC2_1. For 5 years increase in the wind turbine lifetime, the NPV increases by 11.7%. Similarly, if the lifetime is 5 years shorter, the NPV decreases by 17.6%. These changes can be regarded as significant; however, the NPV in the 5-year shorter lifetime, which can be regarded as a worst-case scenario, is still very profitable.

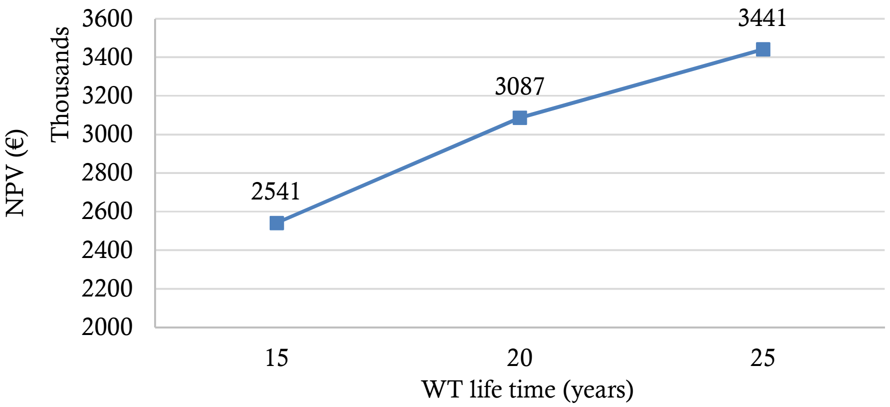


Figure 8-34: Effect of changing WT life time on the on the NPV in Microgrid Configuration GC2_1

8.10 CHAPTER SUMMARY AND CONCLUDING REMARKS

This chapter explored the techno-economic feasibility of the application of a hybrid microgrid with renewables and demand response for the subject plant. A background on hybrid microgrids were provided. The application methodology followed in the feasibility analysis was presented and the optimisation simulation software HOMER used in the analysis was introduced. A representative plant energy consumption model needed to use in the HOMER simulation was generated. Energy supply options and microgrid components were introduced and modelled to use in the simulation. The simulation results showing the performance of renewable generators, techno-economic potentials for standalone and grid-connected microgrid configurations with/without demand response, and impact of energy efficiency were presented together with the discussions of them. Also, a sensitivity analysis was performed on various parameters to see the effect of uncertainties on the economic results.

The following remarks can be drawn from this chapter:

- The simulation results showed that a standalone microgrid configuration requires enormous number of WTs and PV system capacity in comparison to what size and capacity the subject plant can handle. Therefore, application of a standalone microgrid system for the subject manufacturing plant is impossible.

- It was found that there are two economically most feasible options for GC system scenarios. These are GC2_1 from 2MW-WT-microgrid group and GC1.8_1 from 1.8MW-WT-microgrid group. In other words, GC2_1 is the economically most feasible design option amongst the microgrid design configurations with a 2.0MW wind turbine while GC1.8_1 is the same amongst microgrid design configurations with a 1.8MW. Other microgrid design configurations was found to be economically infeasible since they showed negative NPVs. In comparison of GC2_1 and GC1.8_1 microgrid design configurations, the NPVs for GC2_1 and GC1.8_1 are €3,086,240 and €2,431,658, respectively, whereas Initial Capital Cost values are €2,451,101 and €2,264,635. Thus, B/C ratios for GC2_1 and GC1.8_1 are 1.138 and 0.978, respectively, which means that GC2_1 has a higher B/C ratio and is a more profitable option to invest. However, it is worth to note that GC1.8_1 is also a technically and economically feasible microgrid configuration, taking the lower initial capital cost into account, the subject plant can opt to invest in GC1.8_1.

- GC2_1 consists of a 2MW wind turbine, a 329kW PV system, a battery bank of 100kW/200kWh, and a 252kW converter. This microgrid system application, which does not incorporate a diesel generator, requires an initial capital cost of €2,451,101 and provides an NPV of €3,086,240. The overall renewable energy generation is 6,573,707 kWh of electricity. 4,530,766 kWh of this amount is sold to the grid to create revenue. The power purchased from the grid for the plant consumption is 898,099.8 kWh. The remaining 2,021,900.2 kWh of the overall plant annual consumption is met by renewable energy. Thus, the subject plant can be partially self-sufficient at a maximum rate of 69%.

- While the amount of the total renewable energy generation is greater than the power consumption of the subject plant so that it can cover the entire power need of the plant, most of the renewable electricity is sold back to the grid to create. This increases the amount of renewable electricity on the main grid network and makes it more **"low carbon"** in absolute terms. While the electricity purchased from the grid is 898,099.8 kWh, the exported renewable electricity to the grid is 4,530,766 kWh. Therefore, the net low carbon electricity gain of the main grid is 3,632,666,2 kWh and the resulting annual CO_2 emissions are – 1,721,132 kg-CO_2.

- The 2MW wind turbine, which is responsible for about 83% of the overall power generation, is the major power producer amongst the other generators. The 329 kW PV system, which is the other renewable generator of the microgrid design, contributes to only 5% of the overall generation. The power contribution of the PV system is very limited because of the available roof area of the subject plant limiting the installed PV power capacity. In addition, during night hours when there is no sun, the wind turbine is the ultimate renewable energy generator in the system, which highlights the importance of the wind turbine for energy intensive manufacturing plants with a limited roof space limiting PV system capacity, given that the plant location is rich in terms of the wind speed.

- If the PV system is removed from the configuration GC2_1, the NPV of the new microgrid design configuration (i.e.GC2_22) becomes €2,335,986. The RE fraction of total energy generation shows a slight reduction to 85.48%. Also, the economic and technical performance parameters do not show significant changes. If the lower initial investment cost is taken into account by the subject plant, GC2_22 can be a more attractive option to invest.

- Performing demand response measures of peak shaving and grid arbitrage positively contribute to the economic feasibility of the microgrid application. For instance, Peak Shaving by limiting the grid purchasing at 1550 kW increases the NPV to € 3,099,090 whereas it is €3,086,240 in the base case. Similarly, while the base case COE in GC2_1 is €-0.0018, it decreases to €-0.002 when the peak shaving with 1550kW is applied.

- As for GA using energy storage system in conjunction with TOU-based pricing, it also increases the economic performance of the GC2_1 microgrid design configuration. In this demand response measure, the grid power is purchased and stored in the batteries during off-peak periods when the grid power is cheapest, and it is used during expensive on-peak periods. When GA is applied in GC2_1, the NPV increases by about 8.3% to €3,368,076 from the base case NPV of €3,086,240. Similarly, the COE decreases from -0.01957 €/kWh to -0.0212 €/kWh. From these figures, it is obvious that the demand response measure GA positively contributes to the economic feasibility of GC2_1. Moreover, if GA is applied together with PS limiting the grid capacity to 1500 kW, the economic merits can be further improved.

- The impact of EE scenarios (i.e. %5, 10%, 15%, 20%) on the feasibility of each microgrid is remarkable. For instance, while the NPV of GC2_1 with no EE is €3,086,240, a 5% EE improvement in the subject plant electric load increases the NPV to €3,357,374. In the same vein, the NPV values for 2MW-WT Microgrid Configurations with 10%, 15%, and 20% EE levels are €3,613,505, €3,873,040, and €4,134,755, respectively. In addition to these, an EE improvement of 5% in Microgrid GC1.8_1 results in an NPV of € 2,694,323 which is higher than that of GC2_1, the highest NPV microgrid configuration option in no EE scenarios. Therefore, EE is of crucial importance in a renewable energy project and EE improvement potentials within a plant should be investigated and materialised depending on the cost-effectiveness prior to attempting a microgrid feasibility analysis.

- The sensitivity analysis conducted to see the impact of various parameters on the NPVs of microgrid investments yields the following results:

    - increasing real discount rate increases the project NPV while vice versa decreases.
    - rising electricity prices decreases the project NPV.
    - increased sellback rate as a support mechanism for using domestically produced renewable energy generators significantly improves the project NPV. However, it is not possible to find any renewable generators which are entirely manufactured in Turkey at present.
    - the life time of the wind turbine, which is the major component of the microgrid designs, has a dramatic influence on the NPV. Increase in the wind

turbine lifetime increases the NPV of the microgrid investment while vice versa decreases.

On a final note, it is worth to note that renewable energy system designs for manufacturing plants should be a part of factory initial design concepts. For example, the plant orientation and roof angles should be designed bearing the optimum PV performances in mind. From a macro perspective, as well as technical, economic, and social factors, the renewable energy potential of a location should be also taken into account when an industrial estate is planned to be established. This is particularly important considering the fact that efficiency and performance of renewable energy generators of the future will be much more than higher than now with lower unit costs, thus smaller and highly efficient renewable generators can be a dispensable part of the power concepts of future of factories.

9

Conclusions, Limitations, and Future Recommendations

9.1 INTRODUCTION

Key findings of the thesis and recommendations for further work are given in this chapter together with an overall summary of the research conducted in this research study. First, a review of the thesis is presented in Section 9.2 together with the main conclusions from the case study application. Section 9.3 provided the main novelties & contributions whereas recommendations for future work are given in Section 9.4.

9.2 THESIS REVIEW

The global paradigm change incidental to the global energy challenge requires manufacturing industries to review the way they treat energy within their facilities. This is imposed on them by various drivers such as soaring energy prices, increased globalisation and fierce competitiveness, governmental policies, and the increasing market demand for environmentally friendly manufactured goods (i.e. greener products). This carries utmost importance for manufacturing enterprises doing business in a global market. The most typical epitome of these enterprises are marine manufacturing plants such as shipyards and marine equipment manufacturers. Doing business in a global market where the competitivess is a critical business factor makes improved energy performance an important issue for marine manufacturing plants. Also, it becomes even more important for those manufacturing plants of the fast-growing outsourced-energy-dependent developing countries which do business in a global market because these countries face the energy challenge very severely as the literature review in Chapter 2 showed.

The most typical example for these countries is Turkey, which has to power her economy using affordable and uninterrupted energy supply and also has to reduce the GHG emissions (i.e. energy trilemma). Concurrent fulfilment of these is a very difficult task for a country with limited fossil-fuel reserves, booming energy demand, and a power generation infrastructure with high rates of fossil-fuel based CG. In this regard, the noteworthy potential of the manufacturing industry, which is a major energy consuming sector, is recognised by the Turkish government and addressed in the Energy Efficiency Strategy 2023.

Within the Turkish manufacturing sector, the marine manufacturing industry such as marine equipment manufacturers and shipbuilding yards is very strategical for Turkey in terms of both the energy challenge and national economy. Although the Turkish shipbuilding and associated marine manufacturing sector, which has a remarkable recognition in the World marine market, has experienced notable improvement in various aspects such as design and production capabilities and technological capacities as well as quality issues through significant investments for modernisation of their manufacturing facilities, good energy management in their manufacturing plants is still lacking. Improved energy performance within their manufacturing systems will enhance their competitiveness against their rivals in the global market through enhanced greener corporate image and reduced energy costs.

The subject of energy management in the manufacturing domain has experienced a recent surge of research interest in the wake of the immense concerns on the global energy challenge. However, the critical review of the state-of-the-art in the field of industrial energy management in Chapter 2 showed that the state-of-the art is missing in terms of energy management issues in the Turkish marine and non-marine manufacturing industries. No matter the geographic focus is Turkey or not, none of them have been related to the unique application of marine manufacturing plants such as shipyards and marine equipment manufacturers in spite of their important potential.

Bearing these state-of-the-art gaps in terms of territorial and sectoral perspectives, it is intended to combine these two motivational reasons in one background. Thus, the initial motivation for committing to undertake the research study in this PhD thesis was recognising the need to introduce the good energy management culture for improved energy performance in the marine manufacturing industry of a fast-growing developing country, Turkey.

Bearing the drivers for improved energy performance for manufacturing plants, a holistic approach for improved energy performance is developed in this thesis. In order to comprehensively deal with the energy challenge, a manufacturing plant has to improve its energy performance through reducing the key energy performance parameters: energy consumption, energy costs, and GHG emissions. Any reduction in these parameters will contribute to improving the overall energy performance of the plant. In this regard, it is essential to consider together three important energy management themes of Energy Efficiency, Renewable Energy Use, Demand Response, which together form a holistic energy management framework incorporating all major aspects of improved energy performance in terms of demand side and supply sides of energy use of a manufacturing plant.

In Chapter 2 it was also found that the state-of-the-art is lacking such a holistic consideration of energy efficiency, renewable energy use, and demand response participation. While the studies into energy efficiency, energy auditing or other energy management themes were found to be either in different industrial branches or at generic machine and equipment level, the major interest of renewable energy applications were electrification of islanded rural or remote areas and microgrid applications for residential and urban areas.

In line with the above motivation, the aim of this research is to develop a holistic framework for improved energy performance in marine manufacturing plants and to demonstrate the applicability to a typical marine components manufacturing plant in Turkey.

The above stated main aim of the research was achieved through the accomplishment of a number of specific objectives. The objectives defined in the introduction Chapter 1 are restated for the reference:

1. To perform a state-of-the art review in the field of global energy challenge and industrial energy management to show the need for the present study and identify the research gaps that this thesis intends to fulfil.
2. To propose a holistic energy management framework that will help manufacturing plants improve their energy performance
3. To choose a good representative marine manufacturing plant, which belongs to a typical Turkish industry marine manufacturing SME, to apply the proposed holistic energy management framework.
4. To conduct a detailed energy audit in the chosen marine manufacturing plant to collect all appropriate data and identify energy saving potentials (ESPs).
5. To assess those ESPs with regards to technical, economic, and environmental merits, and make decisions based on the economic evaluations.

6. To perform a techno-economic feasibility analysis of a microgrid application for the audited plant to integrate renewable energy use together with demand response measures.
7. To conclude the research with recommendations and future research.

These objectives were accomplished through the reasearch work presented in this thesis from Chapter 1 to 9. Chapter 2 focused on the first objective of the thesis to justify the major research gaps in terms of methodology and application perspectives that this thesis intends to fulfil.

As the second objective was to propose a holistic energy management framework that will help manufacturing plants improve their energy performance, a holistic energy management framework was developed and presented in Chapter 3. The methodology to apply the proposed energy management framework in a main application case study was also described in this chapter. Thus, this chapter serves Objective 2. A brief summary of the developed and proposed framework and its application methodology is given below.

Brief summary of the developed framework

Referring to the drivers of improved energy performance for manufacturing plants because of the energy challenge they face, the development of an energy management framework for assesssment and improvement of the energy performance of a plant is approached by using the following critical energy management themes:

- energy efficiency
- renewable energy use
- demand response participation

Increased energy efficiency requires the identification and application of ESPs which can be explored through conducting an energy audit. Increased use of renewable energy requires the application of a renewables based microgrid. A microgrid controller also enables demand response participation. Taking a holistic approach to improved energy performance, the methodology to apply the proposed framework consits of two major steps: 1. Energy audit; 2. Microgrid application.

The application of the proposed framework starts with conducting an energy audit in the plant. Energy auditing is carried out in two main phases: Phase-1: Plant-wide Auditing; Phase-2: Auditing Target Energy Consuming Systems. The Phase-2 is performed in three major steps:

- Step 1: Detailed study of the target energy consuming systems.
- Step 2: Detailed study of the collected data and analysis.
- Step 3: LCC assessments of ESPS, evaluation and priorisation for decision making.
- Step 4: Sensitivity analysis

In Phase-1 of the energy auditing, all the relevant data for energy performance including basic information about the plant, energy use and consumption figures, and energy consuming systems are collected. The target energy consuming systems for auditing in Phase-2 are determined in this phase. In Phase-2, energy performances of the target energy consuming systems determined in Phase-1 are investigated through a detailed study and analysis of them to identify the ESPs (Step 1-2 of Phase 2). The identified ESPs in Step 1-2 are deemed to be technically feasible. Their economic feasibility are assessed and evaluated in Step 3 of Phase-2 through conducting LCC asssesments and decision making is done by priorisition of them with respect to economic merits. Sensitivity analyses are conducted to see the impact of uncertain parameters on the economic feasibility. Thus, technically and economically feasible ESPs which will increase energy efficiency of the audited plant are determined and the Energy Audit step of the proposed methodology is completed.

Following the Energy Audit step, the objective of the Microgrid Application step of the proposed framework methodology is to determine the technically and economically optimal sized microgrid design which is capable of producing and suppling power to the energy-audited plant on a reliable manner and satisfy the constraints at the lowest cost. Adopting HOMER Pro software in the proposed methodology framework and exploiting the data collected throughout the Energy Audit step, the techno-economic feasibility analysis for microgrid application is conducted through the following major steps:

- Step 1: Plant electricity consumption modelling
- Step 2: Modelling microgrid components and resources
- Step 3: Demand response modelling
- Step 4: Energy efficiency modelling
- Step 5: Sensitivity analysis

The simulations are run in HOMER based on the modelling and scenarios in order to get optimisation results. The outcomes of this step of the developed methodology framework are the most optimum renewables-based microgrid configurations and demand response measures of which application will improve the energy performance of the energy-audited plant through increased power-self sufficiency, reduced energy costs, and reduced CO_2 emissions.

Brief summary of the remaning chapters

As a requirement of the third objective of the thesis, a marine manufacturing plant was chosen for the main application case study to apply the developed framework. Chapter 4 introduced the chosen marine manufacturing plant giving its main characteristic features.

An energy audit as a requirement of the third objective of the thesis was conducted in the chosen manufacturing plant and presented through Chapters 4-7.

The results of the Phase-1 of the energy auditing methodology (i.e. plant wide auditing) was presented in Chapter 4. Background information about the chosen plant, production processes, energy consuming systems and energy consumption figures were given. The target energy consuming systems/processes to be energy-audited in the Phase-2 (i.e auditing target energy consuming systems) of the energy auditing methodology was determined in this chapter.

The results of the Phase-2 (i.e auditing target energy consuming systems) of the energy auditing were presented in from Chapter 5 to 7. The applications and results of the Step 1-2 of the Phase-2 were presented in Chapter 5 and 6. While Chapter 5 presented the energy audit conducted on the target energy consuming systems in the production process systems group of the subject plant, Chapter 6 was devoted to the target energy consuming systems of the production support systems group. The outcomes of the Step 1 and Step 2 of Phase-2 of the energy auditing presented in Chapter 5 and 6 are annual ESPs with associated annual PESP, ECSP, and CO_2-ERP identified in each target energy consuming systems. Thus, Chapter 5 and 6 served Objective 4.

The ESPs identified in Chapter 5 and 6 are technically feasible. The fifth objective of the thesis requires the economic assesssments of these technically feasible ESPs. To meet this objective, the Step 3 of the Phase-2 of the proposed framework methodology was conducted through LCC assessments of the ESPs, evaluation and priorisation of them for decision making. The applications and results of the Step 3 of Phase-2 was presented in Chapter 7. Thus, Objective 5 was satisfied.

Thus far, the application the Energy Audit step of the proposed methodology and the results have been presented throughout Chapter 4 to 7. The objective of the energy auditing was to identify the ESPs of which application increase energy efficiency of the plant, which is the first pillar of the proposed holistic framework.

The other major aspects of the thesis, renewable energy use and demand response participation, which requires the application of a hybrid microgrid, were the subject of Chapter 8. Therefore, Chapter 8 explored the techno-economic feasibility of the application of a hybrid microgrid with renewable and demand response for the subject plant. Thus, the 6th objective of the thesis was satisfied.

9.2.1 CONCLUSIONS FROM THE CASE STUDY APPLICATION OF THE DEVELOPED FRAMEWORK

The application of the developed holistic energy management framework in the subject marine manufacturing plant has demonstrated that there exist a considerable energy performance improvement potential within the subject manufacturing plant through increased energy efficiency, increased use of renewables, and demand response participation.

The following conclusions can be drawn from the application of the holistic framework in the subject marine manufacturing plant:

- The energy auditing conducted in the subject plant has clearly demonstrated that there exist considerable energy efficiency potentials with various levels within the audited energy consuming systems. Based on the results of the energy auditing, the energy efficiency of the existing energy consuming systems can be improved through the following measures:
    - Energy efficiency retrofits/replacement
    - Using right sized equipment/system
    - Avoiding/eliminating non-value added equipment/system operations
    - Changing behavior for energy efficiency and increased awareness
    - Process improvement and resource efficiency
    - Preventative maintenance
    - System energy performance monitoring

- The results of the energy audit have shown that the subject plant can be technically 17.8% more energy efficient in comparison its baseline energy consumption. Furthermore, it is technically possible to further reduce the energy consumption of the subject plant by 23.4% through a best-case-scenario in when the subject plant performs best melting process practices which are more energy efficient and productive.

- The economic assesssments of the technically feasible ESPs have shown that it is technically and economically possible to reduce the annual energy consumption by 15.2%. This also means 15.2% energy cost saving for the energy-audited plant. The environmental benefit of 15.2% energy efficiency is CO_2 emission reduction of 221,205.6 kg-CO_2/year.

- The sum of the cost-free ESPs, which do not involves any investment cost to implement, accounts for 39.4% of the total technically and economically feasible ESP.

- The energy inefficiencies emaneting from the behaviour of labours (i.e. human factors) accounts for 5.2% of the total technically and economically feasible ESP. This is greater than some technicalities-related ESPs which require an initial capital cost to implement. Therefore, it is possible to increase the energy efficiency of the plant by 5.2% through behaviour changes. An awareness raising training should be conducted to encourage the plant workers for changing behaviour for energy efficency.

- Due to the energy intensive nature of the subject manufacturing plant, very large sizes and capacities of renewable energy generators are required for a 100% power self-sufficiency through a stand-alone system. Materialisation of 100% power self-sufficiency is technically infeasible because the subject manufacturing plant cannot accommodate such large scale systems. Considering the fact that efficiency and performance of renewable energy generators of the future will be much more than higher than now with lower unit costs, 100% power self-sufficiency for a manufacturing plant is promissing.

- The subject plant can be self-sufficient at a maximum of 69% through the application of a grid-connected microgrid configuration comprises a 2MW wind turbine, a 329kW PV system, a battery bank of 100kW/200kWh, and a 252 kW converter while no diesel generator is needed. Such a system with the support of the main grid can continuously supply power to the subject manufacturing plant providing an NPV of €3,086,240 whereas the overall energy cost of the subject plant would be -€4,106,105 if the plant is powered only by the grid throughout project life. The annual CO_2 emissions of the subject plant will be -1,721,132 kg-CO_2 whereas it is 1,427,880 kg-CO_2 year if the plant is powered only by the grid.

- It has been found that the demand response measure "peak shaving" positively contributes to the feasibility of the optimum microgrid application. If peak shaving by limiting the maximum grid demand in the optimum microgrid configuration to 1550 kW is applied, the NPV of the microgrid investment rises to €3,099,099.

- "Grid arbitrage" through purchasing and storing cheap grid electricity during off-peak periods and using it during on-peak periods has been found to a very promising demand response measure for the subject plant. Its application increases the NPV of the microgrid investment by 8.3%. What is more, it can be applied in conjunction with the peak shaving demand response measure to further increase the NPV of the investment.

- The effect of energy efficiency on the microgrid feasibility is found to be remarkable. A 5% energy efficiency improvement in the subject plant electric load increases the NPV of the optimum microgrid design by 8%. Therefore, exploring energy saving potentials through an energy audit prior to any renewable energy investments like in the proposed methodology framework in this thesis carries utmost importance.

In addition to the above, the results of this study have shown that "improvement energy performance" should be a part of initial factory/plant design stage. For example, production process and support systems should be chosen keeping optimum size/capacity and energy efficiency in mind. Similarly, initial factory layout design should also consider energy efficiency; for example, optimum design of piping fitting & installments of the pumping and compressed air systems for energy effficiency should be a part of factory layout designing. Also, renewable energy system designs for manufacturing plants should be a part of initial factory design. For example, the plant orientation and roof angles should be designed bearing the optimum PV performances in mind.

9.3 ORIGINAL CONTRIBUTIONS AND NOVELTIES

This thesis focuses on the energy performance improvement in manufacturing plants through the development of an holistic methodology framework. The following contributions and novelties can be listed:

- This research develops an energy performance improvement framework which incorporates three critical themes of energy management: energy efficiency, renewable energy use, and demand response. Such a holistic approach enables a compherensive assessment and improvement of energy performance in manufacturing plants.

- The identification of energy saving potentials in the energy auditing methodology of the proposed framework are done based on power consumption measurements. Combined with the observations performed on energy consuming systems, power consumption profiles obtained through power measurements provides invaluable data and insights enabling to explore energy inefficiencies and root causes which normally cannot be explored with the existing methods. Moreover, real-time power consumption data based on measurements provides more realistic and accurate results whereas existing approaches simply approximates the power consumption of a system based on its power rating and operation time.

- The methodology of the proposed framework brings human factors into the energy performance assessment and improvement while it is hidden in the existing approaches.

- The assessment of renewable energy integration in the proposed framework is done through modelling the dynamic power consumption of a plant based on the power consumption measurements conducted on each energy consuming systems. This provides more accurate and realistic results in comparison to the existing approaches which approximates the power consumption based on nominal power rating data of energy consuming systems.

- As a part of the proposed methodology framework, a new model for exploring the potential of demand response participation through peak shaving and grid arbitrage measures is developed based on HOMER software. For peak shaving, grid power is limited and costly peak power demands are supplied by using renewable energy. For grid arbitrage, cheap power during off-peak hours is stored in the batteries to be used during expensive on-peak periods as well as to supply expensive peak demands. These provide energy cost savings to a plant without no distruption to production planning or load shedding whereas conventional means of performing peak shaving and grid arbitrage require shifting the work load to off-peak hours or shedding the peak loads to reduce demand charges which can have a negative impact on the production.

- Energy consumptions and intensities of various energy consuming process and systems were mapped and presented in the case study application of the proposed framework. Some of the energy saving potentials identified in the energy consuming systems stem from the design of energy consuming machine and systems. Therefore, these invaluable data can be exploited by other researchers and machine manufacturers and designers.

- In the case study application of the proposed framework, a step-wise and systematical approach is adopted to identify energy saving potentials on energy consuming systems and energy saving measures are formulated and developed. The approaches adopted to identify energy saving potentials and formulated energy saving measures can be exploitied by other researchers or plants who are interested in energy efficiency.

- In addition to the above, in terms of a sectoral perspective, this research can also be seen as one of the first attempts in the area of energy management in marine manufacturing which is an important segment of the maritime industry. As Olcer (2018) states, coordinated action of all components of the maritime industry is a must to achieve a low carbon and energy-efficient maritime future. Therefore, a significant contribution has been made in addressing the importance of improved energy performance and energy management issues among marine manufacturing plants such as shipyards and marine component/equipment manufacturers.
- Moreover, from a territorial perspective, this study is also the first-time attempt from a Turkey context. Thus, exploiting of this study by Turkish marine or non-marine manufacturing plants will also contribute to achieving the Turkey`s targets of NDCs set by Paris Agreement.

The developed methodology in this study was successfully applied to a real case. Because it is a generalized model, it can be exploited by not only other marine and non-marine manufacturing plants but also other industrial plants in different sectors through tailoring it to the particular needs of other cases. As well as the developed methodology, the approaches adopted in the formulation and development of energy saving measures for the identification of ESPs in the case study application can be adopted by other plants which employ common energy consuming systems.

Overall, in line with the above novelties and contributions enriching the existing knowledge, it is envisaged that this PhD work will be relevant to anyone with an interest in improved energy performance in manufacturing plants, such as: academics, policy-makers, energy auditors, manufacturing companies, machine designers and produces, and production managers.

9.4 RECOMMENDATIONS FOR FUTURE WORK

Creating an increased awareness towards the importance of effective energy management and culture through development and application of a holistic energy performance improvement framework, the Author believes that this thesis has proved the importance of effective energy management in the marine and non-marine manufacturing industries of Turkey and alike developing countries. One would appreciate that the research presented in this thesis was limited and demonstrative in nature on the grounds of the time constraints and available resources. For this reason, a number further research on the subject can be proposed as recommendations for future work as listed below:

- Energy efficiency dimension of the proposed framework considers technical factors and human factors. While technical factors consider energy efficiency of energy consuming systems, the impact of plant layout on energy efficiency could be taken into account. For example, the layout of the subject plant in the case study application in this thesis could be optimised and the distances that the overhead travelling cranes are travelling could be optimised and their energy consumption could be reduced. Therefore, the energy auditing methodology in the proposed framework can be extented so as to include "plant layout factor".

- The proposed framework proposed in this thesis focused on "electricity consuming systems". However, there can be also other energy inputs in a manufacturing plant. Particularly, natural gas can be a major energy input for some manufacturing plants. Therefore, the proposed framework can be modified to include e.g. natural gas consumers in the energy auditing to identify energy saving potentials.

- Environmental benefits of improved energy performance is addressed based on CO_2 ERP. Other GHG emissions and air pollutants as well as their environmental impact assessments can be included in the proposed framework for a more compherensive environmental benefits assessment.

- While the application of energy saving measures such as using a VFD provides energy savings together with associated environmental benefits in an energy consuming sytem, energy is also consumed for the manufacture and end-of-life-treatment of these measures. Furthermore, energy can be used for their repair and maintenance during their service life. This also applies to renewable energy generators and other microgrid components. Bearing this in mind, the environmental impact associated with the energy consumed for its manufacturing, repair and maintenance, and disposal/recycling phases throughout its lifecycle can be greater than the emissions reduction benefits it provides in-service. Therefore, from an environmental point of view, the embodied energy during the life cycle stages other than the use phase of energy efficiency retrofits & replacement measures, renewable energy generators, and microgrid components should be accounted for a more compherensive environmental benefits assessments. Therefore, environmental cost-benefit analysis based on the embodied-energy life cycle assessment model can be developed and integrated to the proposed framework for a more compherensive assessment of the environmental benefits of the improved energy performance measures.

- The developed framework can be extended to include the concept of waste heat recovery. For example, there are several waste heat resources in the subject plant studied in the case study. These include air compressors, induction furnace vents, ventilation vents, and heat treatment furnace. Waste heat recovery potential on such systems in a manufacturing can be studied. Depending on the availability and energy potential of the waste heat in a manufacturing plant, the techno-economic potential of power generation from the waste heat using, for example, Organic-Rankine cycle can be explored. The power generation from the waste heat can be integrated to the hybrid microgrid in the proposed framework. In addition, the waste heat can be reused or recycled for various purposes such as the domestic hot water requirement of a plant.
- Improved energy performance has socio-economic benefits because energy consumption based on fossil-fuel has a significant impact on the human health through the release of air pollutants. Therefore, external health cost savings through improved energy peformance measures could be quantified. Also, external health cost models can be developed and integrated to the proposed framework for a more compherensive analysis for the social benefits of the improved energy performance measures.
- In terms of EnMS application for a plant, the proposed framework can be applied in the planning phase of an EnMS. Another critical phase of an EnMS implementation is the monitoring phase. An energy performance monitoring system at major individual energy consuming system level or overall plant level can be developed.
- While the proposed holistic framework in this thesis was developed for energy performance improvement of the existing plants, as also mentioned in the previous section, the case study application has revealed the importance of initial factory/plant design stage for energy performance. Bearing this in mind, an energy-oriented factory/plant design framework that can be useful in the design stage of plants can be developed. Such a framework should integrate the energy performance improvement

measures into the planning phase as a design criteria through incorporating various energy management themes such as energy efficiency, renewable energy generator sizing, plant location selection for renewable energy, and so on.

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Appendix A

Plant Layout

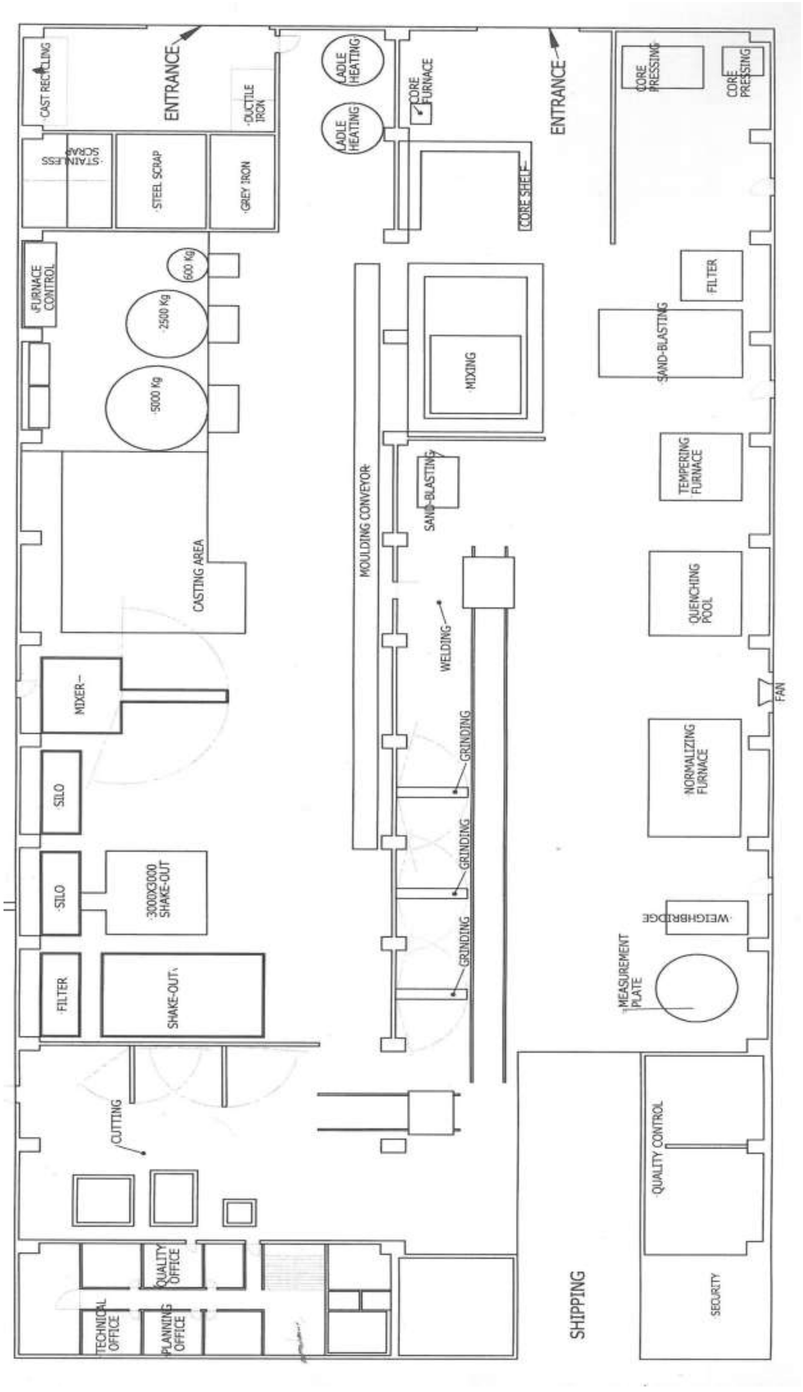


Figure A-1: Subject plant layout

Appendix B

Energy Efficiency and Savings in Induction Motors

B.1 INTRODUCTION

A number of alternating current (AC) induction motors with diverse power ratings are employed integrated to the energy using systems in the subject plant of this study. Therefore, this section will provide a background on the energy efficiency aspects of electric motors and then the methodology used for energy savings calculations in this thesis will be presented.

B.1 BACKGROUND

Electric motors are the backbone of the industry. They are employed in a large number of applications to drive various systems motor-driven systems such as pumps, compressors, conveyors, machine tools, fans, etc. in the industry as well as other sectors like residential and service. Motor-driven systems are responsible a remarkable fraction of worldwide electricity use, where vast majority of this is due to the electric motor itself (Waide and Brunner, 2011). Approximately 60% of global industrial electricity consumption can be attributed to the electric motors (Fleiter and Eichhammer, 2012) representing a huge improvement potential and great impact on the environment. The largest share of motor electricity use is due to the mid-size asynchronous AC electric motors (i.e. 0.75 kW to 375 kW) (Waide and Brunner, 2011). Bearing this in mind, most OECD and many non-OECD countries impose minimum energy performance standards (MEPS) on mid-size AC motors (Waide and Brunner, 2011).

B.2 ENERGY EFFICIENCY AND ENERGY EFFICIENCY CLASSES IN ELECTRIC MOTORS

It is well known that an electric motor converts electric energy to useful mechanical energy. A simplified diagram of this process is shown in Figure B-1.

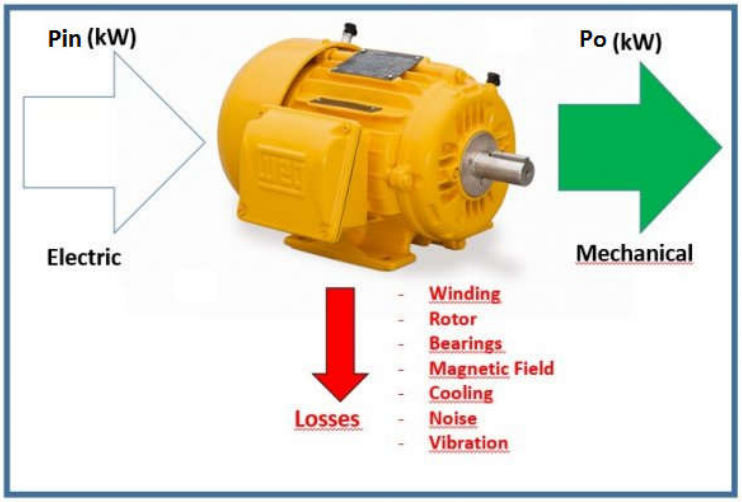


Figure B-1**:** A simplified depiction of motor losses (modified from Livoti, 2014)

During the conversion process, input energy cannot be completely converted to the output energy due to the intrinsic motor losses which is expressed by the motor efficiency. The motor losses are the difference between the output power and input power. Therefore, the efficiency of an electric motor is the ratio of useful mechanical output from the motor shaft to electrical input power to the motor and it can be expressed by Equation B-1 as follows (DOE, 1996):

$$\eta = \frac{P_i}{P_0} \qquad Eq.(B-1)$$

where;

η is motor efficiency as operated in kW,

P_i is three-phase power in kW drawn by the motor (i.e. power input),

P_o is mechanical power out in kW.

Po is dictated by the intrinsic motor losses originate from the motor design (Saidur, 2010) and improvements in motor design increases the energy efficiency of an electric motor. Therefore, electric motors with various energy efficiencies are available from different motor manufacturers in the market. In this respect, energy efficiency quality of electric motors are expressed by efficiency classes (Waide and Brunner, 2011) which can be used for decision making when purchasing an electric motor.

The International Electrotechnical Commission (IEC) introduced an energy efficiency classification for electric motors, known as the IE codes, which are summarised in IEC International Standard: IEC 60034-30-1:2014 which was based on the advanced efficiency measurement standard in IEC 60034-2-1. Four levels of efficiency are defined in the standard (IEA-4E, 2015):

- IE4 Super premium efficiency
- IE3 Premium efficiency
- IE2 High Efficiency
- IE1 Standard Efficiency

Figure B-2 shows a comparison of efficiency classes for 4-pole electric motors with the IEC 60034-30-1:2014 standard.

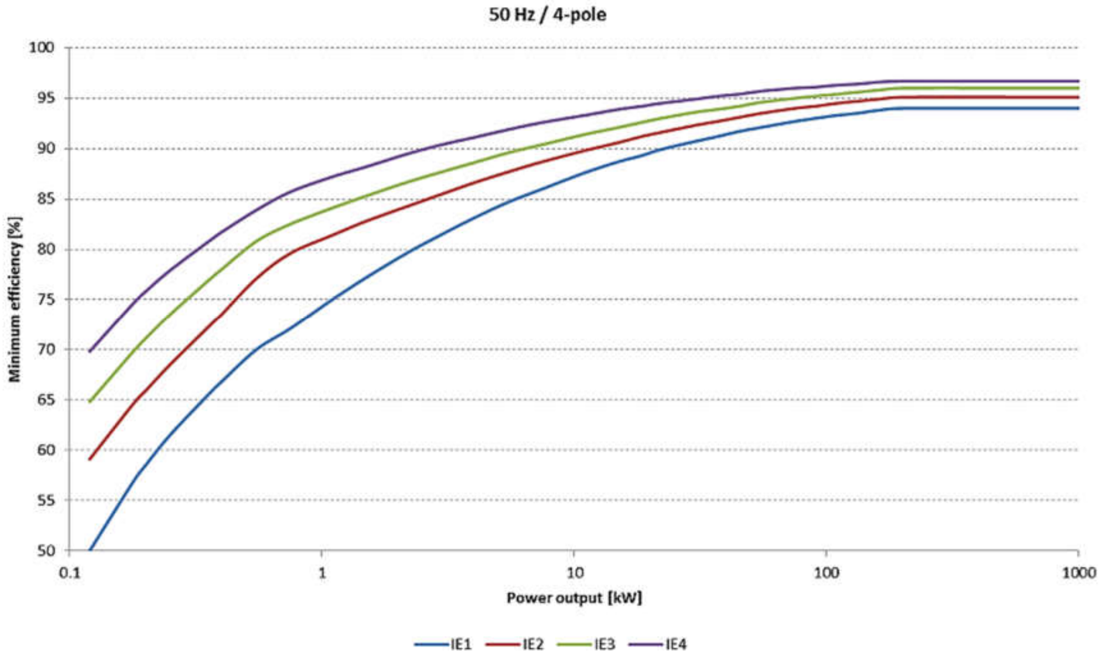


Figure B-2: IE class for 50Hz 4-pole electric motors according to IEC 60034-30-1:2014 (EC, 2014)

A competition among motor manufacturers leading to massive technology improvements in electric motors have been stimulated by the IEC 60034-30-1 classification system (Blondeau, 2015). Also, regulators are aided by the IE codes which form a reference procedure to determine the minimum efficiency levels for electric motor energy performances in national policies aimed at increasing the use of more efficient motor (Blondeau, 2015; IEA-4E, 2015).

Although IEC International Standards are voluntary, the IEC classification system have been today adopted in the EU and several other countries and form a basis for the minimum energy performance standards (MEPS) which are in force in these countries (Blondeau, 2015; IEA-4E, 2015).

For example, in the EU, the regulation 640/2009 (amended by Regulation 4/2014) set mandatory minimum efficiency levels for electric motors in the European market. It covers 2-, 4-, and 6-pole, single speed, 3-Phase induction motors rated up to 1000 V. According to the regulation, as of January 2015, motors with rated output of 7.5-375 kW must meet either IE3 or IE2 if fitted with

VSDs. From 2017, for motors with a rated power output from 0.75-375 kW must meet either IE3 energy efficiency level kW must meet either IE3 efficiency level or IE2 if fitted with VSDs. This regulation is referred as the EU MEPS and expected to lead to energy improvements of 20% to 30% (EC, 2014; IEA-4E, 2015).

Before the IEC 60034-30-1 classification system, a motor classification scheme with three energy efficiency levels, EFF3, EFF2, and EFF1, which was defined based on a voluntary agreement between CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics) and the EU was being used as the European system (see Table X-1). Other national systems such as NEMA in the USA were being developed and very different from the European system. This motivated the IEC and the above-described IEC 60034-30-1 classification system was developed as a common international standard which would replace all the different national systems (EC, 2014).

Figure B-3 shows the correlation between the efficiency classes in the IEC 60034-30-1 and other efficiency classes in system. The efficiency levels of existing motors labelled with an old classification system can be converted to the new classes using this correlation in Figure B-3.

Table B- 1: Obsolete energy efficiency classes

EFF3	Low efficiency level	1,1 kW < P < 90 kW (electric motor power range)
EFF2	Improved efficiency level	
EFF1	High efficiency level	

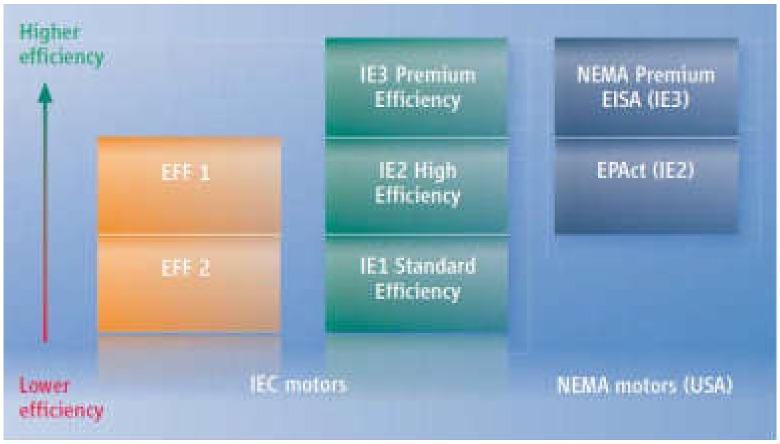


Figure B-3**:** Correlation between IEC 60034-30-1 and other electric motor efficiency classes

In line with the preceding section, one can say that energy saving can be achieved by replacing the existing low efficiency electric motors with the energy efficient motors labelled with the new IEC classification system. To be able to estimate the energy saving potential, the existing motor to be replaced should be examined in detail to see its operational characteristics while it is in normal operation. This will show whether the existing motor is suitable and properly sized or not for the application. Even if an electric motor has a high energy efficiency class, it will operate inefficiently if not properly sized for the application it serves. Therefore, the first step will be to understand if the existing motor is suitable for the application. This can be realised by analysing Load Factor (LF) of the motor. Prior to that, the nominal values (i.e. rated current, voltage, PF, and power) and annual operation hours of the existing electric motor should be collected. This information can be obtained from the nameplate of the electric motor. After that, the next task is to determine the LF of the electric motor which will give an insight regarding its operational characteristics. The methodologies for determining the LF will be explained with a brief definition of the LF in the following sections.

LOAD FACTOR (LF)

LF can be defined as the ratio of the load that an electric motor actually draws while it is in normal operation to the load it could draw at full load (i.e. rated load). In other words, it shows the percent of the full power that the motor draws in actual operation. This ratio provides an understanding of the motor operating characteristics. It shows whether the motor is operating at an efficient load range or not. Most electric motors are designed to operate at 50% to 100% of its rated load and the maximum efficiency is achieved at around 75% of the rated load. Below about 50% load, the efficiency of the electric motor will dramatically decrease (DOE, 1996) as can be seen in Figure B-4.

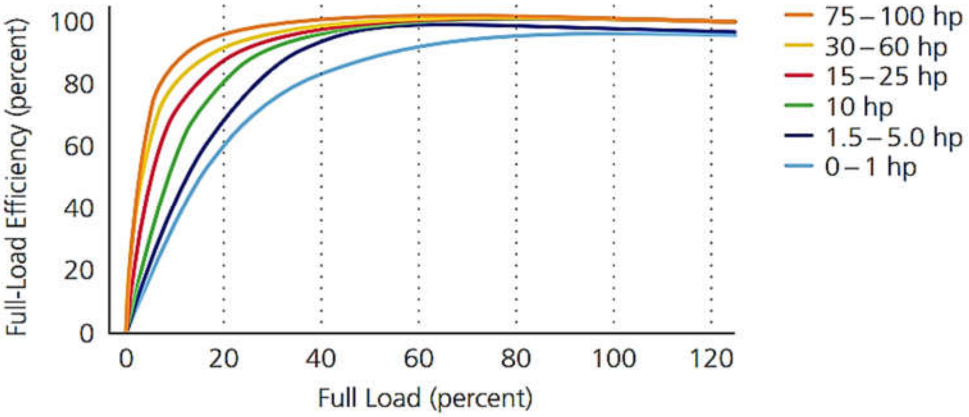


Figure B-4: Motor part load efficiency (as a function of % full-load efficiency) (OEE, 2004)

Therefore, determining the LF of a motor shows whether the motor is operating at an acceptable load range or not; that is the motor is properly sized or not for the application it drives. A very low LF means that the motor is oversized and underloaded and it is operating inefficiently. For this reason, it can be replaced with an energy efficient properly sized one based on the cost effectiveness of the replacement.

Determining LF by conducting measurements

There are three different means of determining the LF of an operating induction electric motor (DOE, 1996):

- Direct Power measurement
- Current measurement
- The slip method

Direct Power Measurement

Direct power measurement by using a measurement device such as power and energy analyser or data logger is the most accurate way of estimating the LF. By using the measured parameters from the measurement device, Equation B-2 can be used to estimate the power drawn by the electric motor (DOE, 1996):

$$P_i = V \; x \; I \; x \; PF \; x \; \sqrt{3} \; / \; 1000 \qquad \text{(Eq. B-2)}$$

where;

v is RMS voltage, mean line-to-line of 3 phases ,
I is RMS current, mean of 3-phases,
PF is power factor as a decimal.

As well as calculating P_i by using the measured parameters in Equation B-2, P_i can be directly read from the measurement device depending on the device specifications. In this case, P_i can be directly used.

P_i, is then used in Equation B-3 which estimates the LF by comparing P_i to the power needed when the motor operates at its rated capacity, P_{ir} (DOE, 1996):

$$LF = \frac{P_i}{P_{ir}} \; x \; 100\% \qquad \text{(Eq. B-3)}$$

where;

LF is load factor as a % of rated power,

P_{ir} is input power at full rated load in kW.

P_{ir} can be calculated by the following equation (DOE, 1996):

$$P_{ir} = \frac{kW}{\eta_{fl}} \; x \; 100\% \qquad \text{(Eq. B-4)}$$

where;

kW is nameplate rated power rating in kW,

η_{fl} is Efficiency at full-rated load.

Current Measurement

In some circumstances, the direct measurement of P_i may not be available due to various reasons. For instance, power measurements by a power and energy data logger or analyser requires the voltage clips (e.g. crocodile clips) to be attached to open leads of the power cables. Open leads cannot be available in some cases. In those cases, only current measurement can be performed for LF estimation due to the fact that current measurement does not require such a connection. Current probes (i.e. sensors) do not require direct contact to the power cables. Else, the available measurement instrument can be capable of only measuring amperage values drawn by the electric motor. In these kinds of cases, LF can be estimated based on the measured current values by using the following equation (DOE, 1996):

$$LF = \frac{I}{I_r} x \frac{V}{V_r} \qquad \text{(Eq. B-5)}$$

where;

I is RMS current, mean of 3-phases,

I_r is Nameplate rated current (i.e. full load current),

V is RMS voltage, mean line-to-line of 3 phases (can be assumed as the 3 phase supply voltage in the plant when cannot be measured),

V_r is Nameplate rated voltage.

The slip method

This method is based on the measurement of the speed the electric motor. The actual speed of an electric motor will be less than its synchronous speed. The synchronous speed of an induction motor depends on the frequency of the power supply and the number of poles which the motor is wound. If the frequency higher, the synchronous speed increases. This is why 60 Hz electric motors runs faster than 50 Hz electric motors at the same load. Vive-versa is true for the pole number (DOE, 1996).

The difference between the actual measured speed and the rated full load speed is referred as **slip.** The amount of slip is proportional to the load that the motor is subjected to. Therefore, measuring the actual speed of an electric motor, one can have an idea for the load factor. The actual motor speed can be measured by using a tachometer and be used in Equation B-6 to estimate the LF (DOE, 1996):

$$LF = \frac{Slip}{S_s - S_r}\ x\ 100\ \% \qquad \text{(Eq. B-6)}$$

where;

Slip is synchronous speed - measured speed in rpm,

S_s is synchronous speed in rpm,

S_r is nameplate full-load speed in rpm.

After determining the LF of the existing electric motor and ensuring that the motor is correctly sized or not, an energy efficient motor with an appropriate procedure for selecting an energy efficient motor will be described in the following part. ESP by replacing the existing motor with an energy efficient one can be estimated.

B.3 ESTIMATION OF ESPs AND ECSPs BY USING ENERGY EFFICIENT ELECTRIC MOTORS

There will be a reduction in the power demand (kW) when an energy efficient electric motor is used. This is called as Demand Saving. Reduction in power demand will result in savings in electricity consumption (kWh). Because the utilities charge the users for demand use and energy use, the cost saving will be sum of the cost savings due to the demand saving and electricity energy saving. Their will be explained in the following parts.

Demand saving s

There will be a demand reduction through the efficiency of the premium efficient electric motor. This is estimated as follows:

$$DS = kW\ x\ LF\ x\ \left(\frac{100}{E_{std}} - \frac{100}{E_{pe}}\right) \qquad \text{(Eq. B-7)}$$

where;

DS is demand saving (kW)

kW is motor nameplate power rating (kW)

E_{std} is existing motor efficiency under actual operating conditions, %

E_{pe} is premium efficiency motor efficiency under actual load conditions, %.

Electric energy saving (i.e. ESP) s

In addition to the demand saving, there will be a reduction in electricity use as a result of the demand reduction. This is estimated as follows:

$$ESP = kW\ x\ LF\ x\ hr\ x\ \left(\frac{100}{E_{std}} - \frac{100}{E_{pe}}\right) \qquad \text{(Eq.B-8)}$$

where;

hr is annual operating hours.

Cost savings (i.e. ECSP) s

As mentioned, the electricity bill for the subject plant consists of two components; Active energy consumption charge (€/kWh) and Demand charge (€/kW). Therefore, total energy cost saving is estimated as follows:

ECSP = ESP x unit cost rate (€/kWh) + DS x unit cost rate (€/kW) (Eq. B-9)

As seen in Equation B-8, annual operation hours of the electric motor have a significant impact on ESP. As such, electric motors with long running hours are the best candidates for energy and energy cost saving potentials and they should be given priority in an energy audit campaign.

In Appendix B, energy efficiency aspects in electric motors were discussed with a particular focus on the energy efficiency of the electric motor itself. As mentioned, energy efficiency classes show the energy efficiency levels of the electric motors and they are useful indicators for the purposes of comparison or benchmarking of electric motors performances. For example, a standard efficiency electric motor can be replaced with a premium energy efficient electric motor on the basis of a cost benefit analysis. It was also mentioned that energy efficiency classes only referred to the efficiency quality of the motor itself and operating characteristics of the motor would also affect its efficiency. It was said that even if an electric motor had a high energy efficiency class, its efficiency would decrease if not properly sized for the application it would serve. Therefore, when a motor is to be replaced, its operation characteristics should be well understood which can be achieved by analysing its LF. After that, an energy efficient motor suitable for the need can be selected and energy and energy cost saving potentials can be estimated accordingly.

Thus far, the effort was to reduce the losses due to the electric motor itself which could be achieved by replacing it with an electric motor of higher efficiency class such as premium efficiency (i.e.IE4). The load side (i.e. power output requirement) in the LF estimation methodology described in the preceding sections was not assessed. If the mechanical power requirement that the electric motor deliver is reduced, then, a small electric motor can be used. For example, a fan or pump which an electric motor is driving can be inefficient or inappropriately-sized. Furthermore, the need for pump or fan work can be reduced by optimising or reducing, for example, required flow or pump head.

Bearing the above stated facts in mind, a systems approach should be followed and the entire system which consists of supply and demand sides should be taken into account when energy saving potentials are to be explored in electric motor driven applications. Therefore, the first step of such an attempt should be to assess the demand side which the electric motor is driving. Once the demand side is optimised, then the efficiency of the electric motor can be assessed and optimised as described in this Appendix.

Appendix C

Compressors Power Demand Graphs, Cycles and Datasheets

C.1 INTRODUCTION

In the analyses presented in Chapter 8, the length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles for Compressor 1 and Compressor 2 was calculated. The results of these analyses are presented in Table C-1 through C-18. The data sheets for the compressors used in the scenarios are also provided through Figure C1-C4.

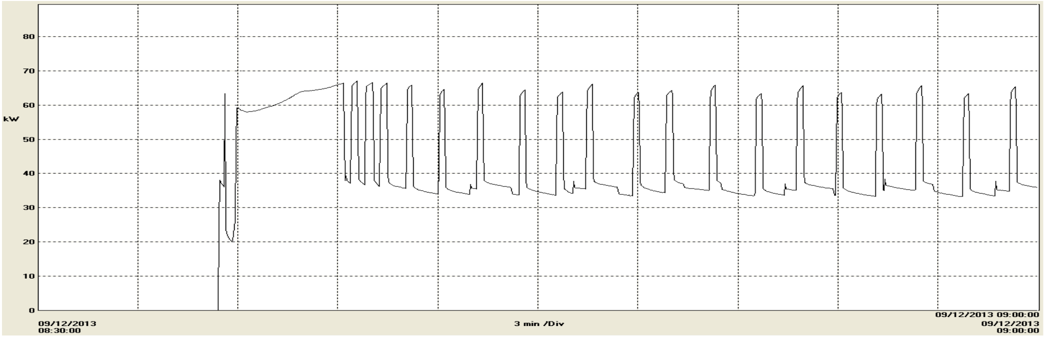


Figure C-1: Compressor1 power demand profile between 08:30-09:00

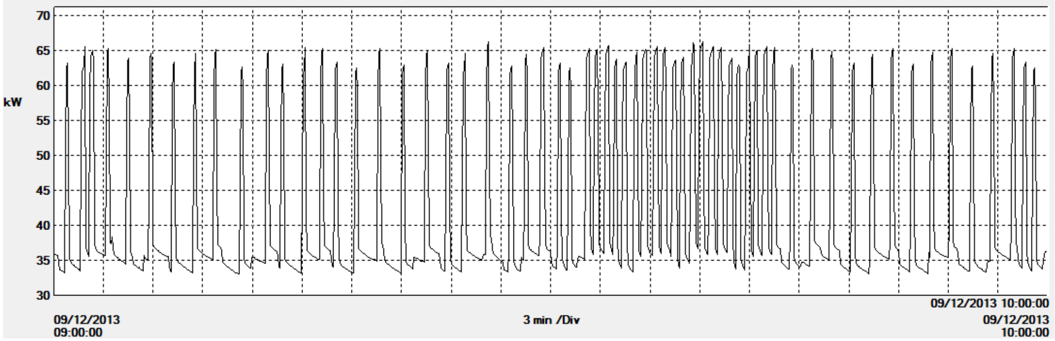


Figure C-2: Compressor 1 power demand profile between 09:00-10:00

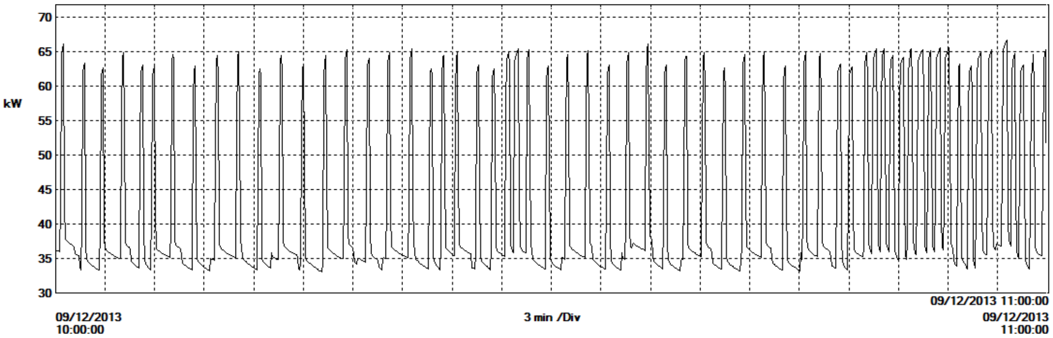


Figure C-3: Compressor 1 power demand profile between 10:00-11:00

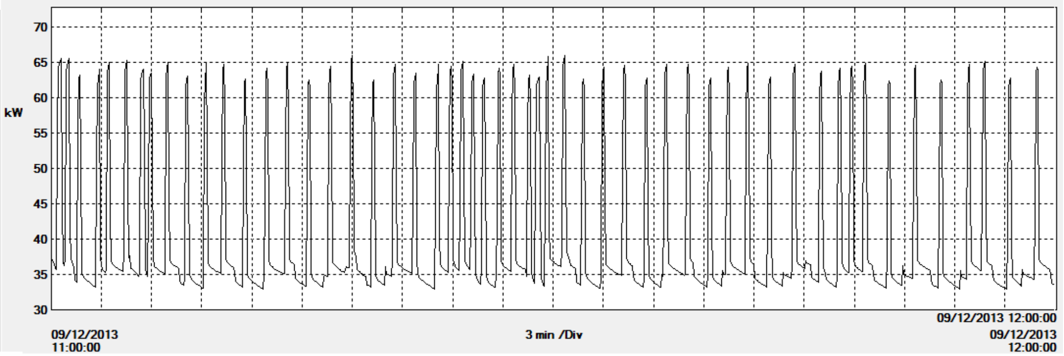


Figure C-4: Compressor 1 power demand profile between 11:00-12:00

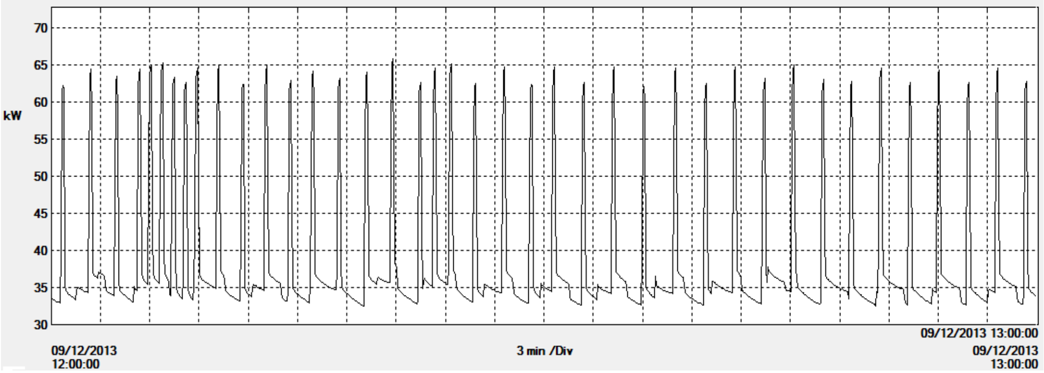


Figure C-5: Compressor 1 power demand profile between 12:00-13:00

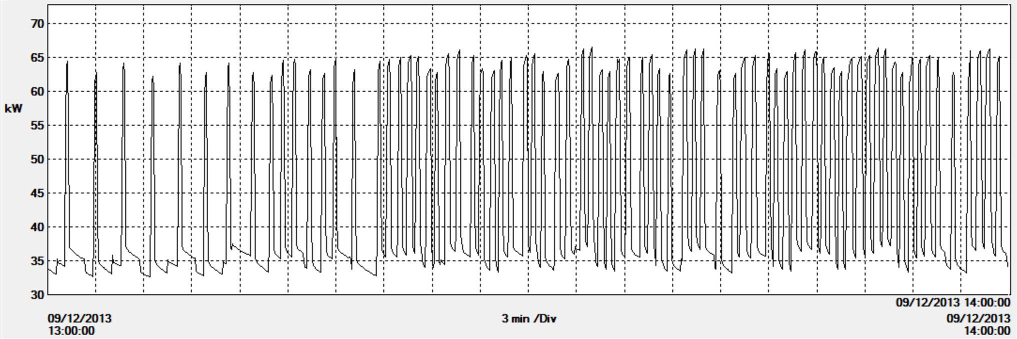


Figure C-6: Compressor 1 power demand profile between 13:00-14:00

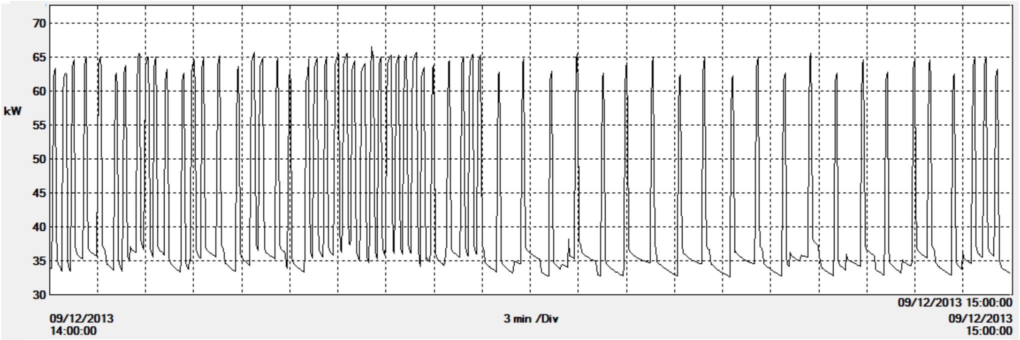


Figure C-7: Compressor 1 power demand profile between 14:00-15:00

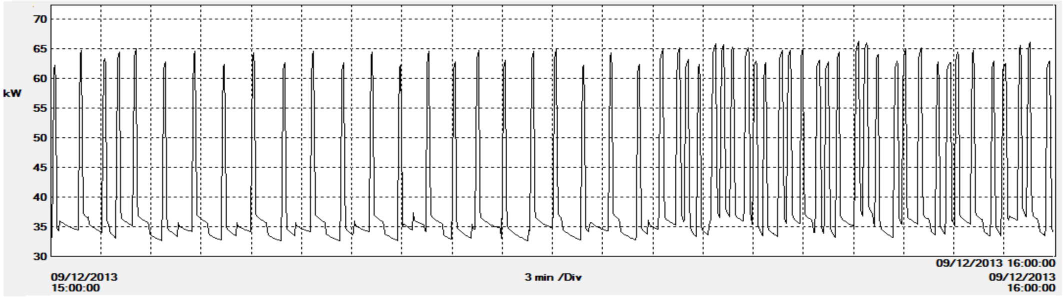


Figure C-8: Compressor 1 power demand profile between 15:00-16:00

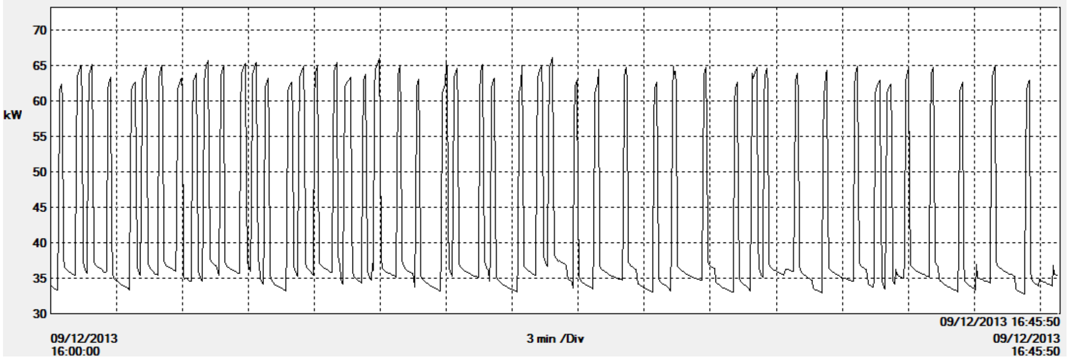


Figure C-9: Compressor 1 power demand profile between 16:00-17:00

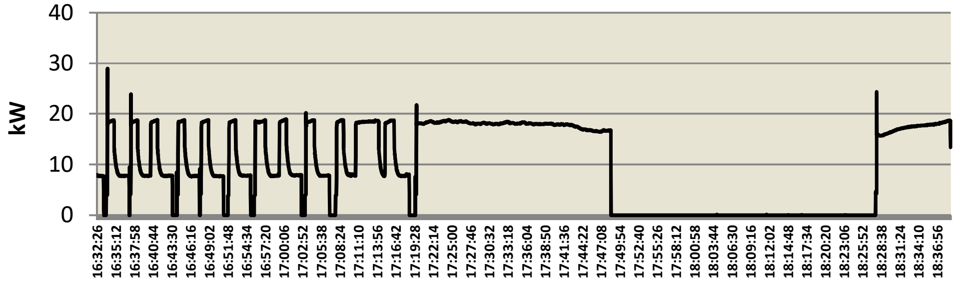


Figure C-10: Compressor 2 power demand profile between 16:32 – 18:36

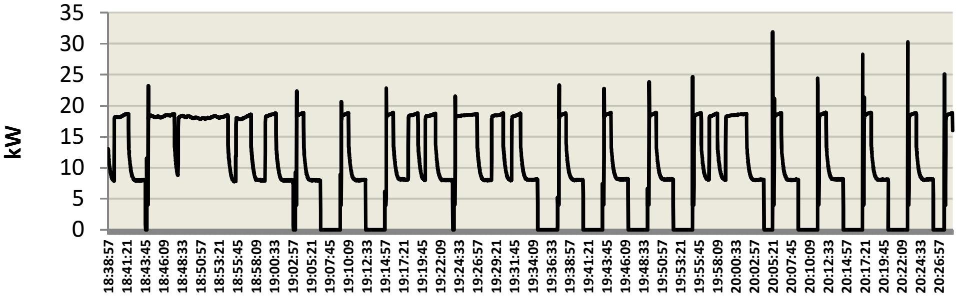


Figure C-11: Compressor 2 power demand profile between 18:38 – 20:26

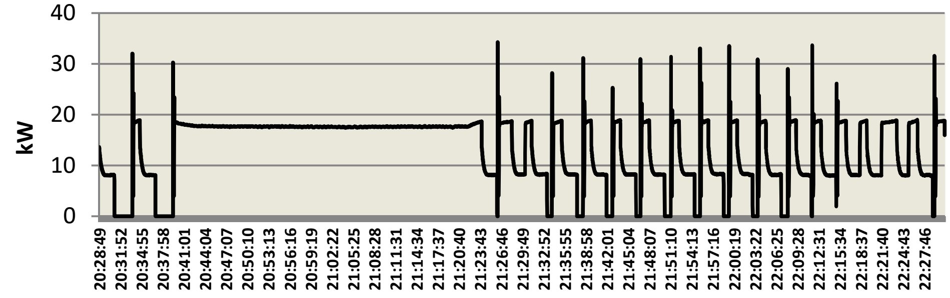


Figure C-12: Compressor-2 power demand profile between 20:28 – 22:28

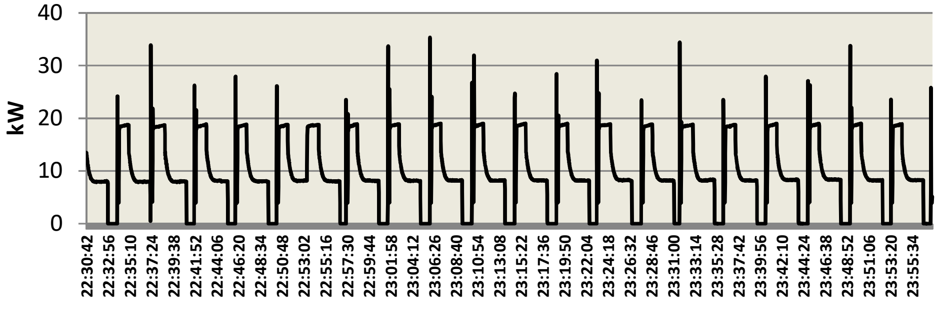


Figure C-13: Compressor-2 power demand profile between 22:30 – 01:26

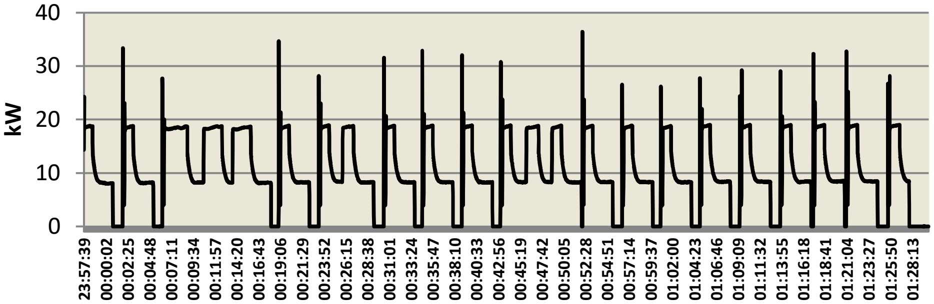


Figure C-14: Compressor-2 power demand profile between 23:57 and 01:30

Table C-1: Compressor 1- the length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 09:00-09:30

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF (%)	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
09:00-09:30	20	10	63.63	39	35.79	49	0.82	20.41%	1.70	2.08	0.0347
09:00-09:30	21	16	63.63	48	35.79	64	1.07	25.00%	2.72	2.55	0.0425
09:00-09:30	22	16	63.63	15	35.79	31	0.52	51.61%	2.72	5.26	0.0877
09:00-09:30	23	10	63.63	45	35.79	55	0.92	18.18%	1.70	1.85	0.0309
09:00-09:30	24	11	63.63	63	35.79	74	1.23	14.86%	1.87	1.52	0.0253
09:00-09:30	25	11	63.63	71	35.79	82	1.37	13.41%	1.87	1.37	0.0228
09:00-09:30	26	11	63.63	72	35.79	83	1.38	13.25%	1.87	1.35	0.0225
09:00-09:30	27	11	63.63	72	35.79	83	1.38	13.25%	1.87	1.35	0.0225
09:00-09:30	28	10	63.63	67	35.79	77	1.28	12.99%	1.70	1.32	0.0221
09:00-09:30	29	11	63.63	63	35.79	74	1.23	14.86%	1.87	1.52	0.0253
09:00-09:30	30	10	63.63	86	35.79	96	1.60	10.42%	1.70	1.06	0.0177
09:00-09:30	31	11	63.63	83	35.79	94	1.57	11.70%	1.87	1.19	0.0199
09:00-09:30	32	11	63.63	43	35.79	54	0.90	20.37%	1.87	2.08	0.0346
09:00-09:30	33	12	63.63	67	35.79	79	1.32	15.19%	2.04	1.55	0.0258
09:00-09:30	34	11	63.63	53	35.79	64	1.07	17.19%	1.87	1.75	0.0292
09:00-09:30	35	12	63.63	40	35.79	52	0.87	23.08%	2.04	2.35	0.0392
09:00-09:30	36	11	63.63	62	35.79	73	1.22	15.07%	1.87	1.54	0.0256
09:00-09:30	37	11	63.63	72	35.79	83	1.38	13.25%	1.87	1.35	0.0225
09:00-09:30	38	11	63.63	76	35.79	87	1.45	12.64%	1.87	1.29	0.0215
09:00-09:30	39	11	63.63	75	35.79	86	1.43	12.79%	1.87	1.30	0.0217
09:00-09:30	40	11	63.63	124	35.79	135	2.25	8.15%	1.87	0.83	0.0139
09:00-09:30	41	11	63.63	75	35.79	86	1.43	12.79%	1.87	1.30	0.0217
09:00-09:30	42	12	63.63	73	35.79	85	1.42	14.12%	2.04	1.44	0.0240
09:00-09:30	43	11	63.63	43	35.79	54	0.90	20.37%	1.87	2.08	0.0346
09:00-09:30	44	15	63.63	46	35.79	61	1.02	24.59%	2.55	2.51	0.0418

Table C-2: Compressor 1- the length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 09:30-10:00

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
09:30-10:00	45	11	63.96	26	35.47	37	0.62	29.73%	1.87	3.03	0.0505
09:30-10:00	46	11	63.96	52	35.47	63	1.05	17.46%	1.87	1.78	0.0297
09:30-10:00	47	16	63.96	15	35.47	31	0.52	51.61%	2.72	5.26	0.0877
09:30-10:00	48	16	63.96	15	35.47	31	0.52	51.61%	2.72	5.26	0.0877
09:30-10:00	49	15	63.96	24	35.47	39	0.65	38.46%	2.55	3.92	0.0654
09:30-10:00	50	16	63.96	17	35.47	33	0.55	48.48%	2.72	4.95	0.0824
09:30-10:00	51	11	63.96	19	35.47	30	0.50	36.67%	1.87	3.74	0.0623
09:30-10:00	52	16	63.96	27	35.47	43	0.72	37.21%	2.72	3.80	0.0633
09:30-10:00	53	14	63.96	15	35.47	29	0.48	48.28%	2.38	4.92	0.0821
09:30-10:00	54	18	63.96	24	35.47	42	0.70	42.86%	3.06	4.37	0.0729
09:30-10:00	55	16	63.96	15	35.47	31	0.52	51.61%	2.72	5.26	0.0877
09:30-10:00	56	15	63.96	21	35.47	36	0.60	41.67%	2.55	4.25	0.0708
09:30-10:00	57	16	63.96	14	35.47	30	0.50	53.33%	2.72	5.44	0.0907
09:30-10:00	58	15	63.96	22	35.47	37	0.62	40.54%	2.55	4.14	0.0689
09:30-10:00	59	16	63.96	14	35.47	30	0.50	53.33%	2.72	5.44	0.0907
09:30-10:00	60	17	63.96	21	35.47	38	0.63	44.74%	2.89	4.56	0.0761
09:30-10:00	61	18	63.96	13	35.47	31	0.52	58.06%	3.06	5.92	0.0987
09:30-10:00	62	16	63.96	21	35.47	37	0.62	43.24%	2.72	4.41	0.0735
09:30-10:00	63	16	63.96	15	35.47	31	0.52	51.61%	2.72	5.26	0.0877
09:30-10:00	64	13	63.96	20	35.47	33	0.55	39.39%	2.21	4.02	0.0670
09:30-10:00	65	16	63.96	15	35.47	31	0.52	51.61%	2.72	5.26	0.0877
09:30-10:00	66	13	63.96	19	35.47	32	0.53	40.63%	2.21	4.14	0.0691

09:30-10:00	67	17	63.96	17	35.47	34	0.57	50.00%	2.89	5.10	0.0850
09:30-10:00	68	11	63.96	55	35.47	66	1.10	16.67%	1.87	1.70	0.0283
09:30-10:00	69	10	63.96	63	35.47	73	1.22	13.70%	1.70	1.40	0.0233
09:30-10:00	70	11	63.96	59	35.47	70	1.17	15.71%	1.87	1.60	0.0267
09:30-10:00	71	11	63.96	67	35.47	78	1.30	14.10%	1.87	1.44	0.0240
09:30-10:00	72	11	63.96	58	35.47	69	1.15	15.94%	1.87	1.63	0.0271
09:30-10:00	73	11	63.96	62	35.47	73	1.22	15.07%	1.87	1.54	0.0256
09:30-10:00	74	11	63.96	63	35.47	74	1.23	14.86%	1.87	1.52	0.0253
09:30-10:00	75	11	63.96	58	35.47	69	1.15	15.94%	1.87	1.63	0.0271
09:30-10:00	76	11	63.96	62	35.47	73	1.22	15.07%	1.87	1.54	0.0256
09:30-10:00	77	11	63.96	63	35.47	74	1.23	14.86%	1.87	1.52	0.0253
09:30-10:00	78	11	63.96	59	35.47	70	1.17	15.71%	1.87	1.60	0.0267
09:30-10:00	79	11	63.96	59	35.47	70	1.17	15.71%	1.87	1.60	0.0267
09:30-10:00	80	11	63.96	65	35.47	76	1.27	14.47%	1.87	1.48	0.0246
09:30-10:00	81	10	63.96	64	35.47	74	1.23	13.51%	1.70	1.38	0.0230
09:30-10:00	82	11	63.96	65	35.47	76	1.27	14.47%	1.87	1.48	0.0246
09:30-10:00	83	11	63.96	29	35.47	40	0.67	27.50%	1.87	2.81	0.0468
09:30-10:00	84	11	63.96	23	35.47	34	0.57	32.35%	1.87	3.30	0.0550
09:30-10:00	85	12	63.96	71	35.47	83	1.38	14.46%	2.04	1.47	0.0246

Table C-3: Compressor 1- the length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 10:00-10:30

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
10:00-10:30	86	11	63.57	67	35.87	78	1.30	14.10%	1.87	1.44	0.0240
10:00-10:30	87	11	63.57	56	35.87	67	1.12	16.42%	1.87	1.67	0.0279
10:00-10:30	88	11	63.57	64	35.87	75	1.25	14.67%	1.87	1.50	0.0249
10:00-10:30	89	12	63.57	56	35.87	68	1.13	17.65%	2.04	1.80	0.0300
10:00-10:30	90	12	63.57	31	35.87	43	0.72	27.91%	2.04	2.85	0.0474
10:00-10:30	91	11	63.57	60	35.87	71	1.18	15.49%	1.87	1.58	0.0263
10:00-10:30	92	11	63.57	67	35.87	78	1.30	14.10%	1.87	1.44	0.0240
10:00-10:30	93	11	63.57	71	35.87	82	1.37	13.41%	1.87	1.37	0.0228
10:00-10:30	94	11	63.57	66	35.87	77	1.28	14.29%	1.87	1.46	0.0243
10:00-10:30	95	11	63.57	68	35.87	79	1.32	13.92%	1.87	1.42	0.0237
10:00-10:30	96	10	63.57	67	35.87	77	1.28	12.99%	1.70	1.32	0.0221
10:00-10:30	97	10	63.57	69	35.87	79	1.32	12.66%	1.70	1.29	0.0215
10:00-10:30	98	11	63.57	69	35.87	80	1.33	13.75%	1.87	1.40	0.0234
10:00-10:30	99	11	63.57	65	35.87	76	1.27	14.47%	1.87	1.48	0.0246
10:00-10:30	100	11	63.57	70	35.87	81	1.35	13.58%	1.87	1.39	0.0231
10:00-10:30	101	11	63.57	63	35.87	74	1.23	14.86%	1.87	1.52	0.0253
10:00-10:30	102	11	63.57	70	35.87	81	1.35	13.58%	1.87	1.39	0.0231
10:00-10:30	103	12	63.57	62	35.87	74	1.23	16.22%	2.04	1.65	0.0276
10:00-10:30	104	10	63.57	33	35.87	43	0.72	23.26%	1.70	2.37	0.0395
10:00-10:30	105	11	63.57	39	35.87	50	0.83	22.00%	1.87	2.24	0.0374
10:00-10:30	106	11	63.57	66	35.87	77	1.28	14.29%	1.87	1.46	0.0243
10:00-10:30	107	11	63.57	45	35.87	56	0.93	19.64%	1.87	2.00	0.0334
10:00-10:30	108	12	63.57	38	35.87	50	0.83	24.00%	2.04	2.45	0.0408
10:00-10:30	109	16	63.57	51	35.87	67	1.12	23.88%	2.72	2.44	0.0406

10:00-10:30	110	18	63.57	46	35.87	64	1.07	28.13%	3.06	2.87	0.0478
10:00-10:30	111	11	63.57	49	35.87	60	1.00	18.33%	1.87	1.87	0.0312
10:00-10:30	112	11	63.57	60	35.87	71	1.18	15.49%	1.87	1.58	0.0263
10:30-11:00	113	11	63.57	73	35.87	84	1.40	13.10%	1.87	1.34	0.0223
10:30-11:00	114	11	63.57	65	35.87	76	1.27	14.47%	1.87	1.48	0.0246
10:30-11:00	115	11	63.57	60	35.87	71	1.18	15.49%	1.87	1.58	0.0263
10:30-11:00	116	11	63.57	60	35.87	71	1.18	15.49%	1.87	1.58	0.0263
10:30-11:00	117	11	63.57	55	35.87	66	1.10	16.67%	1.87	1.70	0.0283
10:30-11:00	118	11	63.57	68	35.87	79	1.32	13.92%	1.87	1.42	0.0237
10:30-11:00	119	12	63.57	54	35.87	66	1.10	18.18%	2.04	1.85	0.0309
10:30-11:00	120	12	63.57	62	35.87	74	1.23	16.22%	2.04	1.65	0.0276
10:30-11:00	121	11	63.57	61	35.87	72	1.20	15.28%	1.87	1.56	0.0260
10:30-11:00	122	11	63.57	61	35.87	72	1.20	15.28%	1.87	1.56	0.0260
10:30-11:00	123	11	63.57	66	35.87	77	1.28	14.29%	1.87	1.46	0.0243
10:30-11:00	124	10	63.57	63	35.87	73	1.22	13.70%	1.70	1.40	0.0233
10:30-11:00	125	11	63.57	44	35.87	55	0.92	20.00%	1.87	2.04	0.0340
10:30-11:00	126	11	63.57	56	35.87	67	1.12	16.42%	1.87	1.67	0.0279
10:30-11:00	127	15	63.57	27	35.87	42	0.70	35.71%	2.55	3.64	0.0607
10:30-11:00	128	15	63.57	43	35.87	58	0.97	25.86%	2.55	2.64	0.0440
10:30-11:00	129	20	63.57	28	35.87	48	0.80	41.67%	3.40	4.25	0.0708
10:30-11:00	130	11	63.57	27	35.87	38	0.63	28.95%	1.87	2.95	0.0492
10:30-11:00	131	15	63.57	38	35.87	53	0.88	28.30%	2.55	2.89	0.0481
10:30-11:00	132	16	63.57	39	35.87	55	0.92	29.09%	2.72	2.97	0.0495
10:30-11:00	133	14	63.57	32	35.87	46	0.77	30.43%	2.38	3.10	0.0517

Table C-4: Compressor 1- the length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 11:00-11:30

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
11:00-11:30	134	17	63.98	14	35.64	31	0.52	54.84%	2.89	5.59	0.0932
11:00-11:30	135	14	63.98	29	35.64	43	0.72	32.56%	2.38	3.32	0.0553
11:00-11:30	136	11	63.98	57	35.64	68	1.13	16.18%	1.87	1.65	0.0275
11:00-11:30	137	12	63.98	24	35.64	36	0.60	33.33%	2.04	3.40	0.0567
11:00-11:30	138	11	63.98	53	35.64	64	1.07	17.19%	1.87	1.75	0.0292
11:00-11:30	139	11	63.98	45	35.64	56	0.93	19.64%	1.87	2.00	0.0334
11:00-11:30	140	16	63.98	15	35.64	31	0.52	51.61%	2.72	5.26	0.0877
11:00-11:30	141	13	63.98	47	35.64	60	1.00	21.67%	2.21	2.21	0.0368
11:00-11:30	142	12	63.98	59	35.64	71	1.18	16.90%	2.04	1.72	0.0287
11:00-11:30	143	12	63.98	56	35.64	68	1.13	17.65%	2.04	1.80	0.0300
11:00-11:30	144	11	63.98	53	35.64	64	1.07	17.19%	1.87	1.75	0.0292
11:00-11:30	145	11	63.98	66	35.64	77	1.28	14.29%	1.87	1.46	0.0243
11:00-11:30	146	11	63.98	67	35.64	78	1.30	14.10%	1.87	1.44	0.0240
11:00-11:30	147	11	63.98	62	35.64	73	1.22	15.07%	1.87	1.54	0.0256
11:00-11:30	148	12	63.98	67	35.64	79	1.32	15.19%	2.04	1.55	0.0258
11:00-11:30	149	10	63.98	66	35.64	76	1.27	13.16%	1.70	1.34	0.0224
11:00-11:30	150	11	63.98	67	35.64	78	1.30	14.10%	1.87	1.44	0.0240
11:00-11:30	151	11	63.98	66	35.64	77	1.28	14.29%	1.87	1.46	0.0243
11:00-11:30	152	11	63.98	65	35.64	76	1.27	14.47%	1.87	1.48	0.0246
11:00-11:30	153	11	63.98	62	35.64	73	1.22	15.07%	1.87	1.54	0.0256
11:00-11:30	154	11	63.98	70	35.64	81	1.35	13.58%	1.87	1.39	0.0231
11:00-11:30	155	11	63.98	37	35.64	48	0.80	22.92%	1.87	2.34	0.0390
11:00-11:30	156	12	63.98	28	35.64	40	0.67	30.00%	2.04	3.06	0.0510
11:00-11:30	157	12	63.98	27	35.64	39	0.65	30.77%	2.04	3.14	0.0523
11:00-11:30	158	12	63.98	27	35.64	39	0.65	30.77%	2.04	3.14	0.0523
11:00-11:30	159	12	63.98	43	35.64	55	0.92	21.82%	2.04	2.23	0.0371
11:00-11:30	160	11	63.98	41	35.64	52	0.87	21.15%	1.87	2.16	0.0360
11:00-11:30	161	12	63.98	44	35.64	56	0.93	21.43%	2.04	2.19	0.0364
11:00-11:30	162	12	63.98	16	35.64	28	0.47	42.86%	2.04	4.37	0.0729
11:00-11:30	163	17	63.98	19	35.64	36	0.60	47.22%	2.89	4.82	0.0803
11:00-11:30	164	11	63.98	50	35.64	61	1.02	18.03%	1.87	1.84	0.0307

Table C-5: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 11:30-12:00

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
11:30-12:00	165	12	63.59	57	35.19	69	1.15	17.39%	2.04	1.77	0.0296
11:30-12:00	166	11	63.59	60	35.19	71	1.18	15.49%	1.87	1.58	0.0263
11:30-12:00	167	12	63.59	64	35.19	76	1.27	15.79%	2.04	1.61	0.0268
11:30-12:00	168	11	63.59	68	35.19	79	1.32	13.92%	1.87	1.42	0.0237
11:30-12:00	169	11	63.59	59	35.19	70	1.17	15.71%	1.87	1.60	0.0267
11:30-12:00	170	12	63.59	68	35.19	80	1.33	15.00%	2.04	1.53	0.0255
11:30-12:00	171	11	63.59	68	35.19	79	1.32	13.92%	1.87	1.42	0.0237
11:30-12:00	172	11	63.59	54	35.19	65	1.08	16.92%	1.87	1.73	0.0288
11:30-12:00	173	11	63.59	59	35.19	70	1.17	15.71%	1.87	1.60	0.0267
11:30-12:00	174	11	63.59	68	35.19	79	1.32	13.92%	1.87	1.42	0.0237
11:30-12:00	175	11	63.59	68	35.19	79	1.32	13.92%	1.87	1.42	0.0237
11:30-12:00	176	11	63.59	85	35.19	96	1.60	11.46%	1.87	1.17	0.0195
11:30-12:00	177	11	63.59	55	35.19	66	1.10	16.67%	1.87	1.70	0.0283
11:30-12:00	178	13	63.59	30	35.19	43	0.72	30.23%	2.21	3.08	0.0514
11:30-12:00	179	12	63.59	37	35.19	49	0.82	24.49%	2.04	2.50	0.0416
11:30-12:00	180	12	63.59	75	35.19	87	1.45	13.79%	2.04	1.41	0.0234
11:30-12:00	181	10	63.59	83	35.19	93	1.55	10.75%	1.70	1.10	0.0183
11:30-12:00	182	11	63.59	82	35.19	93	1.55	11.83%	1.87	1.21	0.0201
11:30-12:00	183	11	63.59	89	35.19	100	1.67	11.00%	1.87	1.12	0.0187
11:30-12:00	184	12	63.59	43	35.19	55	0.92	21.82%	2.04	2.23	0.0371
11:30-12:00	185	11	63.59	80	35.19	91	1.52	12.09%	1.87	1.23	0.0205
11:30-12:00	186	11	63.59	87	35.19	98	1.63	11.22%	1.87	1.14	0.0191
11:30-12:00	187	12	63.59	91	35.19	103	1.72	11.65%	2.04	1.19	0.0198

Table C-6: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 12:0-12:30

Interval	**Cycle No**	**Load time (sec)**	**Power demand in load mode (kW)**	**Unload time (sec)**	**Power demand in unload mode (kW)**	**Cycle time (sec)**	**CYCLE time(min)**	**LF**	**CAD in a cycle (m3)**	**CAD rate in cycle (m3/min)**	**CAD in cycle (m3/sec)**
12:00-12:30	188	11	63.53	91	35.18	102	1.70	10.78%	1.87	1.10	0.0183
12:00-12:30	189	11	63.53	84	35.18	95	1.58	11.58%	1.87	1.18	0.0197
12:00-12:30	190	12	63.53	72	35.18	84	1.40	14.29%	2.04	1.46	0.0243
12:00-12:30	191	12	63.53	28	35.18	40	0.67	30.00%	2.04	3.06	0.0510
12:00-12:30	192	12	63.53	30	35.18	42	0.70	28.57%	2.04	2.91	0.0486
12:00-12:30	193	12	63.53	31	35.18	43	0.72	27.91%	2.04	2.85	0.0474
12:00-12:30	194	12	63.53	31	35.18	43	0.72	27.91%	2.04	2.85	0.0474
12:00-12:30	195	12	63.53	30	35.18	42	0.70	28.57%	2.04	2.91	0.0486
12:00-12:30	196	10	63.53	68	35.18	78	1.30	12.82%	1.70	1.31	0.0218
12:00-12:30	197	11	63.53	79	35.18	90	1.50	12.22%	1.87	1.25	0.0208
12:00-12:30	198	11	63.53	75	35.18	86	1.43	12.79%	1.87	1.30	0.0217
12:00-12:30	199	11	63.53	76	35.18	87	1.45	12.64%	1.87	1.29	0.0215
12:00-12:30	200	10	63.53	72	35.18	82	1.37	12.20%	1.70	1.24	0.0207
12:00-12:30	201	11	63.53	85	35.18	96	1.60	11.46%	1.87	1.17	0.0195
12:00-12:30	202	11	63.53	89	35.18	100	1.67	11.00%	1.87	1.12	0.0187
12:00-12:30	203	11	63.53	84	35.18	95	1.58	11.58%	1.87	1.18	0.0197
12:00-12:30	204	11	63.53	90	35.18	101	1.68	10.89%	1.87	1.11	0.0185
12:00-12:30	205	11	63.53	43	35.18	54	0.90	20.37%	1.87	2.08	0.0346
12:00-12:30	206	11	63.53	48	35.18	59	0.98	18.64%	1.87	1.90	0.0317
12:00-12:30	207	11	63.53	78	35.18	89	1.48	12.36%	1.87	1.26	0.0210
12:00-12:30	208	11	63.53	95	35.18	106	1.77	10.38%	1.87	1.06	0.0176
12:00-12:30	209	12	63.53	88	35.18	100	1.67	12.00%	2.04	1.22	0.0204
12:00-12:30	210	10	63.53	75	35.18	85	1.42	11.76%	1.70	1.20	0.0200

Table C-7: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 12:30-13:00

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
12:30-13:00	211	11	63.46	79	34.85	90	1.50	12.22%	1.87	1.25	0.0208
12:30-13:00	212	11	63.46	98	34.85	109	1.82	10.09%	1.87	1.03	0.0172
12:30-13:00	213	11	63.46	98	34.85	109	1.82	10.09%	1.87	1.03	0.0172
12:30-13:00	214	10	63.46	101	34.85	111	1.85	9.01%	1.70	0.92	0.0153
12:30-13:00	215	11	63.46	105	34.85	116	1.93	9.48%	1.87	0.97	0.0161
12:30-13:00	216	11	63.46	100	34.85	111	1.85	9.91%	1.87	1.01	0.0168
12:30-13:00	217	11	63.46	95	34.85	106	1.77	10.38%	1.87	1.06	0.0176
12:30-13:00	218	11	63.46	96	34.85	107	1.78	10.28%	1.87	1.05	0.0175
12:30-13:00	219	11	63.46	96	34.85	107	1.78	10.28%	1.87	1.05	0.0175
12:30-13:00	220	11	63.46	97	34.85	108	1.80	10.19%	1.87	1.04	0.0173
12:30-13:00	221	10	63.46	94	34.85	104	1.73	9.62%	1.70	0.98	0.0163
12:30-13:00	222	11	63.46	97	34.85	108	1.80	10.19%	1.87	1.04	0.0173
12:30-13:00	223	11	63.46	96	34.85	107	1.78	10.28%	1.87	1.05	0.0175
12:30-13:00	224	11	63.46	94	34.85	105	1.75	10.48%	1.87	1.07	0.0178
12:30-13:00	225	11	63.46	98	34.85	109	1.82	10.09%	1.87	1.03	0.0172
12:30-13:00	226	11	63.46	94	34.85	105	1.75	10.48%	1.87	1.07	0.0178
12:30-13:00	227	11	63.46	94	34.85	105	1.75	10.48%	1.87	1.07	0.0178

Table C-8: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 13:00-13:30

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
13:00-13:30	228	11	63.13	99	36.58	110	1.83	10.00%	1.87	1.02	0.0170
13:00-13:30	229	11	63.13	97	36.58	108	1.80	10.19%	1.87	1.04	0.0173
13:00-13:30	230	11	63.13	93	36.58	104	1.73	10.58%	1.87	1.08	0.0180
13:00-13:30	231	11	63.13	98	36.58	109	1.82	10.09%	1.87	1.03	0.0172
13:00-13:30	232	11	63.13	91	36.58	102	1.70	10.78%	1.87	1.10	0.0183
13:00-13:30	233	10	63.13	86	36.58	96	1.60	10.42%	1.70	1.06	0.0177
13:00-13:30	234	11	63.13	76	36.58	87	1.45	12.64%	1.87	1.29	0.0215
13:00-13:30	235	11	63.13	80	36.58	91	1.52	12.09%	1.87	1.23	0.0205
13:00-13:30	236	12	63.13	58	36.58	70	1.17	17.14%	2.04	1.75	0.0291
13:00-13:30	237	12	63.13	31	36.58	43	0.72	27.91%	2.04	2.85	0.0474
13:00-13:30	238	13	63.13	30	36.58	43	0.72	30.23%	2.21	3.08	0.0514
13:00-13:30	239	12	63.13	45	36.58	57	0.95	21.05%	2.04	2.15	0.0358
13:00-13:30	240	12	63.13	40	36.58	52	0.87	23.08%	2.04	2.35	0.0392
13:00-13:30	241	11	63.13	32	36.58	43	0.72	25.58%	1.87	2.61	0.0435
13:00-13:30	242	10	63.13	60	36.58	70	1.17	14.29%	1.70	1.46	0.0243
13:00-13:30	243	12	63.13	84	36.58	96	1.60	12.50%	2.04	1.28	0.0213
13:00-13:30	244	14	63.13	23	36.58	37	0.62	37.84%	2.38	3.86	0.0643
13:00-13:30	245	12	63.13	29	36.58	41	0.68	29.27%	2.04	2.99	0.0498
13:00-13:30	246	19	63.13	21	36.58	40	0.67	47.50%	3.23	4.85	0.0808
13:00-13:30	247	14	63.13	14	36.58	28	0.47	50.00%	2.38	5.10	0.0850
13:00-13:30	248	18	63.13	25	36.58	43	0.72	41.86%	3.06	4.27	0.0712
13:00-13:30	249	12	63.13	14	36.58	26	0.43	46.15%	2.04	4.71	0.0785
13:00-13:30	250	16	63.13	27	36.58	43	0.72	37.21%	2.72	3.80	0.0633
13:00-13:30	251	14	63.13	26	36.58	40	0.67	35.00%	2.38	3.57	0.0595
13:00-13:30	252	12	63.13	41	36.58	53	0.88	22.64%	2.04	2.31	0.0385
13:00-13:30	253	17	63.13	18	36.58	35	0.58	48.57%	2.89	4.95	0.0826
13:00-13:30	254	16	63.13	26	36.58	42	0.70	38.10%	2.72	3.89	0.0648
13:00-13:30	255	13	63.13	15	36.58	28	0.47	46.43%	2.21	4.74	0.0789
13:00-13:30	256	11	63.13	26	36.58	37	0.62	29.73%	1.87	3.03	0.0505
13:00-13:30	257	17	63.13	41	36.58	58	0.97	29.31%	2.89	2.99	0.0498

Table C-9: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 13:30-14:00

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
13:30-14:00	258	14	64.08	15	36.05	29	0.48	48.28%	2.38	4.92	0.0821
13:30-14:00	259	11	64.08	23	36.05	34	0.57	32.35%	1.87	3.30	0.0550
13:30-14:00	260	16	64.08	40	36.05	56	0.93	28.57%	2.72	2.91	0.0486
13:30-14:00	261	14	64.08	25	36.05	39	0.65	35.90%	2.38	3.66	0.0610
13:30-14:00	262	13	64.08	42	36.05	55	0.92	23.64%	2.21	2.41	0.0402
13:30-14:00	263	15	64.08	16	36.05	31	0.52	48.39%	2.55	4.94	0.0823
13:30-14:00	264	17	64.08	22	36.05	39	0.65	43.59%	2.89	4.45	0.0741
13:30-14:00	265	13	64.08	15	36.05	28	0.47	46.43%	2.21	4.74	0.0789
13:30-14:00	266	17	64.08	19	36.05	36	0.60	47.22%	2.89	4.82	0.0803
13:30-14:00	267	16	64.08	22	36.05	38	0.63	42.11%	2.72	4.29	0.0716
13:30-14:00	268	11	64.08	39	36.05	50	0.83	22.00%	1.87	2.24	0.0374
13:30-14:00	269	17	64.08	18	36.05	35	0.58	48.57%	2.89	4.95	0.0826
13:30-14:00	270	13	64.08	15	36.05	28	0.47	46.43%	2.21	4.74	0.0789
13:30-14:00	271	11	64.08	29	36.05	40	0.67	27.50%	1.87	2.81	0.0468
13:30-14:00	272	17	64.08	44	36.05	61	1.02	27.87%	2.89	2.84	0.0474
13:30-14:00	273	12	64.08	19	36.05	31	0.52	38.71%	2.04	3.95	0.0658
13:30-14:00	274	13	64.08	20	36.05	33	0.55	39.39%	2.21	4.02	0.0670
13:30-14:00	275	15	64.08	46	36.05	61	1.02	24.59%	2.55	2.51	0.0418
13:30-14:00	276	13	64.08	46	36.05	59	0.98	22.03%	2.21	2.25	0.0375
13:30-14:00	277	18	64.08	16	36.05	34	0.57	52.94%	3.06	5.40	0.0900
13:30-14:00	278	15	64.08	25	36.05	40	0.67	37.50%	2.55	3.83	0.0638
13:30-14:00	279	14	64.08	38	36.05	52	0.87	26.92%	2.38	2.75	0.0458
13:30-14:00	280	14	64.08	15	36.05	29	0.48	48.28%	2.38	4.92	0.0821
13:30-14:00	281	17	64.08	22	36.05	39	0.65	43.59%	2.89	4.45	0.0741

13:30-14:00	282	16	64.08	14	36.05	30	0.50	53.33%	2.72	5.44	0.0907
13:30-14:00	283	14	64.08	22	36.05	36	0.60	38.89%	2.38	3.97	0.0661
13:30-14:00	284	18	64.08	26	36.05	44	0.73	40.91%	3.06	4.17	0.0695
13:30-14:00	285	13	64.08	15	36.05	28	0.47	46.43%	2.21	4.74	0.0789
13:30-14:00	286	17	64.08	20	36.05	37	0.62	45.95%	2.89	4.69	0.0781
13:30-14:00	287	15	64.08	14	36.05	29	0.48	51.72%	2.55	5.28	0.0879
13:30-14:00	288	22	64.08	15	36.05	37	0.62	59.46%	3.74	6.06	0.1011
13:30-14:00	289	23	64.08	15	36.05	38	0.63	60.53%	3.91	6.17	0.1029
13:30-14:00	290	17	64.08	12	36.05	29	0.48	58.62%	2.89	5.98	0.0997
13:30-14:00	291	19	64.08	15	36.05	34	0.57	55.88%	3.23	5.70	0.0950
13:30-14:00	292	13	64.08	15	36.05	28	0.47	46.43%	2.21	4.74	0.0789
13:30-14:00	293	17	64.08	19	36.05	36	0.60	47.22%	2.89	4.82	0.0803
13:30-14:00	294	12	64.08	15	36.05	27	0.45	44.44%	2.04	4.53	0.0756
13:30-14:00	295	17	64.08	20	36.05	37	0.62	45.95%	2.89	4.69	0.0781
13:30-14:00	296	22	64.08	16	36.05	38	0.63	57.89%	3.74	5.91	0.0984
13:30-14:00	297	18	64.08	18	36.05	36	0.60	50.00%	3.06	5.10	0.0850
13:30-14:00	298	12	64.08	21	36.05	33	0.55	36.36%	2.04	3.71	0.0618
13:30-14:00	299	11	64.08	46	36.05	57	0.95	19.30%	1.87	1.97	0.0328
13:30-14:00	300	12	64.08	48	36.05	60	1.00	20.00%	2.04	2.04	0.0340
13:30-14:00	301	17	64.08	24	36.05	41	0.68	41.46%	2.89	4.23	0.0705
13:30-14:00	302	20	64.08	14	36.05	34	0.57	58.82%	3.40	6.00	0.1000
13:30-14:00	303	14	64.08	22	36.05	36	0.60	38.89%	2.38	3.97	0.0661

Table C-10: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 14:00-14:30

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
14:00-14:30	304	11	64.08	39	35.12	50	0.83	22.00%	1.87	2.24	0.0374
14:00-14:30	305	11	64.08	26	35.12	37	0.62	29.73%	1.87	3.03	0.0505
14:00-14:30	306	17	64.08	16	35.12	33	0.55	51.52%	2.89	5.25	0.0876
14:00-14:30	307	12	64.08	34	35.12	46	0.77	26.09%	2.04	2.66	0.0443
14:00-14:30	308	14	64.08	41	35.12	55	0.92	25.45%	2.38	2.60	0.0433
14:00-14:30	309	11	64.08	49	35.12	60	1.00	18.33%	1.87	1.87	0.0312
14:00-14:30	310	12	64.08	21	35.12	33	0.55	36.36%	2.04	3.71	0.0618
14:00-14:30	311	13	64.08	37	35.12	50	0.83	26.00%	2.21	2.65	0.0442
14:00-14:30	312	17	64.08	17	35.12	34	0.57	50.00%	2.89	5.10	0.0850
14:00-14:30	313	13	64.08	15	35.12	28	0.47	46.43%	2.21	4.74	0.0789
14:00-14:30	314	12	64.08	31	35.12	43	0.72	27.91%	2.04	2.85	0.0474
14:00-14:30	315	11	64.08	56	35.12	67	1.12	16.42%	1.87	1.67	0.0279
14:00-14:30	316	17	64.08	24	35.12	41	0.68	41.46%	2.89	4.23	0.0705
14:00-14:30	317	12	64.08	22	35.12	34	0.57	35.29%	2.04	3.60	0.0600
14:00-14:30	318	13	64.08	47	35.12	60	1.00	21.67%	2.21	2.21	0.0368
14:00-14:30	319	11	64.08	60	35.12	71	1.18	15.49%	1.87	1.58	0.0263
14:00-14:30	320	17	64.08	42	35.12	59	0.98	28.81%	2.89	2.94	0.0490
14:00-14:30	321	17	64.08	14	35.12	31	0.52	54.84%	2.89	5.59	0.0932
14:00-14:30	322	11	64.08	46	35.12	57	0.95	19.30%	1.87	1.97	0.0328
14:00-14:30	323	11	64.08	36	35.12	47	0.78	23.40%	1.87	2.39	0.0398
14:00-14:30	324	15	64.08	53	35.12	68	1.13	22.06%	2.55	2.25	0.0375

14:00-14:30	325	16	64.08	15	35.12	31	0.52	51.61%	2.72	5.26	0.0877
14:00-14:30	326	12	64.08	25	35.12	37	0.62	32.43%	2.04	3.31	0.0551
14:00-14:30	327	18	64.08	26	35.12	44	0.73	40.91%	3.06	4.17	0.0695
14:00-14:30	328	18	64.08	14	35.12	32	0.53	56.25%	3.06	5.74	0.0956
14:00-14:30	329	15	64.08	14	35.12	29	0.48	51.72%	2.55	5.28	0.0879
14:00-14:30	330	19	64.08	20	35.12	39	0.65	48.72%	3.23	4.97	0.0828
14:00-14:30	331	15	64.08	16	35.12	31	0.52	48.39%	2.55	4.94	0.0823
14:00-14:30	332	13	64.08	14	35.12	27	0.45	48.15%	2.21	4.91	0.0819
14:00-14:30	333	21	64.08	19	35.12	40	0.67	52.50%	3.57	5.36	0.0893
14:00-14:30	334	15	64.08	13	35.12	28	0.47	53.57%	2.55	5.46	0.0911
14:00-14:30	335	15	64.08	14	35.12	29	0.48	51.72%	2.55	5.28	0.0879
14:00-14:30	336	20	64.08	17	35.12	37	0.62	54.05%	3.40	5.51	0.0919
14:00-14:30	337	15	64.08	14	35.12	29	0.48	51.72%	2.55	5.28	0.0879
14:00-14:30	338	12	64.08	25	35.12	37	0.62	32.43%	2.04	3.31	0.0551
14:00-14:30	339	11	64.08	48	35.12	59	0.98	18.64%	1.87	1.90	0.0317
14:00-14:30	340	12	64.08	40	35.12	52	0.87	23.08%	2.04	2.35	0.0392
14:00-14:30	341	16	64.08	18	35.12	34	0.57	47.06%	2.72	4.80	0.0800
14:00-14:30	342	15	64.08	15	35.12	30	0.50	50.00%	2.55	5.10	0.0850
14:00-14:30	343	11	64.08	60	35.12	71	1.18	15.49%	1.87	1.58	0.0263
14:00-14:30	344	10	64.08	80	35.12	90	1.50	11.11%	1.70	1.13	0.0189

Table C-11: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 14:30-15:00

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
14:30-15:00	345	10	63.40	93	35.02	103	1.72	9.71%	1.70	0.99	0.0165
14:30-15:00	346	12	63.40	85	35.02	97	1.62	12.37%	2.04	1.26	0.0210
14:30-15:00	347	11	63.40	88	35.02	99	1.65	11.11%	1.87	1.13	0.0189
14:30-15:00	348	10	63.40	77	35.02	87	1.45	11.49%	1.70	1.17	0.0195
14:30-15:00	349	11	63.40	87	35.02	98	1.63	11.22%	1.87	1.14	0.0191
14:30-15:00	350	11	63.40	91	35.02	102	1.70	10.78%	1.87	1.10	0.0183
14:30-15:00	351	11	63.40	81	35.02	92	1.53	11.96%	1.87	1.22	0.0203
14:30-15:00	352	10	63.40	96	35.02	106	1.77	9.43%	1.70	0.96	0.0160
14:30-15:00	353	11	63.40	82	35.02	93	1.55	11.83%	1.87	1.21	0.0201
14:30-15:00	354	11	63.40	92	35.02	103	1.72	10.68%	1.87	1.09	0.0182
14:30-15:00	355	11	63.40	86	35.02	97	1.62	11.34%	1.87	1.16	0.0193
14:30-15:00	356	11	63.40	86	35.02	97	1.62	11.34%	1.87	1.16	0.0193
14:30-15:00	357	11	63.40	89	35.02	100	1.67	11.00%	1.87	1.12	0.0187
14:30-15:00	358	11	63.40	79	35.02	90	1.50	12.22%	1.87	1.25	0.0208
14:30-15:00	359	11	63.40	92	35.02	103	1.72	10.68%	1.87	1.09	0.0182
14:30-15:00	360	11	63.40	48	35.02	59	0.98	18.64%	1.87	1.90	0.0317
14:30-15:00	361	11	63.40	79	35.02	90	1.50	12.22%	1.87	1.25	0.0208
14:30-15:00	362	11	63.40	64	35.02	75	1.25	14.67%	1.87	1.50	0.0249
14:30-15:00	363	12	63.40	31	35.02	43	0.72	27.91%	2.04	2.85	0.0474
14:30-15:00	364	12	63.40	31	35.02	43	0.72	27.91%	2.04	2.85	0.0474
14:30-15:00	365	12	63.40	51	35.02	63	1.05	19.05%	2.04	1.94	0.0324

Table C-12: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 15:00-15:30

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
15:00-15:30	366	11	63.20	83	35.02	94	1.57	11.70%	1.87	1.19	0.0199
15:00-15:30	367	10	63.20	75	35.02	85	1.42	11.76%	1.70	1.20	0.0200
15:00-15:30	368	11	63.20	39	35.02	50	0.83	22.00%	1.87	2.24	0.0374
15:00-15:30	369	12	63.20	48	35.02	60	1.00	20.00%	2.04	2.04	0.0340
15:00-15:30	370	11	63.20	95	35.02	106	1.77	10.38%	1.87	1.06	0.0176
15:00-15:30	371	11	63.20	96	35.02	107	1.78	10.28%	1.87	1.05	0.0175
15:00-15:30	372	11	63.20	95	35.02	106	1.77	10.38%	1.87	1.06	0.0176
15:00-15:30	373	11	63.20	95	35.02	106	1.77	10.38%	1.87	1.06	0.0176
15:00-15:30	374	11	63.20	99	35.02	110	1.83	10.00%	1.87	1.02	0.0170
15:00-15:30	375	11	63.20	93	35.02	104	1.73	10.58%	1.87	1.08	0.0180
15:00-15:30	376	11	63.20	97	35.02	108	1.80	10.19%	1.87	1.04	0.0173
15:00-15:30	377	11	63.20	93	35.02	104	1.73	10.58%	1.87	1.08	0.0180
15:00-15:30	378	10	63.20	92	35.02	102	1.70	9.80%	1.70	1.00	0.0167
15:00-15:30	379	11	63.20	90	35.02	101	1.68	10.89%	1.87	1.11	0.0185
15:00-15:30	380	11	63.20	83	35.02	94	1.57	11.70%	1.87	1.19	0.0199
15:00-15:30	381	11	63.20	73	35.02	84	1.40	13.10%	1.87	1.34	0.0223
15:00-15:30	382	11	63.20	84	35.02	95	1.58	11.58%	1.87	1.18	0.0197
15:00-15:30	383	11	63.20	91	35.02	102	1.70	10.78%	1.87	1.10	0.0183
15:00-15:30	384	11	63.20	71	35.02	82	1.37	13.41%	1.87	1.37	0.0228

Table C-13: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 15:30-16:00

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
15:30-16:00	385	11	63.69	89	35.82	100	1.67	11.00%	1.87	1.12	0.0187
15:30-16:00	386	11	63.69	88	35.82	99	1.65	11.11%	1.87	1.13	0.0189
15:30-16:00	387	11	63.69	89	35.82	100	1.67	11.00%	1.87	1.12	0.0187
15:30-16:00	388	11	63.69	70	35.82	81	1.35	13.58%	1.87	1.39	0.0231
15:30-16:00	389	14	63.69	46	35.82	60	1.00	23.33%	2.38	2.38	0.0397
15:30-16:00	390	15	63.69	16	35.82	31	0.52	48.39%	2.55	4.94	0.0823
15:30-16:00	391	14	63.69	37	35.82	51	0.85	27.45%	2.38	2.80	0.0467
15:30-16:00	392	10	63.69	42	35.82	52	0.87	19.23%	1.70	1.96	0.0327
15:30-16:00	393	17	63.69	35	35.82	52	0.87	32.69%	2.89	3.33	0.0556
15:30-16:00	394	14	63.69	21	35.82	35	0.58	40.00%	2.38	4.08	0.0680
15:30-16:00	395	13	63.69	38	35.82	51	0.85	25.49%	2.21	2.60	0.0433
15:30-16:00	396	15	63.69	23	35.82	38	0.63	39.47%	2.55	4.03	0.0671
15:30-16:00	397	11	63.69	43	35.82	54	0.90	20.37%	1.87	2.08	0.0346
15:30-16:00	398	16	63.69	15	35.82	31	0.52	51.61%	2.72	5.26	0.0877
15:30-16:00	399	15	63.69	32	35.82	47	0.78	31.91%	2.55	3.26	0.0543
15:30-16:00	400	11	63.69	46	35.82	57	0.95	19.30%	1.87	1.97	0.0328
15:30-16:00	401	16	63.69	15	35.82	31	0.52	51.61%	2.72	5.26	0.0877
15:30-16:00	402	15	63.69	27	35.82	42	0.70	35.71%	2.55	3.64	0.0607
15:30-16:00	403	11	63.69	55	35.82	66	1.10	16.67%	1.87	1.70	0.0283
15:30-16:00	404	16	63.69	16	35.82	32	0.53	50.00%	2.72	5.10	0.0850
15:30-16:00	405	15	63.69	28	35.82	43	0.72	34.88%	2.55	3.56	0.0593

15:30-16:00	406	11	63.69	55	35.82	66	1.10	16.67%	1.87	1.70	0.0283
15:30-16:00	407	14	63.69	16	35.82	30	0.50	46.67%	2.38	4.76	0.0793
15:30-16:00	408	15	63.69	43	35.82	58	0.97	25.86%	2.55	2.64	0.0440
15:30-16:00	409	14	63.69	51	35.82	65	1.08	21.54%	2.38	2.20	0.0366
15:30-16:00	410	11	63.69	26	35.82	37	0.62	29.73%	1.87	3.03	0.0505
15:30-16:00	411	17	63.69	14	35.82	31	0.52	54.84%	2.89	5.59	0.0932
15:30-16:00	412	14	63.69	45	35.82	59	0.98	23.73%	2.38	2.42	0.0403
15:30-16:00	413	11	63.69	61	35.82	72	1.20	15.28%	1.87	1.56	0.0260
15:30-16:00	414	11	63.69	27	35.82	38	0.63	28.95%	1.87	2.95	0.0492
15:30-16:00	415	16	63.69	43	35.82	59	0.98	27.12%	2.72	2.77	0.0461
15:30-16:00	416	11	63.69	27	35.82	38	0.63	28.95%	1.87	2.95	0.0492
15:30-16:00	417	11	63.69	57	35.82	68	1.13	16.18%	1.87	1.65	0.0275
15:30-16:00	418	15	63.69	30	35.82	45	0.75	33.33%	2.55	3.40	0.0567

Table C-14: Compressor 1- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 16:00-16:45

Interval	Cycle No	Load time (sec)	Power demand in load mode (kW)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time(min)	LF	CAD in a cycle (m3)	CAD rate in cycle (m3/min)	CAD in cycle (m3/sec)
16:00-16:45	419	11	63.52	38	35.75	49	0.82	22.45%	1.87	2.29	0.0382
16:00-16:45	420	16	63.52	15	35.75	31	0.52	51.61%	2.72	5.26	0.0877
16:00-16:45	421	14	63.52	39	35.75	53	0.88	26.42%	2.38	2.69	0.0449
16:00-16:45	422	11	63.52	52	35.75	63	1.05	17.46%	1.87	1.78	0.0297
16:00-16:45	423	16	63.52	14	35.75	30	0.50	53.33%	2.72	5.44	0.0907
16:00-16:45	424	16	63.52	31	35.75	47	0.78	34.04%	2.72	3.47	0.0579
16:00-16:45	425	12	63.52	39	35.75	51	0.85	23.53%	2.04	2.40	0.0400
16:00-16:45	426	15	63.52	26	35.75	41	0.68	36.59%	2.55	3.73	0.0622
16:00-16:45	427	14	63.52	17	35.75	31	0.52	45.16%	2.38	4.61	0.0768
16:00-16:45	428	15	63.52	30	35.75	45	0.75	33.33%	2.55	3.40	0.0567
16:00-16:45	429	12	63.52	44	35.75	56	0.93	21.43%	2.04	2.19	0.0364
16:00-16:45	430	16	63.52	14	35.75	30	0.50	53.33%	2.72	5.44	0.0907
16:00-16:45	431	15	63.52	21	35.75	36	0.60	41.67%	2.55	4.25	0.0708
16:00-16:45	432	12	63.52	50	35.75	62	1.03	19.35%	2.04	1.97	0.0329
16:00-16:45	433	15	63.52	15	35.75	30	0.50	50.00%	2.55	5.10	0.0850
16:00-16:45	434	17	63.52	26	35.75	43	0.72	39.53%	2.89	4.03	0.0672
16:00-16:45	435	11	63.52	41	35.75	52	0.87	21.15%	1.87	2.16	0.0360
16:00-16:45	436	12	63.52	18	35.75	30	0.50	40.00%	2.04	4.08	0.0680
16:00-16:45	437	20	63.52	30	35.75	50	0.83	40.00%	3.40	4.08	0.0680
16:00-16:45	438	11	63.52	21	35.75	32	0.53	34.38%	1.87	3.51	0.0584
16:00-16:45	439	17	63.52	46	35.75	63	1.05	26.98%	2.89	2.75	0.0459
16:00-16:45	440	11	63.52	40	35.75	51	0.85	21.57%	1.87	2.20	0.0367
16:00-16:45	441	11	63.52	60	35.75	71	1.18	15.49%	1.87	1.58	0.0263

16:00-16:45	442	16	63.52	15	35.75	31	0.52	51.61%	2.72	5.26	0.0877
16:00-16:45	443	14	63.52	58	35.75	72	1.20	19.44%	2.38	1.98	0.0331
16:00-16:45	444	11	63.52	20	35.75	31	0.52	35.48%	1.87	3.62	0.0603
16:00-16:45	445	12	63.52	64	35.75	76	1.27	15.79%	2.04	1.61	0.0268
16:00-16:45	446	11	63.52	39	35.75	50	0.83	22.00%	1.87	2.24	0.0374
16:00-16:45	447	16	63.52	15	35.75	31	0.52	51.61%	2.72	5.26	0.0877
16:00-16:45	448	14	63.52	56	35.75	70	1.17	20.00%	2.38	2.04	0.0340
16:00-16:45	449	11	63.52	45	35.75	56	0.93	19.64%	1.87	2.00	0.0334
16:00-16:45	450	13	63.52	66	35.75	79	1.32	16.46%	2.21	1.68	0.0280
16:00-16:45	451	11	63.52	72	35.75	83	1.38	13.25%	1.87	1.35	0.0225
16:00-16:45	452	11	63.52	39	35.75	50	0.83	22.00%	1.87	2.24	0.0374
16:00-16:45	453	12	63.52	73	35.75	85	1.42	14.12%	2.04	1.44	0.0240
16:00-16:45	454	11	63.52	74	35.75	85	1.42	12.94%	1.87	1.32	0.0220
16:00-16:45	455	11	63.52	35	35.75	46	0.77	23.91%	1.87	2.44	0.0407
16:00-16:45	456	17	63.52	17	35.75	34	0.57	50.00%	2.89	5.10	0.0850
16:00-16:45	457	11	63.52	73	35.75	84	1.40	13.10%	1.87	1.34	0.0223
16:00-16:45	458	11	63.52	66	35.75	77	1.28	14.29%	1.87	1.46	0.0243
16:00-16:45	459	13	63.52	73	35.75	86	1.43	15.12%	2.21	1.54	0.0257
16:00-16:45	460	11	63.52	45	35.75	56	0.93	19.64%	1.87	2.00	0.0334
16:00-16:45	461	16	63.52	15	35.75	31	0.52	51.61%	2.72	5.26	0.0877
16:00-16:45	462	16	63.52	36	35.75	52	0.87	30.77%	2.72	3.14	0.0523
16:00-16:45	463	11	63.52	57	35.75	68	1.13	16.18%	1.87	1.65	0.0275
16:00-16:45	464	11	63.52	69	35.75	80	1.33	13.75%	1.87	1.40	0.0234
16:00-16:45	465	11	63.52	76	35.75	87	1.45	12.64%	1.87	1.29	0.0215
16:00-16:45	466	12	63.52	83	35.75	95	1.58	12.63%	2.04	1.29	0.0215
16:00-16:45	467	11	63.52	78	35.75	89	1.48	12.36%	1.87	1.26	0.0210

Table C-15: Compressor 2- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 16:30-18:30

period	Cycle No	Load time (sec)	Power Demand in Load Mode (kW)	unload time (no power) (sec)	unload time (with power) (sec)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time (min)	LF (%)	CAP (m3)	CAD (m3/min)	CAD (m3/sec)
16:30-18:30	1	60	18.34	22	70	92	8.55	152	2.53	39.47	3.22	1.27	0.0212
	2	60	18.34	5	145	150	8.55	210	3.50	28.57	3.22	0.92	0.0153
	3	60	18.34	0	116	116	8.55	176	2.93	34.09	3.22	1.10	0.0183
	4	60	18.34	40	143	183	8.55	243	4.05	24.69	3.22	0.80	0.0133
	5	65	18.34	0	145	145	8.55	210	3.50	30.95	3.49	1.00	0.0166
	6	60	18.34	38	143	181	8.55	241	4.02	24.90	3.22	0.80	0.0134
	7	90	18.34	30	144	174	8.55	264	4.40	34.09	4.83	1.10	0.0183
	8	63	18.34	0	124	124	8.55	187	3.12	33.69	3.38	1.08	0.0181
	9	75	18.34	31	143	174	8.55	249	4.15	30.12	4.03	0.97	0.0162
	10	60	18.34	53	145	198	8.55	258	4.30	23.26	3.22	0.75	0.0125
	11	203	18.34	0	110	110	8.55	313	5.22	64.86	10.90	2.09	0.0348
	12	81	18.34	0	57	57	8.55	138	2.30	58.70	4.35	1.89	0.0315
	13	1729	18.34	51	147	198	8.55	1927	32.12	89.72	92.80	2.89	0.0482
	14	1314	18.34	1308	10	1318	8.55	2632	43.87	49.92	70.53	1.61	0.0268

Table C-16: Compressor 2- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 18:30-20:30

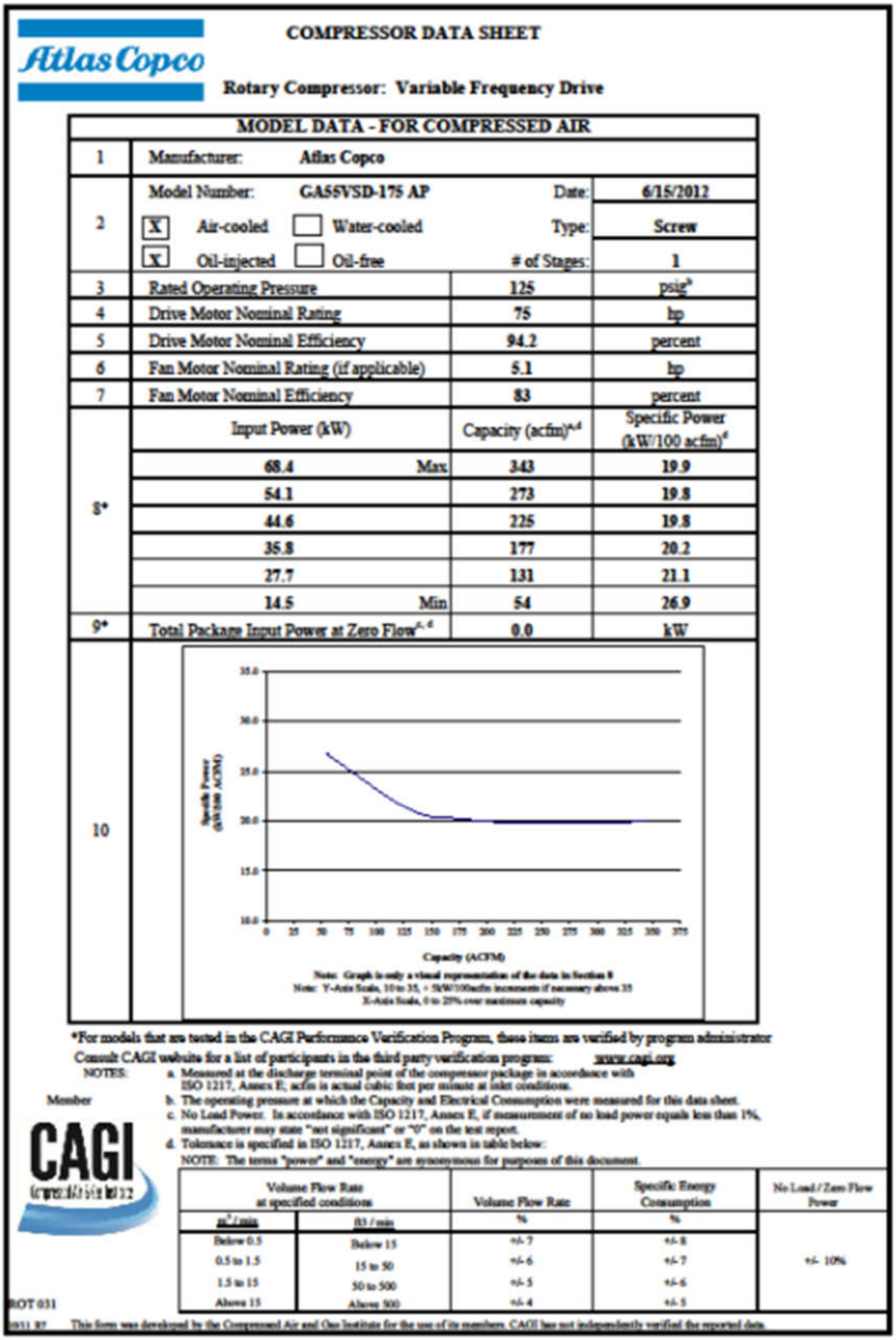
period	Cycle No	Load time (sec)	Power Demand in Load Mode (kW)	unload time (no power) (sec)	unload time (with power) (sec)	Unload time (sec)	Power demand in unload mode (kW)	Cycle time (sec)	CYCLE time (min)	LF (%)	CAP (m3)	CAD (m3/min)	CAD (m3/sec)
18:30-20:30	15	657	18.50	0	202	202	8.55	859	14.32	76.48	35.57	2.48	0.0414
	16	113	18.50	0	152	152	8.55	265	4.42	42.64	6.12	1.39	0.0231
	17	206	18.50	0	28	28	8.55	234	3.90	88.03	11.15	2.86	0.0477
	18	390	18.50	0	63	63	8.55	453	7.55	86.09	21.12	2.80	0.0466
	19	118	18.50	0	110	110	8.55	228	3.80	51.75	6.39	1.68	0.0280
	20	85	18.50	27	133	160	8.55	245	4.08	34.69	4.60	1.13	0.0188
	21	54	18.50	150	145	295	8.55	349	5.82	15.47	2.92	0.50	0.0084
	22	56	18.50	149	145	294	8.55	350	5.83	16.00	3.03	0.52	0.0087
	23	56	18.50	0	116	116	8.55	172	2.87	32.56	3.03	1.06	0.0176
	24	76	18.50	0	56	56	8.55	132	2.20	57.58	4.11	1.87	0.0312
	25	81	18.50	0	152	152	8.55	233	3.88	34.76	4.39	1.13	0.0188
	26	173	18.50	0	113	113	8.55	286	4.77	60.49	9.37	1.97	0.0328
	27	90	18.50	0	67	67	8.55	157	2.62	57.32	4.87	1.86	0.0310
	28	68	18.50	154	146	300	8.55	368	6.13	18.48	3.68	0.60	0.0100
	29	55	18.50	150	146	296	8.55	351	5.85	15.67	2.98	0.51	0.0085
	30	56	18.50	151	144	295	8.55	351	5.85	15.95	3.03	0.52	0.0086
	31	55	18.50	0	63	63	8.55	118	1.97	46.61	2.98	1.51	0.0252
	32	65	18.50	0	64	64	8.55	129	2.15	50.39	3.52	1.64	0.0273
	33	164	18.50	68	146	214	8.55	378	6.30	43.39	8.88	1.41	0.0235
	34	56	18.50	150	145	295	8.55	351	5.85	15.95	3.03	0.52	0.0086
	35	56	18.50	150	146	296	8.55	352	5.87	15.91	3.03	0.52	0.0086
	36	56	18.50	150	145	295	8.55	351	5.85	15.95	3.03	0.52	0.0086
	37	56	18.50	85	145	230	8.55	286	4.77	19.58	3.03	0.64	0.0106
	38	55	18.50	66	81	147	8.55	202	3.37		2.98	0.88	0.0147

Table C-17: Compressor 2- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 20:30-22:30

period	Cycle No	Load time (sec)	Power demand in Load mode (kW)	Unload time (no power) (sec)	unload time (with power) (sec)	unload time (total) (sec)	Power demand in unload mode (kW)	CYLCE (sec)	CYCLE time (min)		CAP (m3)	CAD (m3/min)	CAD (m3/sec)
20:30-22:30	38	55	18.55	166	132	298	8.69	353	5.88	15.58	2.99	0.51	0.0085
	39	2660	18.55	150	146	296	8.69	2956	49.27	89.99	144.41	2.93	0.0489
	40	113	18.55	4	144	148	8.69	261	4.35	43.30	6.13	1.41	0.0235
	41	56	18.55	0	115	115	8.69	171	2.85	32.75	3.04	1.07	0.0178
	42	75	18.55	42	144	186	8.69	261	4.35	28.74	4.07	0.94	0.0156
	43	60	18.55	50	144	194	8.69	254	4.23	23.62	3.26	0.77	0.0128
	44	58	18.55	50	145	195	8.69	253	4.22	22.92	3.15	0.75	0.0124
	45	66	18.55	50	134	184	8.69	250	4.17	26.40	3.58	0.86	0.0143
	46	61	18.55	54	143	197	8.69	258	4.30	23.64	3.31	0.77	0.0128
	47	62	18.55	47	144	191	8.69	253	4.22	24.51	3.37	0.80	0.0133
	48	61	18.55	46	143	189	8.69	250	4.17	24.40	3.31	0.79	0.0132
	49	59	18.55	44	143	187	8.69	246	4.10	23.98	3.20	0.78	0.0130
	50	61	18.55	58	143	201	8.69	262	4.37	23.28	3.31	0.76	0.0126
	51	64	18.55	6	145	151	8.69	215	3.58	29.77	3.47	0.97	0.0162
	52	72	18.55	0	145	145	8.69	217	3.62	33.18	3.91	1.08	0.0180
	53	61	18.55	0	120	120	8.69	181	3.02	33.70	3.31	1.10	0.0183
	54	132	18.55	0	127	127	8.69	259	4.32	50.97	7.17	1.66	0.0277
	55	76	18.55	12	90	102	8.69	178	2.97	42.70	4.13	1.39	0.0232
	56	79	18.55	0	152	152	8.69	231	3.85	34.20	4.29	1.11	0.0186

Table C-18: Compressor 2- length of load and unload modes of each cycle as well as the average power demands in each load and unload modes of the cycles between 22:30-00:30

period	Cycle No	Load time (sec)	Power demand in Load mode (kW)	Unload time (no power) (sec)	unload time (with power) (sec)	unload time (total) (sec)	Power demand in unload mode (kW)	CYLCE (sec)	CYCLE time (min)		CAP (m3)	CAD (m3/min)	CAD (m3/sec)
22:30-00:30	57	60	18.62	58	145	203	8.7	263	4.38	22.81	3.27	0.75	0.0124
	58	75	18.62	0	147	147	8.7	222	3.70	33.78	4.09	1.10	0.0184
	59	65	18.62	47	144	191	8.7	256	4.27	25.39	3.54	0.83	0.0138
	60	58	18.62	38	153	191	8.7	249	4.15	23.29	3.16	0.76	0.0127
	61	58	18.62	51	144	195	8.7	253	4.22	22.92	3.16	0.75	0.0125
	62	72	18.62	0	119	119	8.7	191	3.18	37.70	3.92	1.23	0.0205
	63	59	18.62	38	41	79	8.7	138	2.30	42.75	3.22	1.40	0.0233
	64	58	18.62	55	145	200	8.7	258	4.30	22.48	3.16	0.74	0.0123
	65	58	18.62	57	143	200	8.7	258	4.30	22.48	3.16	0.74	0.0123
	66	60	18.62	61	141	202	8.7	262	4.37	22.90	3.27	0.75	0.0125
	67	59	18.62	59	203	262	8.7	321	5.35	18.38	3.22	0.60	0.0100
	68	59	18.62	55	144	199	8.7	258	4.30	22.87	3.22	0.75	0.0125
	69	74	18.62	46	144	190	8.7	264	4.40	28.03	4.03	0.92	0.0153
	70	58	18.62	51	150	201	8.7	259	4.32	22.39	3.16	0.73	0.0122
	71	72	18.62	34	144	178	8.7	250	4.17	28.80	3.92	0.94	0.0157
	72	63	18.62	54	144	198	8.7	261	4.35	24.14	3.43	0.79	0.0132
	73	59	18.62	53	144	197	8.7	256	4.27	23.05	3.22	0.75	0.0126
	74	59	18.62	59	143	202	8.7	261	4.35	22.61	3.22	0.74	0.0123
	75	58	18.62	57	143	200	8.7	258	4.30	22.48	3.16	0.74	0.0123
	76	57	18.62	51	144	195	8.7	252	4.20	22.62	3.11	0.74	0.0123
	77	58	18.62	44	143	187	8.7	245	4.08	23.67	3.16	0.77	0.0129
	78	58	18.62	65	143	208	8.7	266	4.43	21.80	3.16	0.71	0.0119
	79	153	18.62	59	143	202	8.7	355	5.92	43.10	8.34	1.41	0.0235
	80	121	18.62	0	107	107	8.7	228	3.80	53.07	6.59	1.74	0.0289
	81	119	18.62	0	69	69	8.7	188	3.13	63.30	6.48	2.07	0.0345
	82	58	18.62	59	136	195	8.7	253	4.22	22.92	3.16	0.75	0.0125
	83	58	18.62	62	142	204	8.7	262	4.37	22.14	3.16	0.72	0.0121
	84	73	18.62	0	87	87	8.7	160	2.67	45.63	3.98	1.49	0.0249
	85	78	18.62	66	132	198	8.7	276	4.60	28.26	4.25	0.92	0.0154



COMPRESSOR DATA SHEET

Atlas Copco

Rotary Compressor: Variable Frequency Drive

MODEL DATA - FOR COMPRESSED AIR

1	Manufacturer: **Atlas Copco**		
2	Model Number: **GA55VSD-175 AP**	Date:	**6/15/2012**
	☒ Air-cooled ☐ Water-cooled	Type:	**Screw**
	☒ Oil-injected ☐ Oil-free	# of Stages:	**1**
3	Rated Operating Pressure	**125**	psig[b]
4	Drive Motor Nominal Rating	**75**	hp
5	Drive Motor Nominal Efficiency	**94.2**	percent
6	Fan Motor Nominal Rating (if applicable)	**5.1**	hp
7	Fan Motor Nominal Efficiency	**83**	percent
8*	Input Power (kW)	Capacity (acfm)[a,d]	Specific Power (kW/100 acfm)[d]
	68.4 Max	**343**	**19.9**
	54.1	**273**	**19.8**
	44.6	**225**	**19.8**
	35.8	**177**	**20.2**
	27.7	**131**	**21.1**
	14.5 Min	**54**	**26.9**
9*	Total Package Input Power at Zero Flow[c, d]	**0.0**	kW
10			

Note: Graph is only a visual representation of the data in Section 8
Note: Y-Axis Scale, 10 to 35, + 5kW/100acfm increments if necessary above 35
X-Axis Scale, 0 to 25% over maximum capacity

*For models that are tested in the CAGI Performance Verification Program, these items are verified by program administrator
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NOTES:
- a. Measured at the discharge terminal point of the compressor package in accordance with ISO 1217, Annex E; acfm is actual cubic feet per minute at inlet conditions.
- b. The operating pressure at which the Capacity and Electrical Consumption were measured for this data sheet.
- c. No Load Power. In accordance with ISO 1217, Annex E, if measurement of no load power equals less than 1%, manufacturer may state "not significant" or "0" on the test report.
- d. Tolerance is specified in ISO 1217, Annex E, as shown in table below:

NOTE: The terms "power" and "energy" are synonymous for purposes of this document.

Volume Flow Rate at specified conditions		Volume Flow Rate	Specific Energy Consumption	No Load / Zero Flow Power
m^3 / min	ft3 / min	%	%	
Below 0.5	Below 15	+/- 7	+/- 8	+/- 10%
0.5 to 1.5	15 to 50	+/- 6	+/- 7	
1.5 to 15	50 to 500	+/- 5	+/- 6	
Above 15	Above 500	+/- 4	+/- 5	

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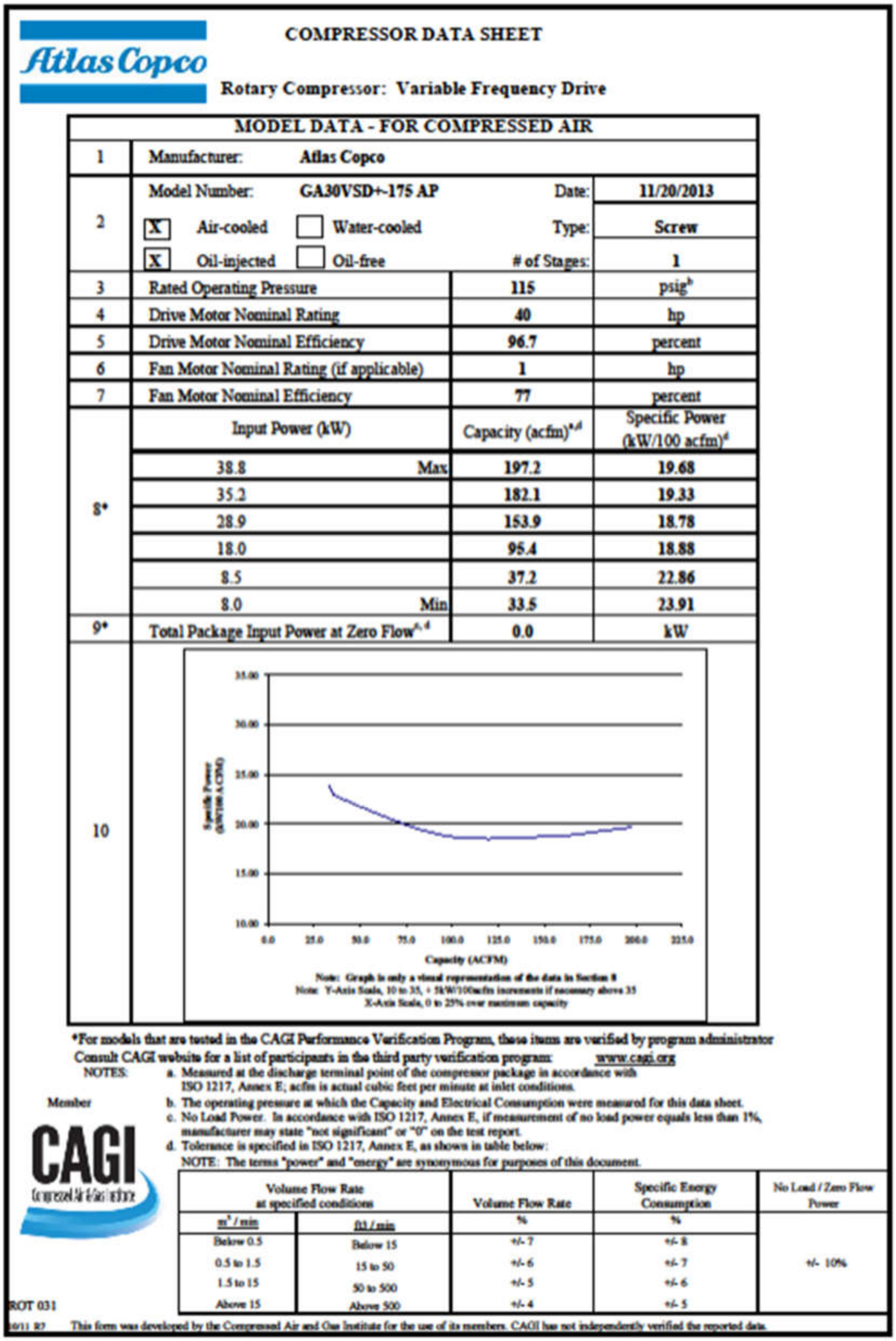
011 R7 This form was developed by the Compressed Air and Gas Institute for the use of its members. CAGI has not independently verified the reported data.

Figure C-15: Datasheet for the VFD compressor used in Scenario 3



COMPRESSOR DATA SHEET

Rotary Compressor: Variable Frequency Drive

MODEL DATA - FOR COMPRESSED AIR			
1	Manufacturer: Atlas Copco		
2	Model Number: GA30VSD+-175 AP	Date:	11/20/2013
	☒ Air-cooled ☐ Water-cooled	Type:	Screw
	☒ Oil-injected ☐ Oil-free	# of Stages:	1
3	Rated Operating Pressure	115	psig[b]
4	Drive Motor Nominal Rating	40	hp
5	Drive Motor Nominal Efficiency	96.7	percent
6	Fan Motor Nominal Rating (if applicable)	1	hp
7	Fan Motor Nominal Efficiency	77	percent
8*	Input Power (kW)	Capacity (acfm)[a,d]	Specific Power (kW/100 acfm)[d]
	38.8 Max	197.2	19.68
	35.2	182.1	19.33
	28.9	153.9	18.78
	18.0	95.4	18.88
	8.5	37.2	22.86
	8.0 Min	33.5	23.91
9*	Total Package Input Power at Zero Flow[c,d]	0.0	kW
10			

Note: Graph is only a visual representation of the data in Section 8
Note: Y-Axis Scale, 10 to 35, + 5kW/100acfm increments if necessary above 35
X-Axis Scale, 0 to 25% over maximum capacity

*For models that are tested in the CAGI Performance Verification Program, these items are verified by program administrator
Consult CAGI website for a list of participants in the third party verification program: www.cagi.org

NOTES:
a. Measured at the discharge terminal point of the compressor package in accordance with ISO 1217, Annex E; acfm is actual cubic feet per minute at inlet conditions.
b. The operating pressure at which the Capacity and Electrical Consumption were measured for this data sheet.
c. No Load Power. In accordance with ISO 1217, Annex E, if measurement of no load power equals less than 1%, manufacturer may state "not significant" or "0" on the test report.
d. Tolerance is specified in ISO 1217, Annex E, as shown in table below:
NOTE: The terms "power" and "energy" are synonymous for purposes of this document.

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Volume Flow Rate at specified conditions		Volume Flow Rate	Specific Energy Consumption	No Load / Zero Flow Power
m³ / min	ft3 / min	%	%	
Below 0.5	Below 15	+/- 7	+/- 8	+/- 10%
0.5 to 1.5	15 to 50	+/- 6	+/- 7	
1.5 to 15	50 to 500	+/- 5	+/- 6	
Above 15	Above 500	+/- 4	+/- 5	

ROT 031
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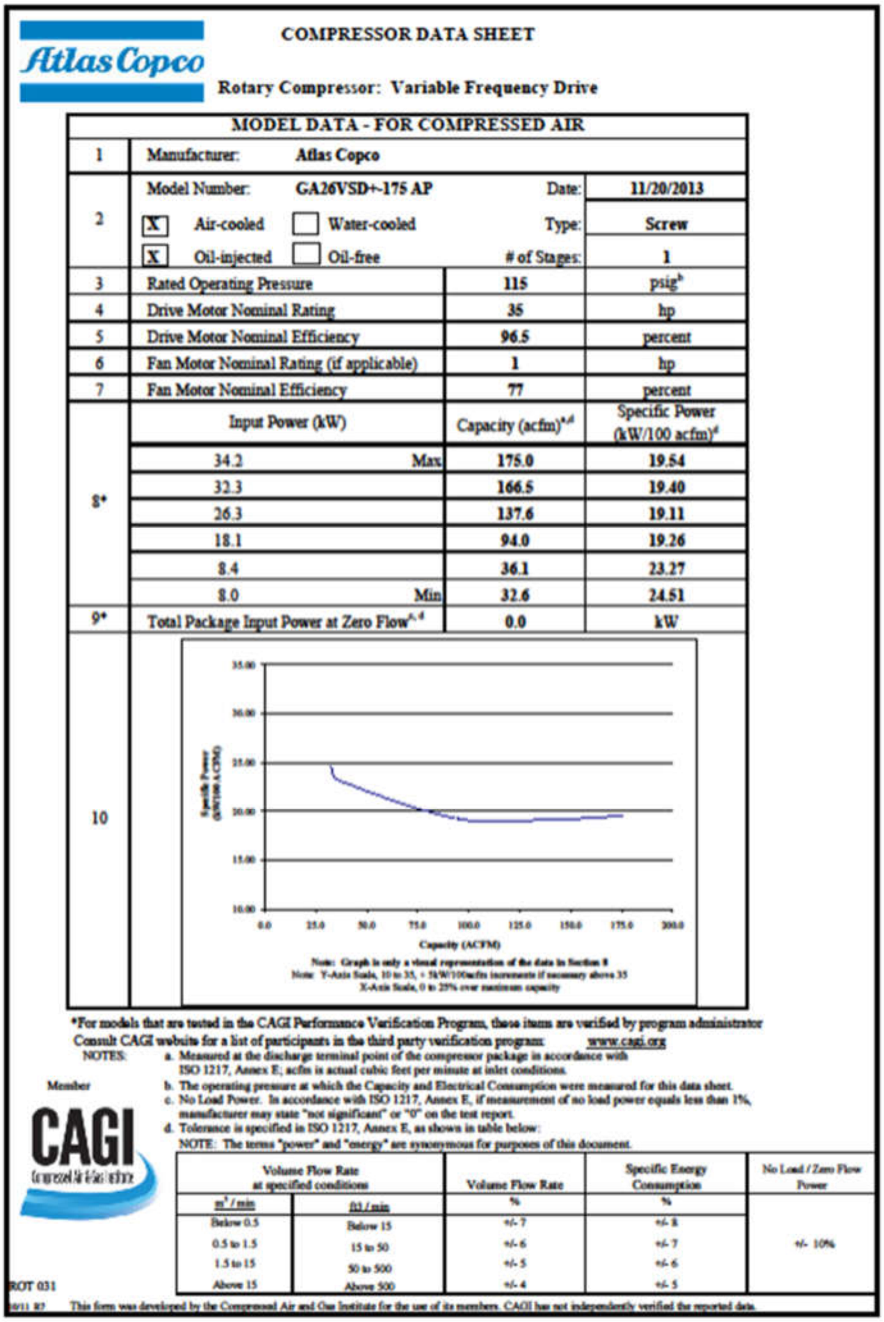
Figure C-16: Datasheet for the VFD compressor used in Scenario 4



Atlas Copco

COMPRESSOR DATA SHEET

Rotary Compressor: Variable Frequency Drive

MODEL DATA - FOR COMPRESSED AIR

1	Manufacturer: **Atlas Copco**		
2	Model Number: **GA26VSD+-175 AP**	Date:	**11/20/2013**
	☒ Air-cooled ☐ Water-cooled	Type:	**Screw**
	☒ Oil-injected ☐ Oil-free	# of Stages:	**1**
3	Rated Operating Pressure	**115**	psig[b]
4	Drive Motor Nominal Rating	**35**	hp
5	Drive Motor Nominal Efficiency	**96.5**	percent
6	Fan Motor Nominal Rating (if applicable)	**1**	hp
7	Fan Motor Nominal Efficiency	**77**	percent
8*	Input Power (kW)	Capacity (acfm)[a,d]	Specific Power (kW/100 acfm)[d]
	34.2 Max	**175.0**	**19.54**
	32.3	**166.5**	**19.40**
	26.3	**137.6**	**19.11**
	18.1	**94.0**	**19.26**
	8.4	**36.1**	**23.27**
	8.0 Min	**32.6**	**24.51**
9*	Total Package Input Power at Zero Flow[c,d]	**0.0**	**kW**
10			

Note: Graph is only a visual representation of the data in Section 8
Note: Y-Axis Scale, 10 to 35, + 5kW/100acfm increments if necessary above 35
X-Axis Scale, 0 to 25% over maximum capacity

*For models that are tested in the CAGI Performance Verification Program, these items are verified by program administrator
Consult CAGI website for a list of participants in the third party verification program: www.cagi.org

NOTES:
- a. Measured at the discharge terminal point of the compressor package in accordance with ISO 1217, Annex E; acfm is actual cubic feet per minute at inlet conditions.
- b. The operating pressure at which the Capacity and Electrical Consumption were measured for this data sheet.
- c. No Load Power. In accordance with ISO 1217, Annex E, if measurement of no load power equals less than 1%, manufacturer may state "not significant" or "0" on the test report.
- d. Tolerance is specified in ISO 1217, Annex E, as shown in table below:

NOTE: The terms "power" and "energy" are synonymous for purposes of this document.

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Volume Flow Rate at specified conditions		Volume Flow Rate	Specific Energy Consumption	No Load / Zero Flow Power
m³ / min	ft3 / min	%	%	
Below 0.5	Below 15	+/- 7	+/- 8	+/- 10%
0.5 to 1.5	15 to 50	+/- 6	+/- 7	
1.5 to 15	50 to 500	+/- 5	+/- 6	
Above 15	Above 500	+/- 4	+/- 5	

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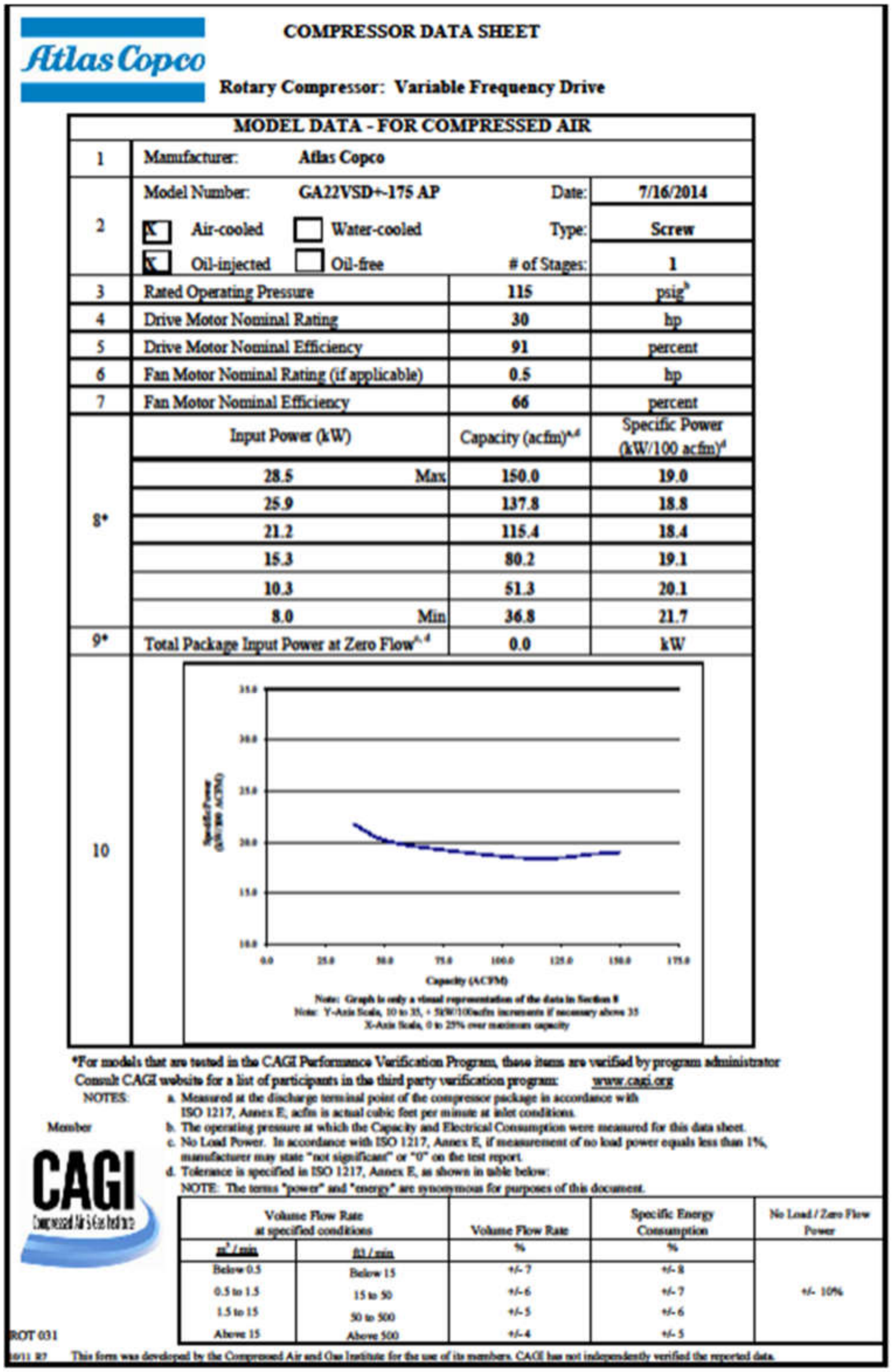
Figure C-17: Datasheet for the VFD compressor used in Scenario 5



Atlas Copco

COMPRESSOR DATA SHEET

Rotary Compressor: Variable Frequency Drive

MODEL DATA - FOR COMPRESSED AIR

1	Manufacturer: **Atlas Copco**			
2	Model Number: **GA22VSD+-175 AP**		Date:	**7/16/2014**
	☒ Air-cooled ☐ Water-cooled		Type:	**Screw**
	☒ Oil-injected ☐ Oil-free		# of Stages:	**1**
3	Rated Operating Pressure		**115**	psig[b]
4	Drive Motor Nominal Rating		**30**	hp
5	Drive Motor Nominal Efficiency		**91**	percent
6	Fan Motor Nominal Rating (if applicable)		**0.5**	hp
7	Fan Motor Nominal Efficiency		**66**	percent
8*	Input Power (kW)		Capacity (acfm)[a,d]	Specific Power (kW/100 acfm)[d]
	28.5	Max	**150.0**	**19.0**
	25.9		**137.8**	**18.8**
	21.2		**115.4**	**18.4**
	15.3		**80.2**	**19.1**
	10.3		**51.3**	**20.1**
	8.0	Min	**36.8**	**21.7**
9*	Total Package Input Power at Zero Flow[c,d]		**0.0**	kW
10				

Note: Graph is only a visual representation of the data in Section 8
Note: Y-Axis Scale, 10 to 35, + 5kW/100acfm increments if necessary above 35
X-Axis Scale, 0 to 25% over maximum capacity

*For models that are tested in the CAGI Performance Verification Program, these items are verified by program administrator
Consult CAGI website for a list of participants in the third party verification program: www.cagi.org

NOTES:
a. Measured at the discharge terminal point of the compressor package in accordance with ISO 1217, Annex E; acfm is actual cubic feet per minute at inlet conditions.
b. The operating pressure at which the Capacity and Electrical Consumption were measured for this data sheet.
c. No Load Power. In accordance with ISO 1217, Annex E, if measurement of no load power equals less than 1%, manufacturer may state "not significant" or "0" on the test report.
d. Tolerance is specified in ISO 1217, Annex E, as shown in table below:
NOTE: The terms "power" and "energy" are synonymous for purposes of this document.

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Volume Flow Rate at specified conditions		Volume Flow Rate	Specific Energy Consumption	No Load / Zero Flow Power
m^3 / min	ft3 / min	%	%	
Below 0.5	Below 15	+/- 7	+/- 8	+/- 10%
0.5 to 1.5	15 to 50	+/- 6	+/- 7	
1.5 to 15	50 to 500	+/- 5	+/- 6	
Above 15	Above 500	+/- 4	+/- 5	

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Figure C-18: datasheet for VFD compressor in Scenario 6

Table C-19: LF of Configuration C3(SC=8.9 m^3/min, Vs=6.35 m^3)

CAD interval	*Average CAD (m3/min) (a)*	*Frequency (b)*	*Frequency % (c)*	*Total CAD m3 (d=a*b)*	*SC (m3/min)*	*Vs (m3)*	*tu (min)*	*tl (min)*	*Average CT (min)*	*LF*	*weighted LF (LF*c)*
0.5<=CAD<1	0.93	10	2.20	9.30	8.9	6.35	0.68	0.08	0.76	10.45	23.0
1<=CAD<1.5	1.23	203	44.62	249.69	8.9	6.35	0.03	0.00	0.03	13.82	616.6
1.5<=CAD<2	1.66	91	20.00	151.06	8.9	6.35	0.04	0.01	0.05	18.65	373.0
2<=CAD<2.5	2.23	37	8.13	82.51	8.9	6.35	0.08	0.03	0.10	25.06	203.8
2.5<=CAD<3	2.75	30	6.59	82.50	8.9	6.35	0.08	0.03	0.11	30.90	203.7
3<=CAD<3.5	3.23	22	4.84	71.06	8.9	6.35	0.09	0.05	0.14	36.29	175.5
3.5<=CAD<4	3.74	15	3.30	56.10	8.9	6.35	0.11	0.08	0.20	42.02	138.5
4<=CAD<4.5	4.27	21	4.62	89.67	8.9	6.35	0.07	0.07	0.14	47.98	221.4
4.5<=CAD<5	4.77	15	3.30	71.55	8.9	6.35	0.09	0.10	0.19	53.60	176.7
5<=CAD<5.5	5.24	9	1.98	47.16	8.9	6.35	0.13	0.19	0.33	58.88	116.5
5.5<=CAD<6	5.91	1	0.22	5.91	8.9	6.35	1.07	2.12	3.20	66.40	14.6
6<=CAD<6.5	6.06	1	0.22	6.06	8.9	6.35	1.05	2.24	3.28	68.09	15.0
total		**455**	**100.00**	**922.57**						**AVG LF=**	**22.78**

Table C-20: LF of Configuration C4 (SC=6.9 m^3/min, Vs=4.92 m^3)

CAD interval	*Average CAD (m3/min) (a)*	*Frequency (min) (b)*	*Frequency % (c)*	*Total CAD m3 (d=a*b)*	*SC (m3/min)*	*Vs (m3)*	*tu (min)*	*tl (min)*	*Average CT (min)*	*LF*	*weighted LF (LF*c)*
0.5<=CAD<1	0.93	10	2.20	9.30	6.9	4.92	0.53	0.08	0.61	13.48	29.6
1<=CAD<1.5	1.23	203	44.62	249.69	6.9	4.92	0.02	0.00	0.02	17.83	795.3
1.5<=CAD<2	1.66	91	20.00	151.06	6.9	4.92	0.03	0.01	0.04	24.06	481.2
2<=CAD<2.5	2.23	37	8.13	82.51	6.9	4.92	0.06	0.03	0.09	32.32	262.8
2.5<=CAD<3	2.75	30	6.59	82.50	6.9	4.92	0.06	0.04	0.10	39.86	262.8
3<=CAD<3.5	3.23	22	4.84	71.06	6.9	4.92	0.07	0.06	0.13	46.81	226.3
3.5<=CAD<4	3.74	15	3.30	56.10	6.9	4.92	0.09	0.10	0.19	54.20	178.7
4<=CAD<4.5	4.27	21	4.62	89.67	6.9	4.92	0.05	0.09	0.14	61.88	285.6
4.5<=CAD<5	4.77	15	3.30	71.55	6.9	4.92	0.07	0.15	0.22	69.13	227.9
5<=CAD<5.5	5.24	9	1.98	47.16	6.9	4.92	0.10	0.33	0.43	75.94	150.2
5.5<=CAD<6	5.91	1	0.22	5.91	6.9	4.92	0.83	4.97	5.80	85.65	18.8
6<=CAD<6.5	6.06	1	0.22	6.06	6.9	4.92	0.81	5.86	6.67	87.83	19.3
total		**455**	**100.00**	**922.57**						**AVG LF=**	**29.39**

Table C-21: LF of Configuration C5 (SC=5.8 m^3/min, Vs=4.14 m^3)

CAD interval	*Average CAD (m3/min) (a)*	*Frequency (b)*	*Frequency % (c)*	*Total CAD m3 (d=a*b)*	*SC (m3/min)*	*Vs (m3)*	*tu (min)*	*tl (min)*	*Average CT (min)*	*LF*	*weighted LF (LF*c)*
0.5<=CAD<1	0.93	10	2.20	9.30	5.8	4.14	0.45	0.09	0.53	16.03	35.2
1<=CAD<1.5	1.23	203	44.62	249.69	5.8	4.14	0.02	0.00	0.02	21.21	946.2
1.5<=CAD<2	1.66	91	20.00	151.06	5.8	4.14	0.03	0.01	0.04	28.62	572.4
2<=CAD<2.5	2.23	37	8.13	82.51	5.8	4.14	0.05	0.03	0.08	38.45	312.7
2.5<=CAD<3	2.75	30	6.59	82.50	5.8	4.14	0.05	0.05	0.10	47.41	312.6
3<=CAD<3.5	3.23	22	4.84	71.06	5.8	4.14	0.06	0.07	0.13	55.69	269.3
3.5<=CAD<4	3.74	15	3.30	56.10	5.8	4.14	0.07	0.13	0.21	64.48	212.6
4<=CAD<4.5	4.27	21	4.62	89.67	5.8	4.14	0.05	0.13	0.18	73.62	339.8
4.5<=CAD<5	4.77	15	3.30	71.55	5.8	4.14	0.06	0.27	0.33	82.24	271.1
5<=CAD<=5.8	5.24	9	1.98	47.16	5.8	4.14	0.09	0.82	0.91	90.34	178.7
5.8<CAD<6	5.91	1	0.22	5.91	5.8	4.14	0.70	-37.64	-36.94	101.90	22.4
6<=CAD<6.5	6.06	1	0.22	6.06	5.8	4.14	0.68	-15.92	-15.24	104.48	23.0
total		**455**	**100.00**	**922.57**						**AVG LF=**	**34.66**

Table C-22: LF of Configuration C6 (SC=4.7 m^3/min, Vs=3.35 m^3)

CAD interval	***Average CAD (m3/min) (a)***	***Frequency (b)***	***Frequency % (c)***	***Total CAD m3 (d=a*b)***	***SC (m3/min)***	***Vs (m3)***	***tu (min)***	***tl (min)***	***Average CT (min)***	***LF***	***weighted LF (LF*c)***
0.5<=CAD<1	0.93	10	2.20	9.30	4.7	3.35	0.36	0.09	0.45	19.79	43.5
1<=CAD<1.5	1.23	203	44.62	249.69	4.7	3.35	0.01	0.00	0.02	26.17	1167.6
1.5<=CAD<2	1.66	91	20.00	151.06	4.7	3.35	0.02	0.01	0.03	35.32	706.4
2<=CAD<2.5	2.23	37	8.13	82.51	4.7	3.35	0.04	0.04	0.08	47.45	385.8
2.5<=CAD<3	2.75	30	6.59	82.50	4.7	3.35	0.04	0.06	0.10	58.51	385.8
3<=CAD<3.5	3.23	22	4.84	71.06	4.7	3.35	0.05	0.10	0.15	68.72	332.3
3.5<=CAD<4	3.74	15	3.30	56.10	4.7	3.35	0.06	0.23	0.29	79.57	262.3
4<=CAD<=4.7	4.36	28	6.15	122.08	4.7	3.35	0.03	0.35	0.38	92.77	570.9
4.7<CAD<5	4.86	8	1.76	38.88	4.7	3.35	0.09	-2.62	-2.53	103.40	181.8
5<=CAD<5.5	5.24	9	1.98	47.16	4.7	3.35	0.07	-0.69	-0.62	111.49	220.5
5.5<=CAD<6	5.91	1	0.22	5.91	4.7	3.35	0.57	-2.77	-2.20	125.74	27.6
6<=CAD<6.5	6.06	1	0.22	6.06	4.7	3.35	0.55	-2.46	-1.91	128.94	28.3
total		**455**	**100.00**	**922.31**						**AVG LF=**	**40.23**

Table C-23: LF of Configuration C7 (SC=3.6 m^3/min, Vs=2.57 m^3)

CAD interval	*Average CAD (m3/min) (a)*	*Frequency (b)*	*Frequency % (c)*	*Total CAD m3 (d=a*b)*	*SC (m3/min)*	*Vs (m3)*	*tu (min)*	*tl (min)*	*Average CT (min)*	*LF*	*weighted LF (LF*c)*
0.5<=CAD<1	0.93	10	2.20	9.30	3.6	2.57	0.28	0.10	0.37	25.83	56.8
1<=CAD<1.5	1.23	203	44.62	249.69	3.6	2.57	2.09	1.08	3.17	34.17	1524.4
1.5<=CAD<2	1.66	91	20.00	151.06	3.6	2.57	0.02	0.01	0.03	46.11	922.2
2<=CAD<2.5	2.23	37	8.13	82.51	3.6	2.57	0.03	0.05	0.08	61.94	503.7
2.5<=CAD<3	2.75	30	6.59	82.50	3.6	2.57	0.03	0.10	0.13	76.39	503.7
3<=CAD<=3.6	3.26	25	5.49	81.50	3.6	2.57	0.03	0.30	0.33	90.56	497.6
3.6<CAD<4	3.78	12	2.64	45.36	3.6	2.57	0.06	-1.19	-1.13	105.00	276.9
4<=CAD<4.5	4.27	21	4.62	89.67	3.6	2.57	0.03	-0.18	-0.15	118.61	547.4
4.5<=CAD<5	4.77	15	3.30	71.55	3.6	2.57	0.04	-0.15	-0.11	132.50	436.8
5<=CAD<5.5	5.24	9	1.98	47.16	3.6	2.57	0.05	-0.17	-0.12	145.56	287.9
5.5<=CAD<6	5.91	1	0.22	5.91	3.6	2.57	0.43	-1.11	-0.68	164.17	36.1
6<=CAD<6.5	6.06	1	0.22	6.06	3.6	2.57	0.42	-1.04	-0.62	168.33	37.0
total		**455**	**100.00**	**922.27**						**AVG LF=**	**46.05**

Table C-24: LF of Configuration C8 (SC=2.9 m^3/min, Vs=1.66 m^3)

CAD interval	***Average CAD (m3/min) (a)***	***Frequency (b)***	***Frequency % (c)***	***Total CAD m3 (d=a*b)***	***SC (m3/min)***	***Vs (m3)***	***tu (min)***	***tl (min)***	***Average CT (min)***	***LF***	***weighted LF (LF*c)***
0.5<=CAD<1	0.93	10	2.20	9.30	2.9	1.66	0.18	0.08	0.26	32.07	70.5
1<=CAD<1.5	1.23	203	44.62	249.69	2.9	1.66	1.35	0.99	2.34	42.41	1892.3
1.5<=CAD<2	1.66	91	20.00	151.06	2.9	1.66	0.01	0.01	0.03	57.24	1144.8
2<=CAD<2.5	2.23	37	8.13	82.51	2.9	1.66	0.02	0.07	0.09	76.90	625.3
2.5<=CAD<=2.9	2.68	23	5.05	61.64	2.9	1.66	0.03	0.33	0.35	92.41	467.1
2.9<CAD<3.5	3.16	29	6.37	91.64	2.9	1.66	0.02	-0.22	-0.20	108.97	694.5
3.5<=CAD<4	3.74	15	3.30	56.10	2.9	1.66	0.03	-0.13	-0.10	128.97	425.2
4<=CAD<4.5	4.27	21	4.62	89.67	2.9	1.66	0.02	-0.06	-0.04	147.24	679.6
4.5<=CAD<5	4.77	15	3.30	71.55	2.9	1.66	0.02	-0.06	-0.04	164.48	542.3
5<=CAD<5.5	5.24	9	1.98	47.16	2.9	1.66	0.04	-0.08	-0.04	180.69	357.4
5.5<=CAD<6	5.91	1	0.22	5.91	2.9	1.66	0.28	-0.55	-0.27	203.79	44.8
6<=CAD<6.5	6.06	1	0.22	6.06	2.9	1.66	0.27	-0.53	-0.25	208.97	45.9
total		**455**	**100.00**	**922.29**						**AVG LF=**	**52.50**

Table C-25: LF of Configuration C9 (SC=2.3 m^3/min, Vs=1.31 m^3)

CAD interval	***Average CAD (m3/min) (a)***	***Frequency (b)***	***Frequency % (c)***	***Total CAD m3 (d=a*b)***	***SC (m3/min)***	***Vs (m3)***	***tu (min)***	***tl (min)***	***Average CT (min)***	***LF***	***weighted LF (LF*c)***
0.5<=CAD<1	0.93	10	2.20	9.30	2.3	1.31	0.14	0.10	0.24	40.43	88.9
1<=CAD<1.5	1.23	203	44.62	249.69	2.3	1.31	1.07	1.22	2.29	53.48	2386.0
1.5<=CAD<2	1.66	91	20.00	151.06	2.3	1.31	0.01	0.02	0.03	72.17	1443.5
2<=CAD<=2.3	2.13	22	4.84	46.86	2.3	1.31	0.03	0.35	0.38	92.61	447.8
2.3<CAD<3	2.6	45	9.89	117.00	2.3	1.31	0.01	-0.10	-0.09	113.04	1118.0
3<=CAD<3.5	3.23	22	4.84	71.06	2.3	1.31	0.02	-0.06	-0.05	140.43	679.0
3.5<=CAD<4	3.74	15	3.30	56.10	2.3	1.31	0.02	-0.06	-0.04	162.61	536.1
4<=CAD<4.5	4.27	21	4.62	89.67	2.3	1.31	0.01	-0.03	-0.02	185.65	856.9
4.5<=CAD<5	4.77	15	3.30	71.55	2.3	1.31	0.02	-0.04	-0.02	207.39	683.7
5<=CAD<5.5	5.24	9	1.98	47.16	2.3	1.31	0.03	-0.05	-0.02	227.83	450.6
5.5<=CAD<6	5.91	1	0.22	5.91	2.3	1.31	0.22	-0.36	-0.14	256.96	56.5
6<=CAD<6.5	6.06	1	0.22	6.06	2.3	1.31	0.22	-0.35	-0.13	263.48	57.9
total		**455**	**100.00**	**921.42**						**AVG LF=**	**60.94**

Table C-26: Table LF of Configuration C10 (SC=1.77 m^3/min, Vs=1.01 m^3)

CAD interval	*Average CAD (m3/min) (a)*	*Frequency (b)*	*Frequency % (c)*	*Total CAD m3 (d=a*b)*	*SC (m3/min)*	*Vs (m3)*	*tu (min)*	*tl (min)*	*Average CT (min)*	*LF*	*weighted LF (LF*c)*
0.5<=CAD<1	0.93	10	2.20	9.30	1.77	1.01	0.11	0.12	0.23	52.54	115.5
1<=CAD<1.5	1.23	203	44.62	249.69	1.77	1.01	0.82	1.87	2.69	69.49	3100.4
1.5<=CAD<1.78	1.6	70	15.38	112.00	1.77	1.01	0.01	0.08	0.09	90.40	1390.7
1.78<=CAD<2.5	2.1	57	12.53	119.70	1.77	1.01	0.01	-0.05	-0.05	118.64	1486.3
2.5<=CAD<3	2.75	30	6.59	82.50	1.77	1.01	0.01	-0.03	-0.02	155.37	1024.4
3<=CAD<3.5	3.23	22	4.84	71.06	1.77	1.01	0.01	-0.03	-0.02	182.49	882.3
3.5<=CAD<4	3.74	15	3.30	56.10	1.77	1.01	0.02	-0.03	-0.02	211.30	696.6
4<=CAD<4.5	4.27	21	4.62	89.67	1.77	1.01	0.01	-0.02	-0.01	241.24	1113.4
4.5<=CAD<5	4.77	15	3.30	71.55	1.77	1.01	0.01	-0.02	-0.01	269.49	888.4
5<=CAD<5.5	5.24	9	1.98	47.16	1.77	1.01	0.02	-0.03	-0.01	296.05	585.6
5.5<=CAD<6	5.91	1	0.22	5.91	1.77	1.01	0.17	-0.24	-0.07	333.90	73.4
6<=CAD<6.5	6.06	1	0.22	6.06	1.77	1.01	0.17	-0.24	-0.07	342.37	75.2
total		**454**	**99.78**	**920.70**						**AVG LF=**	**74.06**

Appendix D

Pumping System Analysis and Design for Energy Efficiency

D.1 INTRODUCTION

Pumps are extensively used in various industrial sectors such as mining, agriculture, power generation, manufacturing, etc. to provide various services such as cooling, lubrication, fluid transportation and circulation, irrigation, motive force for hydraulic systems, and so on. Pumps account for 27% of the electricity consumption in the manufacturing sector (DOE, 2006) and they require special attention for energy saving purposes.

Centrifugal pumps are the most widely used pump type in industry. The subject plant also use centrifugal pumps. This Appendix will provide some background information about energy efficiency aspects in centrifugal pumps. Pump will refer to a centrifugal pump in this study. Pumping systems in industrial applications represent one of areas with high energy saving potentials. Employing a pump with high efficiency in a pumping system does not mean that the system will operate in maximum efficiency. Achieving maximum efficiency in a pumping system requires not only a high efficiency pump, but also proper sizing and good design of the complete system with regards to actual system requirements. Energy efficiency can be considered in two stages of pumping systems: design stage and operation stage (i.e. existing pumping systems).

D.2 ENERGY EFFICIENCY IN PUMPING SYSTEMS

Energy efficiency can be considered in two stages of pumping systems: design stage and operation stage (i.e. existing pumping systems).

D.2.1 ENERGY EFFICIENCY IN PUMPING SYSTEMS

The key aspect of pumping system design is to properly understand the needs of the system that the pumping system will serve. In practise, the most commonly made mistake is to select a pump first without a proper understanding of the system needs. This results in oversized or undersized pumps which operate inefficiently resulting in higher life cycle costs. It should be borne in mind that a pump is not the only element of a pump system. All pumping systems consist of a pump, a driver such as an electric motor, pipe installation which transport the pumping fluid, operating controls such as valves, and end use equipment. Each of these components should be considered individually. (DOE, 2001). There are two parameters that must be determined to size a pump: capacity and total head (Volk, 2014). These are called as "pump duty" and indicates the working points of a pump.

Determining Pump Duty

1- System Capacity (Q_{duty})

An effective pumping system design should begin with determining the capacity need of the system that pumping will serve. The need will vary depending on the system. For instance, a water tank needs to be filled in a certain amount of time or a cooling tower needs a particular flow rate of a coolant to perform the cooling job it is designed for. These system requirements dictate "flow rate (m^3/h)" and fluid type in a pumping system which is termed as "Capacity (Q_{duty})". Thus, Capacity (Q_{duty}) is the first element that needs to be borne in mind in a pumping system design. Once the Q_{duty} is determined, the next key step is to determine another important element of pumping system design: Total Head (H_{duty}).

2- Total System Head (H_{duty})

A centrifugal pump operating at a fixed speed and with a fixed impeller diameter generates a differential pressure or differential head (Volk, 2014). The head of a pump express how high the pump can lift a liquid and it is measured in meter (m) (Grundfos, 2004). H_{duty} is expressed as the sum of the total pressure head minus total suction head. It can be expressed as follows:

Total pump head (H_{duty}) = total discharge head (h_d) + total suction head (h_s) (Eq. D1)

h_d, total discharge head will have the following components:

- h_{sd}, discharge static head.
- h_{pfd}, discharge pipe friction head.
- h_{fld}, discharge fitting losses head.
- h_{fud}, discharge furnace systems losses head.

Hence, h_d can be expressed as follows:

$$h_d = h_{sd} + h_{pfd} + h_{fld} + h_{fud} \qquad \text{(Eq. D2)}$$

h_s, total suction head for Pump 1 will have the following components:

- h_{ss}, suction static head.
- h_{pfs}, suction pipe friction head.
- h_{fls}, suction fitting losses head.

Hence, h_s can be expressed as follows:

$$h_s = h_{ss} + h_{pfs} + h_{fls} \qquad \text{(Eq. D3)}$$

Hs, static head of the system:

H_S, static head of a system, is the total elevation change of the liquid across the system. It is measured from the surface of the liquid in the suction tank to the surface of the discharge tank where the liquid is being transported. Figure D-1 shows the total static head in a simplified pumping system scheme. Some systems do not involve elevation change; thus, there is no static head. These systems are closed loop systems where the liquid is recirculated and all the static head from the pump to the highest point in the piping system is recovered in the downhill leg of the system (Volk, 2014). Therefore, the static head is zero in these systems.

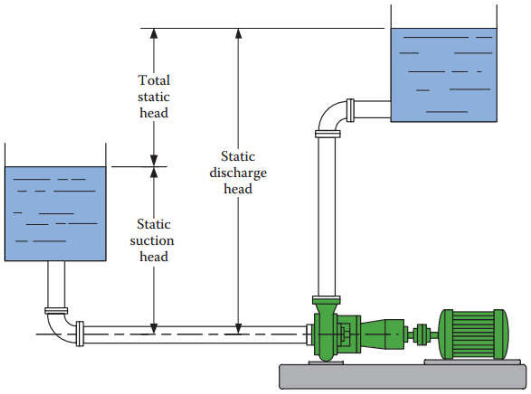


Figure D-1: Total static head in a pumping system

h_f, head due to the pipe friction:

When the liquid flows through, there occurs friction between the liquid and internal walls of the pipe lines. This means that energy of the fluid will be lost due to the frictions. The sum of these losses is expressed as friction head (h_f). When designing a pumping system, h_f should be considered and added to the pump size to be overcome. h_f in a pipe flow is calculated by using the following equation:

$$h_f = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right) \qquad (Eq. D4)$$

where;

f is friction factor.

L is is pipe length (m).

D is pipe internal diameter (m).

V is average flow velocity through pipe (m/s).

g is gravitational acceleration.

V can be estimated by using the following equation:

$$V = \frac{Q}{A} = \frac{Q}{\frac{\pi D^2}{4}} \qquad (Eq. D5)$$

where;

Q is flow rate (m^3/h).

A is cross-sectional area of the pipe (m^2).

In a laminar flow, friction factor f equals to 64/Re, where Re is Reynolds number. In a turbulent flow, the Moody`s diagram (Figure D-2) is used to find the friction factor. Re can be estimated by the following formula:

$$Re = D\frac{V}{\upsilon} \qquad (Eq. D6)$$

where; υ is viscosity of the liquid (m^2/s).

In cylindrical pipe flows, the flow is laminar if the Reynolds number is less than 2300, whereas it is turbulent if the Reynolds number is greater than 4000 (for cylindrical pipe flow).

Having estimated the Re number, the Moody`s diagram can be employed to find the friction factor. Another parameter that will be used with the Re number is relative roughness of the pipes. The relative roughness can be estimated as follows:

$$Relative\ Roughness = \frac{\varepsilon}{D} \qquad (Eq. D7)$$

where; ε is roughness for the pipe depending on its material. This value is provided for various materials as a table on the Moody`s diagram in Figure D-2.

Re and relative roughness values are used on the Moody`s diagram and the friction factor the pipe can be read off.

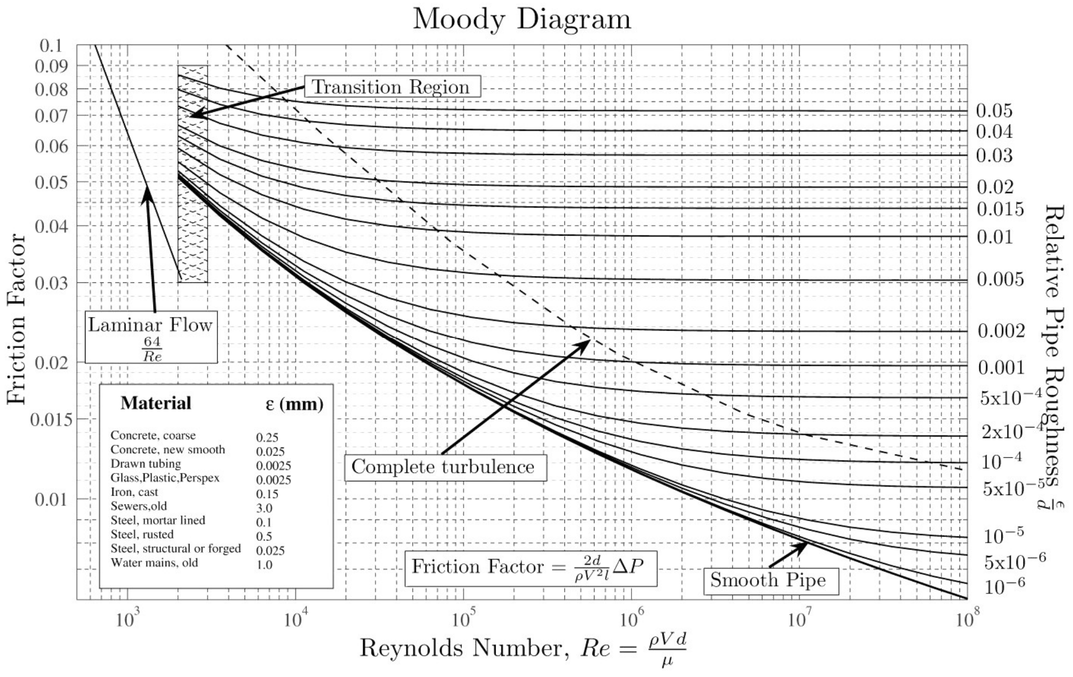


Figure D-2: The Moody`s Diagram

h_L, head loss due to the local losses:

When the liquid flows through, there occurs friction between the liquid and internal walls of the pipe lines. This means that energy of the fluid will be lost due to the frictions. The sum of these losses is expressed as friction head (h_f).

When the liquid flowing through the pipe encounters any fittings, elbows, valves, etc., there occurs pressure lose. This can be estimated as follows:

$$h_L = K\left(\frac{V^2}{2g}\right) \qquad (Eq.D8)$$

where; K is the total resistance coefficient of individual fittings.

Local resistance coefficients for each individual elements on the piping system can be chosen from friction tables or charts.

The sum of Hs, h_f, and h_L gives the total head, H_T. It should be noted that if a pump is equipped with a pressure gauge at its discharge exit, the value read from the pressure gauge when the pump is in operation shows the total discharge head. Similarly, the pressure gauge at the suction side shows the total suction head.

By using H_{duty} and Q_{duty}, the system needs are determined. H_T and Q are also called as “duty cycle” of a pump. The next step will be to select an appropriate pump based on H_{duty} and Q_{duty}.

Importance of Piping Layout Design

From Equations D4 and D8, one can notice that head losses due to the pipe friction, h_f, and local system elements, h_L, depend on the following parameters (Toppi and Labanca, 2009):

- L, Length of the pipe: the length of the piping circuit should be designed shorter as much as possible to decrease the friction head loss.

- D, the pipe diameter: as seen in Equation D4, the head loss depends inversely on the fifth power of D which implies that even a small increase in pipe diameter will significantly increase the friction head loss. Therefore, the pipe diameter should be maximum as much as possible to reduce the friction head losses. However, increasing the pipe diameter will increase the initial purchasing cost of the pipes while it in turns decreases the pumping system energy cost and pump initial purchasing cost owing to reduced head. Therefore, an optimum pipe diameter should be determined.

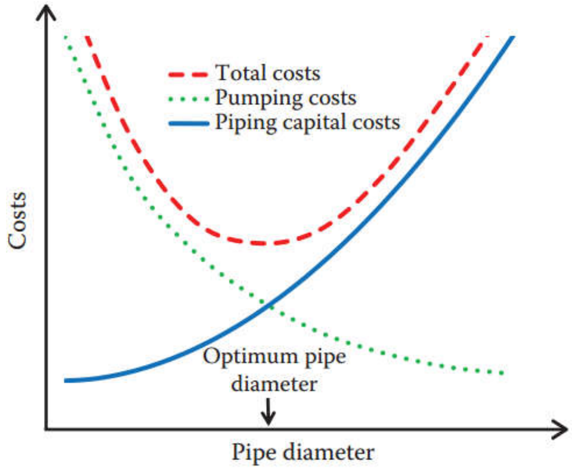


Figure D-3: Relationship between pumping costs and piping capital costs based on the pipe diameter (Volk, 2014)

- f, friction coefficient: friction coefficient depends on the value of the Reynolds (Re) number as mentioned above. The Re number characterize the flow inside pipes. In turbulent flows, friction factor decreases with low relative roughness values as seen on the Moody`s diagram. As Equation D6 shows, low relative roughnes can be achieved with pipes with low ε values (i.e.smooth surfaces) and large diameters.

- K, total loss coefficient of individual fittings: unnessary fittings and curves on pipe line should be avoided because these will cause to pressure losses. The pipeline should be flat as much as possible.

Bearing the all aboves in mind, one can say that piping layout design has a paramount importance in pumping system design. This is particularly a case in the design stage of manufacturing plants. Therefore, piping layout design should be integrated into the plant layout design, which normally considers only the allocation of machines, equipment and material handling and neglects the design piping layout in most cases. In this traditional layout design approach, pipes are paid little attention because they are deemed to be inexpensive in comparison to the other machine and equipment in a plant. This results in long pipes running throughout the plants with sharp right-angles turns. Indeed, pipes are cheaper than other machine and equipment. However, as a part of a pumping system, their contribution to pumping head losses and thus, to pumping system life cycle costs can be great when poorly designed as explained above (Chan-Lizardo et al., 2011). Taking the above explained parameters which affects the head losses into account, the ideal piping layout from energy efficiency stand point should have:

- short pipes in length with optimum large diameter.
- straight pipe lines with minimal bends. Bends should be smooth if unavoidable.
- minimal fittings such as valves.
- pipes with smooth internal walls.

Such a piping system will result in less losses in fluid flow and thus smaller pump which will provide lower capital and life cycle costs can be employed.

__Determining Fluid Power to be Supplied by the Pump__

Having calculated the total head requirement of the system next is to estimate the power to be supplied to the fluid by the pump. This can be expressed as follows:

$$P_T = P_s + P_f + P_L \qquad \textit{Eq. D9}$$

$$P_s = \rho.Q.H_s.g \qquad \textit{Eq. D10}$$

$$P_f = \rho.Q.h_f.g \qquad \textit{Eq. D11}$$

$$P_L = \rho.Q.h_L.g \qquad \textit{Eq. D12}$$

where;

P_T is total power to be supplied to the fluid by the pump.
P_s is power supply due to static head.
P_f is power supply due to pipe friction.
P_L is power supply due to local losses.

The pump to be chosen should be able to supply required system fluid power, P_T. **While choosing the pump**, P_T and motor efficiency should be taken into account. Besides, another important aspect to be borne in mind is "available net positive suction head ($NPSH_A$)" for the pumping system to prevent cavitation.

Determining $NPSH_A$ for the System to Prevent Cavitation

Cavitation is an important phenomenon that should be kept in mind in pumping system designs. If the pressure of a liquid is reduced to some certain state (i.e. vapor pressure of the liquid) without changing the temperature, the liquid can boil or vaporise. If this occurs in a pumping system, it can cause to hydraulic and mechanical failures. The pressure at the suction side of a pump is lower than the pressure side. Besides, the local pressure in the suction side can further decrease due to various factors such as head reduction, pipe friction and local losses such as valves and fitting. If the total local pressure in the suction side allows the liquid to fall below its vapor pressure, then the liquid begin to vaporise or boil. While the vapor bubbles move along the path of pump impeller vane from low pressure side to high pressure side, the local pressure increases and becomes greater than the pressure inside the bubbles. In this point, the bubbles implode and collapse because of the greater pressure, causing to formation on impeller vane. This is called as "cavitation". Cavitation causes to various hydraulic and mechanical problems. For instance, the pump curve and performance change unpredictably resulting in a lower than expected head and flow values. Furthermore, pump impeller will damage because of cavitating and pump shaft can be broken due to vibration (BAC, 2013; Volk, 2014). $NPSH_A$ and $NPSH_R$ are two important aspects to see the potential of cavitation occurrence in a pumping system design.

$NPSH_A$ is the absolute pressure at the suction port of the pump. It is a function of the suction system. $NPSH_A$ must be greater than "required net positive suction head ($NPSH_R$)" for the pump system to operate without cavitating. $NPSH_R$ is the minimum pressure required at the suction port of the pump to keep the pump free from cavitating. It is a function of pump inlet design and must be greater than liquid vapor pressure. $NPSH_R$ is established by the pump's manufacturer and shown on the performance curve (Volk, 2014)

In a cooling tower application, $NPSH_A$ can be calculated as follows:

$$NPSH_A = H_a + H_z - H_f - H_{vp} \qquad \textit{Eq.D13}$$

where;

H_a is absolute pressure on the surface of the water in the cooling tower (this equals to atmospheric pressure if cooling tower is open to the atmosphere.) (m).

H_z is vertical distance between the surface of the water in the cooling tower tank and the centreline of the pump (m).

H_f is friction losses in the suction piping (m).

H_{vp} is absolute vapor pressure of the water at the pumping temperature (m).

As stated above, the calculated $NPSH_A$ of a pumping system must be greater than the $NPSH_R$ for the pump to be used. The comparison can be done with the maximum expected flow rate as a worst-case scenario (Volk, 2014).

Selecting a Pump Based on the Pump Duty and NPS_A

In the preceding subsections, the three main inputs for the pump selection, which are the total head (m), flow rate (m^3/h), and $NPSH_A$ (m) have been explained. In addition to the piping issues discussed above the pump selection is also of importance for energy efficiency. A pump operates most efficiently when it is operating at its best efficiency point (BEP) that is usually shown on the performance curve of that pump. Therefore, the BEP of a pump should be close to the desired operating point, that is, head and flow rate (i.e. system curve) so that the pump operates close to its maximum efficiency. In practise, a pump should be chosen so that the system curve will intersects the pump curve within 20% of the pump`s BEP (DOE, 2006). Besides, for the same operating characteristics, there can be pumps which can show higher efficiency. Pumps with higher efficiency can be chosen to minimise energy and other operational costs since a few improvements in efficiency can result in huge savings over the live cycle of the pump. Pumps can be chosen from vendor`s catalogues. In this study, the Author used an online software PUMP-FLO® which has an extensive database of pump manufacturers (PumpFlo, 2015).

Selecting an Electric Motor to Drive the Pump

After selecting the pump, the next task is to select an appropriate electric motor. The efficiency of the electric motor also contributes the energy efficiency of the overall all pumping system. The relevant efficiency descriptions for a pumping system are shown in Figure D-4.

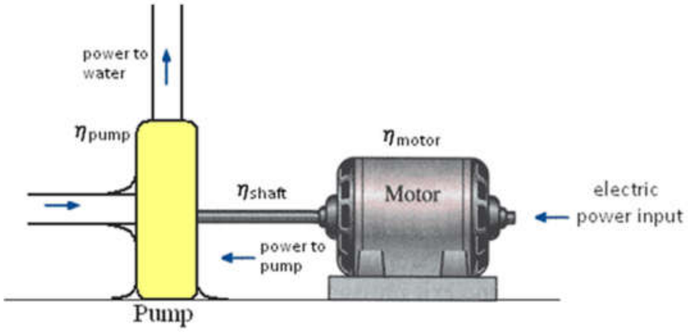


Figure D-4: Pumping system efficiencies

The pump efficiency, shaft efficiency and electric motor efficiency determines the overall efficiency of the system. The best pump efficiency is determined based on the determination of head losses of the system as described in the preceding subsection. Hence, the pump will demand less mechanical energy to give hydraulic energy to the liquid because of its better mechanical efficiency. The mechanical energy required by the pump will be supplied by an electric motor which converts electric energy to mechanical form. The efficiency of the motor determines the power to be drawn. Therefore, after choosing the pump, next is to determine an appropriate electric motor to drive the pump. Energy efficiency in electric motors are discussed in detailed in Appendix B.

So far, rational pumping system design from the energy efficiency point of view has been discussed. Energy efficiency issues for the existing pumping systems will be discussed in the following section.

D.2.3 Energy Efficiency in Operation Stage (Existing Systems)

An existing pumping system can operate inefficiently due to the various factors that were not borne in mind during the design stage discussed in the preceding section. As mentioned earlier, using an efficient pump than others do not imply that pumping system will be energy efficient. A pumping system should be analysed from a system perspective and each components of pumping system from electric motors to piping should be properly sized and selected based on the application system it will serve. In auditing a pumping system in an industrial facility, each design steps explained in the previous section can be followed. A proper system design can be performed for an existing application (e.g. cooling tower pumping system application) in the facility and then can be compared with the existing pumping system in operation. The objective is to see whether the existing pumping system is properly designed and sized for that application.

If a pumping system is not properly designed for the existing application, there will an imbalance between the duty of the pump and the pump`s BEP. A pump operates most efficiently at its BEP. To see this imbalance and efficiency improvement potential, the actual operating efficiency of the pump can be calculated. Then, this can be compared with the pump`s performance curve which shows the BEP that the pump was designed to work at. The pump operating efficiency can be estimated as follows:

$$\eta = \frac{P_T}{P_{in}} = \frac{Q_{duty}\ x\ H_{duty}\ x\ \rho\ x\ g}{P_{in}}\ \%$$

Eq. D14

where;

P_T is power delivered to the liquid by the pump (kW).

P_{in} is power consumed by the pump (kW).

Q_{duty} is measured flow rate at (m^3/h).

H_{duty} is measured discharge head (m).

ρ is density of the liquid (kg/m^2).

g is acceleration of gravity (m/s^2).

Q_{duty}, the measured flow rate can be measured by using an ultrasonic flow meter. This method can provide high accuracy, but it is an expensive way. An alternative to this is estimating the Q_{duty} by using affinity laws which are presented in the following paragraphs. H_{duty}, the measured discharge head is the discharge head plus suction head. This is the pressure head read from the pressure gauge fitted at the pump when the system is at full operational pressure minus suction head.

Affinity Laws

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

Eq. D15

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

Eq. D16

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

Eq. D17

where;

Q is flow (m^3/h).

N is speed (rpm).

H is head (m).
P is power use (kW).

The subscripts 1 and 2 refer to “existing condition” and “new condition”, respectively.

Appendix E

LCC structures and Analysis

E.1 INTRODUCTION

This appendix will provide lifecycle cost components and analyses of each ESP identified in the energy audit. Electric motors and pumps are the most widely used energy using systems in the plant; therefore, their initial purchasing costs and other assumptions are presented in Section E.2 and Section E.3. Cost structures and initial investment costs are estimated and presented in the form of tables for each ESPs in Section E.4. The initial purchasing cost and other assumptions for energy saving measures apart from electric motors and pumps are given in the associated Tables. LCC assessments for each ESPs for base case energy scenario (i.e. 0% increase in energy unit cost) are presented in Section E.5.

E.2 ELECTRIC MOTORS

Table E-1 lists the prices for premium efficiency electric motors for various power ratings which are used in this study as energy saving measures. These electric motor costs figures presented in Table E-1 are obtained from a company based in Turkey (http://www.adsmuhendislik.com.tr/deppo/dosya/14441977176.pdf). These costs are for 2017. The cost figures for existing electric motors of the plant with standard or lower efficiency levels are assumed to be approximately 20% lower than that of the premium efficiency class electric motors based on IEC (2010). The annual maintenance cost for electric motors are generally assumed to be 1% of the initial purchasing cost based on IEC (2010). However, the subject plant electrician team is capable of doing various maintenance and repair works and they work based on a constant monthly salary; hence, this cost will be zero for the subject plant. Electric motors often have a lifespan of 15 to 20 years IEC (2010). 15 years is assumed to be useful lifespan of an electric motor.

The salvage value for an electric motor at the end of its lifespan is assumed to be 5% of its initial cost.

Table E-1 IE3 efficiency class ABB electric motors purchasing costs

	Premium efficiency (IE3)	Standard or lower efficiency
5.5kW	€375	€300
7.5kW	€478	€382
11kW	€570	€463
15kW	€752	€602
18.5kW	€864	€692
22kW	€1030	€824
30kW	€1284	€1027
37kW	€1615	€1292
45kW	€1890	€1512
55kW	€2440	€1952

E.3 PUMPS

Table E-2 lists the purchasing prices for new centrifugal pumps for various power rating which are used in this thesis as energy saving measures. The prices are collected from a supplier in Turkey. There are no energy efficiency classes for centrifugal pumps like energy efficiency classes for electric motors at present. A company can manufacture more efficient pumps than another for the same capacity. Therefore, the collected cost data is assumed to be for lower efficiency pumps used in the subject plant and more efficiency pumps will cost 20% higher as presented in Table E-2. The annual maintenance cost for the pumps is assumed to be 10% of the initial purchasing costs based on the supplier. Life span of centrifugal pumps varies from 15 to 20 years (DOE, 2001). 15 years is assumed to be the useful lifespan of a centrifugal pump in this study. The salvage value for a pump at the end of its lifespan was reported to be 10% of its initial cost by Zhang and Du (2013). However, 5% is taken into account in this study based on the recommendation by the subject plant management based on their previous experiences.

Table E-2: Purchasing Costs for Pumps

Power Rating	Lower Efficiency Pumps	Higher Efficiency Pumps
5.5kW	€740	€888
7.5kW	€778	€935
11kW	€973	€1168
15kW	€1055	€1266
18.5kW	€1168	€1402
22kW	€1440	€1730
30kW	€1678	€2013.6

E.4 COST STRUCTURES AND INITIAL INVESTMENT COSTS FOR ESPs

Table E-13: Cost components for ESP 5-4

ESP 5-4: ESP by using premium efficiency motor -LCC components

	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components				
Initial purchasing cost for a new 5.5 kW electric motor(a)	€ 375	3	-€ 1,126	Table E-2
Total Initial Cost (€)			-€ 1,126	
Salvage value of the existing 5.5 kW electric motor (b)	€ 15	3	€ 45	5% of initial purchasing cost, Table E-2
Salvage value of the new 5.5 kW electric motor at the end of the project lifespan, 15 years from now (c)	€ 18.75	3	€ 56.25	5% of initial purchasing cost, Table E-2
Avoided cost of replacing the existing standard efficiency 5.5 kW electric motor with a new one at the end of its useful life span (d)	€ 300	3	€ 900	The existing e. motor was put in-service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one 8 years later after now on if the project was not realized. This cost is avoided by replacing the motor with a new one.
ANNUAL MAINTENANCE COST	0	0	0	Explained in Section E-2

Table E-4: Cost components for ESP 5-5

ESP 5-5: ESP by using notched V belts - LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components				
Initial purchasing cost for notched V belts (a)	€ 86	3	-€ 258	Because the notched V belts last longer than normal V belts, the replacement times of the notched V belts will be half of normal V belts. Therefore, it is assumed that notched belts will be replaced 8 times. https://www.v-kayislari.com/tr/xpcx3750lw--u
Total			-€ 258	
Avoided cost of replacing the existing V belts with a new one at the end of its useful life span (b)	€ 12	3	€ 36	Based on the subject plant, the existing V belts are replaced every year. Therefore, they will be replaced 15times. https://www.v-kayislari.com/tr/xpcx3750lw--u
Annual Maintenance Cost	€ 0	0	€ 0	

Table E-5: Cost Components for ESP 5-7

ESP 5-7: ESP by using premium efficiency motor - LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components				
Initial purchasing cost for a new 22 kW electric motor (a)	€ 1,030	2	-€ 2,060	Table E-1
Total initial purchasing cost			-€ 2,060	
Salvage value of the existing 22 kW electric motor (b)	€ 41.20	2	€ 82.40	5% of initial purchasing cost, Table E-2
Salvage value of the new 22 kW electric motor at the end of the project lifespan (c)	€ 51.50	2	€ 103	5% of initial purchasing cost
Avoided cost of replacing the existing 22 kW electric motor with a new one at the end of its useful life span (d)	€ 824	2	€ 1,648	The existing e. motor was put in-service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new during the project lifespan if the project is not realized. This cost is avoided by replacing the motor with a new one.
Annual Maintenance Cost	0	0	€ 0	Explained in Section E-2

Table E-6: Cost components for ESP 5-8

ESP 5-8: ESP by more efficient transmission belt (using notched V belts) -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components				
Initial purchasing cost for notched V belts	€ 86	2x8	-€ 1,376	Because the notched V belts last longer than normal V belts, the replacement times of the notched V belts will be half of normal V belts. Therefore, it is assumed that notched belts will be replaced 8 times. https://www.v-kayislari.com/tr/xpcx3750lw--u
Avoided cost of replacing the existing V belts with a new one at the end of its useful life span	€ 12	2x15	€ 360	Based on the subject plant, the existing V belts are replaced every year. Therefore, they will be replaced 15times. https://www.v-kayislari.com/tr/xpcx3750lw--u
Annual Maintenance Cost	€ 0	0	€ 0	

Table E-7: Cost components for ESP 5-9

ESP 5-9: ESP by replacing the old machine tool with a new one -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS				
New CNC Lathe	€ 100,000	1	-€ 100,000	A market survey through internet conducted to have an idea about the prices for new CNC lathes of similar capacity. It varies around €100,000. €100,000 euro is assumed for this study
Total Initial Cost (i)			-€ 100,000	
Salvage Value of the existing old lathe			€ 10,000.00	A market survey through internet conducted to have an idea about the prices for second hand similar machines. It varies around €14,000. €10,000 euro is assumed for this study
Salvage Value of the new lathe at the end of the project life			€ 10,000	10% of initial cost
ANNUAL MAINTENANCE COST	€ 0	1	€ 0	It is assumed that the old lathe and the new one will have the same costs.Therefore, there won't be additional costs due the new lathe.

Table E-8: Cost components for ESP 5-13

ESP 5-13: ESP by using premium efficiency motor -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components				
Initial purchasing cost for a new 5.5 kW electric motor (a)	375	1	-€ 375	Table E-1
Total initial purchasing cost			-€ 375	
Salvage value of the existing 5.5 kW electric motor (b)	€ 15	1	€ 15	5% of initial purchasing cost, Table E-1
Salvage value of the new 5.5 kW electric motor at the end of the project lifespan, 15 years from now (c)	€ 18.75	1	€ 18.70	5% of initial purchasing cost
Avoided cost of replacing the existing 5.5 kW electric motor with a new one at the end of its useful life span (d)	€ 300	1	€ 300	The existing e. motor was put in-service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one during the project life span if the project is not realized. This cost is avoided by replacing the motor with a new one.
Annual Maintenance Cost	€ 0	0	€ 0	Explained in Section E-2

Table E-9: Cost Components for ESP ESP 5-14

ESP 5-14: ESP by using premium efficiency motor in quenching pool -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components				
Initial purchasing cost for a new 30 kW electric motor (a)	€ 1,284	1	-€ 1,284	Table E-1
Salvage value of the existing 30 kW electric motor (b)	€ 51.36	1	€ 51.36	5% of initial purchasing cost, Table E-2
Salvage value of the new 30 kW electric motor at the end of the project lifespan (c)	€ 64.2	1	€ 64.2	5% of initial purchasing cost
Avoided cost of replacing the existing 30 kW electric motor with a new one at the end of its useful life span (d)	€1,027	1	€1,027	The existing e. motor was put in-service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one during the project life span if the project is not realized. This cost is avoided by replacing the motor with a new one.
TOTAL Cost (e)			-€141.2	e=a+b+c+d
Annual Maintenance Cost	0	0	€ 0	electric motor maintenance is done by the plant electrician on a constant salary

Table E-10: Cost Structure for ESP 6-1

ESP 6-1: ESP by using a DCVS -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS				
Controller (a)	€ 1,000	1	-€ 1,000	Supplier
Sensors(b)	€ 650	5	-€ 3,250	Supplier
Fuses, control board, programming, wiring (c)	€ 2,000	1	-€ 2,000	Supplier
Blast gates (d)	€ 180	10	-€ 1,800	Supplier
Installation (e)	€ 1,000	1	-€ 1,000	Supplier
Total Initial Cost (i)			-€ 9,050	
Salvage Value (f)			€ 80.50	1% of initial cost, Supplier
Salvage value of the new VFD at the end of project life (h)			€ 20	1% of initial cost
Replacement cost of the existing VFD (g)	€ 2,000	1	-€ 2,000	The existing VFD was put in service in 2007. Considering that the average lifespan of a VFD is about 15 years (Halcyon, 2016) years, the existing VFD needs to be replaced at the 5th year of the project. The current price for 45 kW is 2000 Euro.
ANNUAL MAINTENANCE COST	€ 905	1	-€ 905	10% of initial cost, Supplier

Table E-11: Cost structure for ESP 6-2

ESP 6-2: ESP by using premium efficiency electric motor -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS				
Initial purchasing cost for a new 45 kW electric motor	€ 1,890	1	-€ 1,890	Table E-1
Salvage value of the existing 45 kW electric motor now	€ 75.60	1	€ 75.60	5% of initial cost
Salvage value of the new 45 kW electric motor at the end of the project lifespan, 15 years from now	€ 94.50	1	€ 94.50	5% of initial cost
Avoided cost of replacing the existing 45kW electric motor with a new one at the end of its useful life span	€1512	1	€ 1,512	Table E-1(The existing electric motor was put in service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one at the 5h year of the project if the project is not realized. This cost is avoided by replacing the motor with a new one at the beginning of the project.
ANNUAL MAINTENANCE COST	€ 19	0	€ 0.00	Explained in Section E-1

Table E-12: Cost structure for ESP 6-3

ESP 6-3: ESP by reconfiguration of air compressors-LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS	€ 6,000*	1	-€ 6,000	Supplier
TOTAL			-€ 6,000	
ANNUAL MAINTENANCE COST	€600	1	-€ 600.0	10% of initial capital cost, Supplier
*Roughly cost estimation given by the supplier				

Table E-13: Cost structure for ESP 6-9

ESP 6-9: ESP by fixing air leaks-LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS	€ 100	1	-€ 100	the repair of the air leaks in the compressed air system requires the regular maintenance of blow guns, pipe joints, and fittings, etc. Loose joints should be screwed/ tightened.If any parts such as clamp sleeves do not function properly, they should be replaced. A periodic leak fixing and maintenance plan can be followed for the compressed air system. This job can be done by the plant management team which are responsbile for various maintenaance and repair works. They are paid based on montly salary. Therefore, there will involve no labour cost for fixing the air leaks. However, there might involve some purchasing cost for screws, bolts, or clamp sleeves. Based on the suggestion by the subject plant management, these components are simple and inexpensive thing and their annual cost to the plant would not be more than €100. Thus, it is assumed that the subject plant will pay €100 per year for the maintenance and repair of air fixes.

Table E-14: Cost structure for ESP 6-10

ESP 6-10: ESP by using VFD for the cooling tower air fan in Cooling Tower 1 -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS				
VFD	€ 850	1	-€ 850	Supplier
Controller	€ 1,000	1	-€ 1,000	Supplier
Thermocouple	€ 300	1	-€ 300	Supplier
Control board and programming	Approximately €2000	1	-€ 2,000	Supplier
Miscellaneous	Approximately €1000	1	-€ 1,000	Supplier
Installing	€ 1,000	1	-€ 1,000	Supplier
Total initial capital cost			-€ 6,150	
Salvage value at the end of the project life			€ 51.50	1% assumption
ANNUAL MAINTENANCE COST	€ 515	1	-€ 515	% of 10 initial capital cost, Supplier

Table E-15: Cost components for ESP 6-11

ESP 6-11: ESP by replacing Pump 2 with an efficient pump and premium efficiency electric motor Cooling Tower 1 - LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components for New Pump				
Initial purchasing cost for a new 18.5kW pump (a)	€1402	1	-€1402	Table E-2
Salvage value of the existing 22 kW pump (b)	€ 72	1	€ 72	5% of initial purchasing cost
Salvage value of the new 18.5 kW pump at the end of the project	€ 70.1	1	€ 70.1	5% of initial purchasing cost
Avoided cost of replacing the existing 22 kW pump with a new one at the end of its useful life span (d)	€1440	1	€1440	The existing 22 kW pump was put in service in 2007. Considering that the useful life for a pump is 15 years (DOE, 2001), it would have been replaced with a new during the lifespan of the project if the project is not realized. This cost is avoided by replacing the pump with a new one at the beginning of the project. This is reduced from the initial cost.
Initial Capital Cost (e)			**€180.1**	e=a+b+c+d
Annual Maintenance Cost for new pump (f)	0	-	0	It is assumed that these costs will be equal for both pumps and there will be no extra maintenance cost, f=g h=f-g=0
Avoided Annual maintenance cost of the existing pump (g)	0	-	0	
Annual Maintenance Cost (h)			**0**	h=f+g
Capital Cost Components for New Electric Motor				
Initial purchasing cost for a new 18.5 kW electric motor (a1)	€ 864	1	-€864	Table E-1
Salvage value of the existing standard efficiency22 kW electric motor (b1)	€ 41.2	1	€41.2	5% of initial purchasing cost.
Salvage value of the new 18.5 kW electric motor at the end of the project lifespan (c1)	€ 43.2	1	€43.2	5% of initial purchasing cost
Avoided cost of replacing the existing 22 kW electric motor with a new one at the end of its useful life span (d1)	€824	1	€824	The existing 22 kW electric motor was put in service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one at the 8th year of the project if the project is not realized. This cost is avoided by replacing the motor with a new one at the beginning of the project. This is reduced from the initial cost.
Initial Capital Cost (e1)			€44.4	E1=a1+b1+c1+d1
Annual Maintenance Cost for New Electric Motor (f1)	0	0	€ 0.00	Explained in Section E-2
TOTAL INITIAL CAPITAL COST (i)			€224.1	i=e+e1
TOTAL AN. MAINTENANCE COST (j)			0	j=h+f1

Table E-16: Cost components for ESP 6-12

ESP 6-12: ESP by replacing Pump 1 with an efficient pump and premium efficiency electric motor Cooling Tower 1 -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components for New Pump				
Initial purchasing cost for a new 15 kW pump (a)	€ 1,266	1	-€ 1,266	Table E-2
Salvage value of the existing 30 kW pump (b)	€ 84	1	€ 84	5% of initial purchasing cost, Table E-2
Salvage value of the new 15 kW pump at the end of the project	€ 63.30	1	€ 63.30	5% of initial purchasing cost
Avoided cost of replacing the existing 30 kW pump with a new one at the end of its useful life span (d)	€ 1,678	1	€ 1,678	The existing 30 kW pump was put in service in 2007. Considering that the useful life for a pump is 15 years (DOE, 2001), it would have been replaced with a new one during the project life if the project is not realized. This cost is avoided by replacing the pump with a new one at the beginning of the project. This is reduced from the initial cost.
Annual Maintenance Cost (h)	0	1	**€ 0**	It is assumed that these costs will be equal for both pumps and there will be no extra maintenance cost, f=g h=f-g=0
Capital Cost Components for New Electric Motor				
Initial purchasing cost for a new 15 kW electric motor (a1)	€ 752	1	**-€ 752**	Table E-1
Salvage value of the existing standard efficiency 30 kW electric motor (b1)	€ 51.36	1	€ 51.36	5% of initial purchasing cost.
Salvage value of the new 15 kW electric motor at the end of the project lifespan (c1)	€ 37.60	1	€ 37.60	5% of initial purchasing cost
Avoided cost of replacing the existing standard efficiency 30kW electric motor with a new one at the end of its useful life span (d1)	€ 1,027	1	€ 1,027	The existing 30 kW electric motor was put in service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one at the 5th year of the project if the project is not realized. This cost is avoided by replacing the motor with a new one at the beginning of the project. This is reduced from the initial cost.
Annual Maintenance Cost for New Electric Motor (f1)	0	0	0	Explained in section E-2
TOTAL INITIAL CAPITAL COST (i)		i=e+e1	-€ 2,018.00	
TOTAL AN. MAINTENANCE COST (j)		j=h+f1	0	

Table E-17: Cost structure for ESP 6-13

ESP 6-13: ESP by replacing the existing electric motor of Pump 1 with a premium efficient electric motor in Cooling Tower 2-LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
CAPITAL COST COMPONENTS				
Initial purchasing cost for a new 37 kW electric motor (a)	€ 1,615	1	-€ 1,615	Table E-1
Salvage value of the existing 37 kW electric motor (b)	€ 65	1	€ 65	5% of initial purchasing cost, Table E-1
Salvage value of the new 37 kW electric motor at the end of the project lifespan(c)	€ 80.75	1	€ 80.75	5% of initial purchasing cost
Avoided cost of replacing the existing standard efficiency 37kW electric motor with a new one at the end of its useful life span (d)	€ 1,292	1	€ 1,292	The existing electric motor was put service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one 6 years later if the project is not realized. This cost is avoided by replacing the motor with a new one at the beginning of the project. This is reduced from the initial cost
ANNUAL MAINTENANCE COST	0	0	€ 0.00	Explained in Section E-2

Table E-18: Cost structure for ESP 6-14

ESP 6-14: ESP by replacing Pump 2 in Cooling Tower 2 with an efficient and right size pump and premium efficiency -LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
cost components for a new pump				
Initial purchasing cost for a new 5.5kW pump (a)	€ 888	1	-€ 888	Table E-2
Salvage value of the existing 15 kW pump (b)	€ 52.70	1	€ 52.70	5% of initial purchasing cost, Table E-2
Salvage value of the new 5.5 kW pump at the end of the project lifespan (c)	€ 44.40	1	€ 44.40	5% of initial purchasing cost
Avoided cost of replacing the existing 15 kW pump with a new one at the end of its useful life span (d)	€ 1,055	1	€ 1,055	The existing pump was put in-service in 2007. Considering that the useful life for a pump is 15 years, it would have been replaced with a new during the project lifetime if the project is not realized. This cost is avoided by replacing the motor with a new one.
Annual maintenance cost				
Maintenance cost for new pump (f)	€ 0	-	0	It is assumed that these costs will be equal for both pumps and there will be no extra maintenance cost, f=g h=f-g=0
Avoided maintenance cost for the existing pump (g)	€ 0	-	0	
Total maintenance cost (h)			0	h=f+g
cost components for an electric motor				
Initial purchasing cost for a new 5.5 kW electric motor (a1)	€ 375	1	-€ 375	Table E-1
Salvage value of the existing 15 kW electric motor (b1)	€ 30	1	€ 30	Table E-1
Salvage value of the new 5.5 kW electric motor at the end of the project lifespan (c1)	€ 18.75	1	€ 18.75	Table E-1

Avoided cost of replacing the existing standard efficiency 15 kW electric motor with a new one at the end of its useful life span (d1)	€ 602	1	€ 602	The existing e. motor was put in-service in 2007. Considering that the useful life for an electric motor is 15 years, it would have been replaced with a new one during the project life span if the project was not realized. This cost is avoided by replacing the motor with a new one.
Annual Repair and Maintenance Cost (f1)	€ 3.75	0	€ 0.00	Explained in Section E-2
TOTAL CAPITAL COST (I)			**€ 1,263**	i=e+e1
TOTAL MAINTENANCE COST (J)			**0**	J=h+f1

Table E-19: Cost components for ESP 6-15

ESP 6-15: ESP by using Hybrid Daylighting System-LCC components				
	Unit Price (€/unit)	Unit	Total (€)	Source
Capital Cost Components for skylights				
Polycarbonate panels (a)	€14.16 /m2	64m2	-€ 906.20	Supplier
Aluminum frame				Supplier
-*Cap profile*	€7.6 /m	128m	-€ 972.80	Supplier
-*Base profile*	€9.93/m	128m	-€ 1,271	Supplier
-*U profile end caps (10 mm)*	€8.6/m	64m	-€ 550.40	Supplier
-*Anti-dust edged tape*	€0.75/m	64m	-€ 48	Supplier
-*H profile (10mm)*	€1.43/m	128m	-€ 183	Supplier
-Others			-€ 39.20	Supplier
Labor cost (installing)	€100/day	10 days	-€ 1,000	Supplier, Subject plant
Salvage			€ 166.00	
Capital Cost Components for control system				
Controller	€ 1,000	1	-€ 1,000	Supplier
Sensors	€55/pcs	6	-€ 330	Supplier
fuses, control board, programming dimmable lamps, wiring,	Approx. € 2,400	1	-€ 2,400	Supplier
installing	€ 1,000	0	€ 0	The subject plant is capable of doing these kind of installation works
Salvage			€ 186.50	

Total Initial Cost			-€ 8,700.60	
Total Salvage			€ 352.50	
Avoided cost of replacing the existing HID lamps with new ones at the end of its useful life span	€ 95.70	32	€3062.4/every 3 years	the life span of HID lamps are 15,000 hours based on the product data sheet. Annual running hours for these lamps in the subject plant is 5162.5 hours. Thus, they have to be replaced about every 3 years if the skylights are not used. This replacement cost is avoided and taken into account in LCC analysis. Because the initial installation date of the existing hid lamps is not known, it will be assumed that they are new. In 15 years, they would have been replaced for 5 times.
Maintenance Cost Components				
Sensors	€249/year	1	-€ 249	5% of initial cost, Supplier
Control system	€187/year	1	-€ 187	5% of initial cost, supplier
Total MAINTENANCE COST			-€ 435	

Table E-20: Cost components for ESP 6-16

ESP 6-16: ESP by using LED tubes -LCC components				
	UnitPrice	Unit	Total (€)	Source
Capital Cost Components				
purchase cost per Led tube (a)	€ 52	22	-€ 1,144	Supplier
installation cost per led tube (b)	€ 10	22	-€ 220	Supplier
Total Initial Cost			-€ 1,364	
Re-purchase cost + installation cost per LED tube (c=a+b)	€ 62	22	-€ 1,364	Life time of LED tubes = 50,000 hours. They need to be replaced at 10th year. it has to be added to the today`s initial cost
Avoided cost of replacing the existing fluorescent tubes with new ones at the end of its useful life span (i.e. 6 times replacement) (d)	€ 22.65	22	498.3/every 2.5 years	Life time of the existing fluorescent = 13,000 hours. Because the initial installation date of the existing fluorescent tubes is not known, it is assumed that they are new at the beginning of the project. Considering annual working hours for is 5162.5 hours, they need to be replaced every 2.5 years. Thus, in 15 years, there would be 6 times replacement. By investing in LED tubes, this replacement cost is avoided. This is reduced from the initial capital cost.
TOTAL (E)				e=a+b+c+d
ANNUAL MAINTENANCE COST	-		€ 0.00	Supplier

E.5 LCC ASSESSMENTS FOR ESPS

Table E-21: LCC assessment for ESP 5-4

ESP 5-4: ESP by using premium efficiency motor- 0% yearly increase in energy unit cost

t	Discounted interest rate i	**Benefits**							**Cost**						**Discounted Benefits Costs Difference (€)**
		Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	
0	1.32%					45	€ 45.0	€ 45.0	-€ 1,126.0				-€ 1,126	-€ 1,126.0	-€ 1,081.0
1	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 243.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 243.7
2	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 240.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 240.5
3	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 237.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 237.4
4	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 234.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 234.3
5	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 900	€ 0.0	€ 1,146.9	€ 1,074.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,074.1
6	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 228.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 228.3
7	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 225.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 225.3
8	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 222.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 222.3
9	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 219.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 219.4
10	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 216.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 216.6
11	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 213.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 213.8
12	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 211.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 211.0
13	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 208.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 208.2
14	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 0.0	€ 246.9	€ 205.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 205.5
15	1.32%	3,770.0	€ 0.0655	€ 246.9	€ 0.0	€ 56.3	€ 303.2	€ 249.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 249.0
						Total Benefits		€ 4,274.6				Total Costs		-€ 1,126.0	
														NPV=	€ 3,148.6
														B/C=	3.79

Table E-22: LCC assessment for ESP 5-5

ESP 5-5: ESP by using notched V belts - 0% yearly increase in energy unit cost															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%							€ 0.0	-€ 258.0				-€ 258	-€ 258.0	-€ 258.0
1	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 0.0	€ 0.0	€ 103.7	€ 102.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 102.3
2	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 136.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 136.1
3	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 134.3	0	-€ 258.0	€ 0	€ 0.0	-€ 258	-€ 248.0	-€ 113.8
4	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 132.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 132.5
5	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 130.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 130.8
6	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 129.1	0	-€ 258.0	€ 0	€ 0.0	-€ 258	-€ 238.5	-€ 109.4
7	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 127.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 127.4
8	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 125.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 125.8
9	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 124.1	0	-€ 258.0	€ 0	€ 0.0	-€ 258	-€ 229.3	-€ 105.1
10	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 122.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 122.5
11	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 120.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 120.9
12	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 119.3	0	-€ 258.0	€ 0	€ 0.0	-€ 258	-€ 220.4	-€ 101.1
13	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 117.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 117.8
14	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 116.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 116.3
15	1.32%	1,582.9	€ 0.0655	€ 103.7	€ 36.0	€ 0.0	€ 139.7	€ 114.7	0	-€ 258.0	€ 0	€ 0.0	-€ 258	-€ 211.9	-€ 97.2
						Total Benefits		€ 1,854.0				Total Costs		-€ 1,406.2	
														NPV=	€ 447.9
														B/C=	1.31

Table E-23: LCC assessment for ESP 5-7

ESP 5-7: ESP by using premium efficiency motor in abrasive blasting system - 0% yearly increase in energy unit cost

		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					82.4	€ 82.4	€ 82.4	-€ 2,060.0				-€ 2,060	-€ 2,060.0	-€ 1,977.6
1	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 67.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 67.2
2	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 66.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 66.3
3	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 65.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 65.5
4	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 64.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 64.6
5	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 1,648.0	€ 0.0	€ 1,716.1	€ 1,607.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,607.2
6	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 62.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 62.9
7	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 62.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 62.1
8	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 61.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 61.3
9	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 60.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 60.5
10	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 59.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 59.7
11	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 58.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 58.9
12	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 58.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 58.2
13	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 57.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 57.4
14	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 0.0	€ 68.1	€ 56.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 56.7
15	1.32%	1,039.4	€ 0.0655	€ 68.1	€ 0.0	€ 103.0	€ 171.1	€ 140.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 140.5
						Total Benefits		€ 2,631.4				Total Costs		-€ 2,060.0	
														NPV=	€ 571.4
														B/C=	1.27

Table E-24: LCC assessment for ESP 5-8

ESP 5-8: ESP by using more efficient transmission belts in abrasive blasting system - 0% yearly increase in energy unit cost															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%							€ 0.0	-€ 172.0				-€ 172	-€ 172.0	-€ 172.0
1	1.32%	662.7	€ 0.0655	€ 43.4	€ 0.0	€ 0.0	€ 43.4	€ 42.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 42.9
2	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 65.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 65.7
3	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 64.8	0	-€ 172.0	€ 0	€ 0.0	-€ 172	-€ 165.4	-€ 100.5
4	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 64.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 64.0
5	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 63.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 63.2
6	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 62.3	0	-€ 172.0	€ 0	€ 0.0	-€ 172	-€ 159.0	-€ 96.7
7	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 61.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 61.5
8	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 60.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 60.7
9	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 59.9	0	-€ 172.0	€ 0	€ 0.0	-€ 172	-€ 152.9	-€ 92.9
10	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 59.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 59.1
11	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 58.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 58.4
12	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 57.6	0	-€ 172.0	€ 0	€ 0.0	-€ 172	-€ 147.0	-€ 89.3
13	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 56.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 56.9
14	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 56.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 56.1
15	1.32%	662.7	€ 0.06554	€ 43.4	€ 24.0	€ 0.0	€ 67.4	€ 55.4	0	-€ 172.0	€ 0	€ 0.0	-€ 172	-€ 141.3	-€ 85.9
						Total Benefits		€ 888.5				Total Costs		-€ 937.4	
														NPV=	-€ 48.9
														B/C=	0.94

Table E-25: LCC assessment for ESP 5-9

ESP 5-9: ESP by replacing the old machine tool with a new one - 0% yearly increase in energy unit cost

		Benefits							Cost						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%	8,025.0				10,000	€ 10,000.0	€ 10,000.0	-€ 100,000.0				-€ 100,000	-€ 100,000.0	-€ 90,000.0
1	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 518.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 518.8
2	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 512.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 512.0
3	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 505.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 505.4
4	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 498.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 498.8
5	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 492.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 492.3
6	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 485.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 485.9
7	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 479.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 479.5
8	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 473.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 473.3
9	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 467.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 467.1
10	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 461.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 461.0
11	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 455.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 455.0
12	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 449.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 449.1
13	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 443.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 443.3
14	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 0.0	€ 525.6	€ 437.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 437.5
15	1.32%	8,025.0	€ 0.0655	€ 525.6	€ 0.0	€ 10,000.0	€ 10,525.6	€ 8,646.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 8,646.1
						Total Benefits		€ 25,325.0				Total Costs		-€ 100,000.0	
														NPV=	-€ 74,675.0
														B/C=	N/A

Table E-26: LCC assessment for ESP 5-12

ESP 5-12: ESP by using premium efficiency motor - 0% yearly increase in energy unit cost															
		Benefits							Cost						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					€ 51.36	€ 51.4	€ 51.4	-€ 1,284.0				-€ 1,284	-€ 1,284.0	-€ 1,232.6
1	1.32%	12,219.0	€ 0.0655	€ 800.8	€ 0.0	€ 0.0	€ 800.8	€ 790.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 790.4
2	1.32%	12,219.0	€ 0.0655	€ 800.8	€ 0.0	€ 0.0	€ 800.8	€ 780.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 780.1
3	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 769.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 769.5
4	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 759.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 759.4
5	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 1,027.0	€ 0.0	€ 1,827.3	€ 1,711.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,711.4
6	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 739.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 739.8
7	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 730.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 730.1
8	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 720.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 720.6
9	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 711.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 711.2
10	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 702.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 702.0
11	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 692.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 692.8
12	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 683.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 683.8
13	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 674.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 674.9
14	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 0.0	€ 800.3	€ 666.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 666.1
15	1.32%	12,219.0	€ 0.0655	€ 800.3	€ 0.0	€ 64.2	€ 864.5	€ 710.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 710.2
						Total Benefits		€ 11,893.8				Total Costs		-€ 1,284.0	
														NPV=	€ 10,609.8
														B/C=	9.26

Table E-27: LCC assessment for ESP 5-13

ESP 5-13: ESP by using more efficient electric motor for the air fan - 0% yearly increase in energy unit cost

		Benefits							Cost						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					15	€ 15.0	€ 15.0	-€ 375.0				-€ 375	-€ 375.0	-€ 360.0
1	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 48.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 48.3
2	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 47.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 47.6
3	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 47.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 47.0
4	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 46.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 46.4
5	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 45.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 45.8
6	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 45.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 45.2
7	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 44.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 44.6
8	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 44.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 44.0
9	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 43.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 43.4
10	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 42.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 42.9
11	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 42.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 42.3
12	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 41.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 41.8
13	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 41.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 41.2
14	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 0.0	€ 48.9	€ 40.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 40.7
15	1.32%	746.4	€ 0.0655	€ 48.9	€ 0.0	€ 18.7	€ 67.6	€ 55.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 55.5
						Total Benefits		€ 691.7				Total Costs		-€ 375.0	
														NPV=	€ 316.7
														B/C=	1.84

Table E-38: LCC assessment for ESP 5-14

ESP 5-14 : ESP by using premium efficiency motor - 0% yearly increase in energy unit cost															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					51.36	€ 51.4	€ 51.4	-€ 1,284.0				-€ 1,284	-€ 1,284.0	-€ 1,232.6
1	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 50.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 50.6
2	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 49.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 49.9
3	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 49.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 49.2
4	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 48.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 48.6
5	1.32%	782.0	€ 0.0655	€ 51.2	€ 1,027.0	€ 0.0	€ 1,078.2	€ 1,009.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,009.8
6	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 47.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 47.3
7	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 46.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 46.7
8	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 46.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 46.1
9	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 45.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 45.5
10	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 44.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 44.9
11	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 44.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 44.3
12	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 43.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 43.8
13	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 43.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 43.2
14	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 0.0	€ 51.2	€ 42.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 42.6
15	1.32%	782.0	€ 0.0655	€ 51.2	€ 0.0	€ 64.2	€ 115.4	€ 94.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 94.8
						Total Benefits		€ 1,758.8				Total Costs		-€ 1,284.0	
														NPV=	€ 474.8
														B/C=	1.37

Table E-29: LCC assessment for ESP 6-1

ESP 6-1: ESP by using DCVS - Base case Energy Cost Scenario: 0% yearly increase in energy unit cost															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%							€ 0.0	€ 9,050.0				€ 9,050	€ 9,050.0	€ 9,050.0
1	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,269.7	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 893.2	€ 1,376.5
2	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,240.1	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 881.6	€ 1,358.6
3	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,211.0	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 870.1	€ 1,340.9
4	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,182.2	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 858.8	€ 1,323.4
5	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,153.7	0	-€ 2,000.0	-€ 905	€ 0.0	-€ 2,905	-€ 2,720.6	-€ 566.9
6	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,125.7	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 836.5	€ 1,289.1
7	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,098.0	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 825.6	€ 1,272.4
8	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,070.6	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 814.9	€ 1,255.8
9	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,043.7	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 804.3	€ 1,239.4
10	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 2,017.0	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 793.8	€ 1,223.3
11	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 1,990.8	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 783.4	€ 1,207.3
12	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 1,964.8	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 773.2	€ 1,191.6
13	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 1,939.2	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 763.2	€ 1,176.1
14	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 0.0	€ 2,299.7	€ 1,914.0	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 753.2	€ 1,160.8
15	1.32%	35,109.6	€ 0.0655	€ 2,299.7	€ 0.0	€ 100.6	€ 2,400.3	€ 1,971.7	0	€ 0.0	-€ 905	€ 0.0	-€ 905	-€ 743.4	€ 1,228.3
						Total Benefits		€ 31,192.2				Total Costs		-€ 5,065.7	
														NPV=	€ 26,126.5
														B/C=	6.15

Table E-30: LCC assessment for ESP 6-2

ESP 6-2: ESP by using premium efficiency electric motor - 0% yearly increase in energy unit cost															
t	Discounted interest rate i	**Benefits**							**Cost**						**Discounted Benefits Costs Difference (€)**
		Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Maintena. Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	
0	1.32%							€ 0.0	-€ 1,890.0				-€ 1,890	-€ 1,890.0	-€ 1,890.0
1	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 248.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 248.5
2	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 245.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 245.2
3	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 242.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 242.0
4	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 238.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 238.9
5	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 1,512.0	€ 0.0	€ 1,763.7	€ 1,651.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,651.8
6	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 232.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 232.7
7	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 229.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 229.7
8	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 226.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 226.7
9	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 223.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 223.7
10	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 220.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 220.8
11	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 217.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 217.9
12	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 215.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 215.1
13	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 212.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 212.3
14	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 0.0	€ 251.7	€ 209.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 209.5
15	1.32%	3,843.3	€ 0.0655	€ 251.7	€ 0.0	€ 170.1	€ 421.8	€ 346.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 346.5
						Total Benefits		€ 4,961.2				Total Costs		-€ 1,890.0	
														NPV=	€ 3,071.2
														B/C=	2.62

Table E- 31: LCC assessment for ESP 6-4

ESP 6-4: ESP by a Multiple Compressor System (Scenario 2) - 0% yearly increase in energy unit cost															
t	Discounted interest rate i	**Benefits**							**Cost**						**Discounted Benefits Costs Difference (€)**
		Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	
0	1.32%	74,015.0						€ 0.00	€ 8,000.00				€ 8,000.00	€ 8,000.00	€ 8,000.00
1	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,787.74	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 789.58	€ 3,998.17
2	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,725.37	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 779.29	€ 3,946.08
3	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,663.81	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 769.14	€ 3,894.67
4	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,603.05	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 759.12	€ 3,843.93
5	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,543.08	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 749.23	€ 3,793.85
6	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,483.89	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 739.47	€ 3,744.42
7	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,425.48	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 729.83	€ 3,695.64
8	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,367.82	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 720.33	€ 3,647.49
9	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,310.92	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 710.94	€ 3,599.98
10	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,254.75	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 701.68	€ 3,553.07
11	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,199.32	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 692.54	€ 3,506.79
12	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,144.61	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 683.51	€ 3,461.10
13	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,090.62	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 674.61	€ 3,416.01
14	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 0.00	€ 4,850.94	€ 4,037.32	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 665.82	€ 3,371.50
15	1.32%	74,015.0	€ 0.07	€ 4,850.94	€ 0.00	€ 80.00	€ 4,930.94	€ 4,050.44	€ 0.00	€ 0.00	€ 800.00	€ 0.00	€ 800.00	€ 657.15	€ 3,393.29
						Total Benefits		€ 65,688.22				Total Costs		€ 18,822.23	
														NPV=	€ 46,866.00
														B/C=	3.490

Table E-32: LCC assessment for ESP 6-9

ESP 6-9: ESP by fixing air leaks: 0% yearly increase in energy unit cost scenario															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	Discounted Benefits Costs Difference (€)
0	1.32%							€ 0.0	-€ 100.0				-€ 100	-€ 100.0	-€ 100.0
1	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 281.9	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 98.7	€ 183.2
2	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 278.3	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 97.4	€ 180.8
3	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 274.6	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 96.1	€ 178.5
4	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 271.0	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 94.9	€ 176.2
5	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 267.5	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 93.7	€ 173.9
6	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 264.0	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 92.4	€ 171.6
7	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 260.6	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 91.2	€ 169.4
8	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 257.2	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 90.0	€ 167.2
9	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 253.8	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 88.9	€ 165.0
10	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 250.5	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 87.7	€ 162.8
11	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 247.3	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 86.6	€ 160.7
12	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 244.1	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 85.4	€ 158.6
13	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 240.9	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 84.3	€ 156.5
14	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 237.7	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 83.2	€ 154.5
15	1.32%	4,361.0	€ 0.0655	€ 285.6	€ 0.0	€ 0.0	€ 285.6	€ 234.6	-€ 100.0	€ 0.0	€ 0	€ 0.0	-€ 100	-€ 82.1	€ 152.5
						Total Benefits		€ 3,864.2				Total Costs		-€ 1,452.8	
														NPV=	€ 2,411.4
														B/C=	1.66

Table E-33: LCC assessment for ESP 6-10

ESP 6-10: ESP by using VFD for the cooling tower air fan Cooling Tower 1 - 0% yearly increase in energy unit cost

		Benefits							Cost						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%						€ 0.00	€ 0.0	-€ 6,150.0				-€ 6,150	-€ 6,150.0	-€ 6,150.0
1	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 2,035.0	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 508.3	€ 1,526.7
2	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 2,008.5	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 501.7	€ 1,506.8
3	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,982.3	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 495.1	€ 1,487.2
4	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,956.5	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 488.7	€ 1,467.8
5	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,931.0	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 482.3	€ 1,448.7
6	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,905.8	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 476.0	€ 1,429.8
7	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,881.0	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 469.8	€ 1,411.2
8	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,856.5	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 463.7	€ 1,392.8
9	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,832.3	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 457.7	€ 1,374.6
10	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,808.4	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 451.7	€ 1,356.7
11	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,784.9	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 445.8	€ 1,339.1
12	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,761.6	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 440.0	€ 1,321.6
13	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,738.7	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 434.3	€ 1,304.4
14	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 0.0	€ 2,061.8	€ 1,716.0	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 428.6	€ 1,287.4
15	1.32%	31,478.5	€ 0.0655	€ 2,061.8	€ 0.0	€ 51.5	€ 2,113.3	€ 1,736.0	0	€ 0.0	-€ 515	€ 0.0	-€ 515	-€ 423.0	€ 1,312.9
						Total Benefits		€ 27,934.5				Total Costs		-€ 13,116.8	
														NPV=	€ 14,817.6
														B/C=	2.13

Table E-34: LCC assessment for ESP 6-12

ESP 6-12: ESP by replacing Pump 1 with an efficient pump and premium efficiency electric motor Cooling Tower 1 - 0% yearly increase in energy unit cost															
		Benefits							Cost						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					€ 113.20	€ 113.20	€ 113.2	-€ 2,266.0				-€ 2,266	-€ 2,266.0	-€ 2,152.8
1	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,488.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,488.7
2	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,417.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,417.2
3	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,346.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,346.7
4	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,277.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,277.0
5	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 2,264.0	€ 0.0	€ 7,825.2	€ 7,328.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 7,328.6
6	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,140.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,140.4
7	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,073.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,073.4
8	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 5,007.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 5,007.3
9	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 4,942.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,942.1
10	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 4,877.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,877.7
11	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 4,814.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,814.2
12	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 4,751.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,751.4
13	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 4,689.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,689.5
14	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 0.0	€ 5,561.2	€ 4,628.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,628.4
15	1.32%	84,903.7	€ 0.0655	€ 5,561.2	€ 0.0	€ 113.3	€ 5,674.5	€ 4,661.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,661.2
						Total Benefits		€ 77,557.2				Total Costs		-€ 2,266.0	
														NPV=	€ 75,291.2
														B/C=	34.22

Table E-35: LCC assessment for ESP 6-*11*

ESP 6-12: ESP by replacing Pump 1 with an efficient pump and premium efficiency electric motor Cooling Tower 1 - 0% yearly increase in energy unit cost

		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					€ 135.36	€ 135.36	€ 135.4	-€ 2,018.0				-€ 2,018	-€ 2,018.0	-€ 1,882.6
1	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,242.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,242.7
2	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,213.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,213.5
3	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,184.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,184.7
4	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,156.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,156.2
5	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 2,705.0	€ 0.0	€ 4,977.3	€ 4,661.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 4,661.4
6	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,100.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,100.4
7	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,073.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,073.0
8	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,046.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,046.0
9	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 2,019.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,019.4
10	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 1,993.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,993.1
11	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 1,967.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,967.1
12	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 1,941.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,941.5
13	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 1,916.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,916.2
14	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 0.0	€ 2,272.3	€ 1,891.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,891.2
15	1.32%	34,692.0	€ 0.0655	€ 2,272.3	€ 0.0	€ 101.0	€ 2,373.3	€ 1,949.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,949.5
						Total Benefits		€ 33,491.2				Total Costs		-€ 2,018.0	
														NPV=	€ 31,473.2
														B/C=	16.59

Table E-36: LCC assessment for ESP 6-13

ESP 6-13: ESP by replacing the existing electric motor of Pump 1 with a premium efficient electric motor in Cooling Tower2 0% yearly increase in energy unit cost															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					€ 65.00	€ 65.00	€ 65.0	-€ 1,615.0				-€ 1,615	-€ 1,615.0	-€ 1,550.0
1	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 77.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 77.3
2	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 76.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 76.3
3	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 75.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 75.3
4	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 74.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 74.4
5	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 1,292.0	€ 0.0	€ 1,370.4	€ 1,283.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 1,283.4
6	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 72.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 72.4
7	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 71.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 71.5
8	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 70.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 70.6
9	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 69.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 69.6
10	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 68.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 68.7
11	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 67.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 67.8
12	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 67.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 67.0
13	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 66.1	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 66.1
14	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 0.0	€ 78.4	€ 65.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 65.2
15	1.32%	1,196.4	€ 0.0655	€ 78.4	€ 0.0	€ 80.8	€ 159.1	€ 130.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 130.7
						Total Benefits		€ 2,401.4				Total Costs		-€ 1,615.0	
														NPV=	€ 786.4
														B/C=	1.48

Table E-37: LCC assessment for ESP 6-14

ESP 6-14: ESP by replacing Pump 2 with an efficient and right size pump and electric motor in Cooling Tower 2

t	Discounted interest rate i	Benefits							Cost						**Discounted Benefits Costs Difference (€)**
		Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	
0	1.32%					€ 82.70	€ 82.70	€ 82.7	-€ 1,263.0				-€ 1,263	-€ 1,263.0	-€ 1,180.3
1	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 633.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 633.9
2	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 625.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 625.7
3	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 617.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 617.5
4	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 609.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 609.5
5	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 1,657.0	€ 0.0	€ 2,299.29	€ 2,153.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 2,153.4
6	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 593.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 593.7
7	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 586.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 586.0
8	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 578.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 578.3
9	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 570.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 570.8
10	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 563.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 563.4
11	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 556.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 556.0
12	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 548.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 548.8
13	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 541.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 541.6
14	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 0.0	€ 642.29	€ 534.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 534.6
15	1.32%	9,806.0	€ 0.0655	€ 642.3	€ 0.0	€ 74.4	€ 716.69	€ 588.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 588.7
						Total Benefits		€ 10,384.5				Total Costs		-€ 1,263.0	
														NPV=	€ 9,121.5
														B/C=	8.19

Table E-38: LCC assessment for ESP 6-15

ESP 6-15: ESP by using Hybrid Daylighting System: 0% yearly increase in energy unit cost															
		Benefits							**Cost**						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) IPC	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%						€ 0.00	€ 0.0	-€ 8,700.6				-€ 8,701	-€ 8,700.6	-€ 8,700.6
1	1.32%	40,974.8	€ 0.0655	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,650.5	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 429.3	€ 2,221.2
2	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,616.0	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 423.7	€ 2,192.2
3	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 3,062.4	€ 0.0	€ 5,747.89	€ 5,526.2	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 418.2	€ 5,107.9
4	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,548.3	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 412.8	€ 2,135.5
5	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,515.1	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 407.4	€ 2,107.7
6	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 3,062.4	€ 0.0	€ 5,747.89	€ 5,313.0	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 402.1	€ 4,910.9
7	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,449.9	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 396.8	€ 2,053.1
8	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,418.0	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 391.7	€ 2,026.4
9	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 3,062.4	€ 0.0	€ 5,747.89	€ 5,108.0	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 386.6	€ 4,721.4
10	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,355.4	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 381.5	€ 1,973.9
11	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,324.8	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 376.6	€ 1,948.2
12	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 3,062.4	€ 0.0	€ 5,747.89	€ 4,911.0	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 371.7	€ 4,539.3
13	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,264.6	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 366.8	€ 1,897.8
14	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 0.0	€ 0.0	€ 2,685.49	€ 2,235.1	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 362.0	€ 1,873.0
15	1.32%	40,974.8	€ 0.06554	€ 2,685.5	€ 3,062.4	€ 352.5	€ 6,100.39	€ 5,011.1	0	€ 0.0	-€ 435	€ 0.0	-€ 435	-€ 357.3	€ 4,653.7
						Total Benefits		€ 50,246.7				Total Costs		-€ 14,585.2	
														NPV=	€ 35,661.5
														B/C=	3.44

Table E-39: LCC assessment for ESP 6-16

ESP 6-16: ESP by using LED tubes - 0% yearly increase in energy unit cost

		Benefits							Cost						
t	Discounted interest rate i	Annual ESP (kWh)	Energy Unit Cost (€/kWh)	Annual ECSP (€)	Avoided Costs (€)	Salvage Income (€)	Total Benefits (€)	Discounted Total Benefits (€)	Initial Invest. Cost (€) I	Replacement Cost (€) R	Yearly Operation Costs (€), O	Other Costs if any (€)	Total Yearly Costs (€)	Discounted Total Yearly Costs (€)	**Discounted Benefits Costs Difference (€)**
0	1.32%					€ 0.00	€ 0.00	€ 0.0	-€ 1,364.0				-€ 1,364	-€ 1,364.0	-€ 1,364.0
1	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 176.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 176.2
2	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 173.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 173.9
3	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 498.3	€ 0.0	€ 676.84	€ 650.7	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 650.7
4	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 169.4	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 169.4
5	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 167.2	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 167.2
6	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 498.3	€ 0.0	€ 676.84	€ 625.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 625.6
7	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 162.9	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 162.9
8	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 160.8	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 160.8
9	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 498.3	€ 0.0	€ 676.84	€ 601.5	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 601.5
10	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 156.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 156.6
11	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 154.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 154.6
12	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 498.3	€ 0.0	€ 676.84	€ 578.3	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 578.3
13	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 150.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 150.6
14	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 0.0	€ 0.0	€ 178.54	€ 148.6	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 148.6
15	1.32%	2,725.8	€ 0.0655	€ 178.5	€ 498.3	€ 0.0	€ 676.84	€ 556.0	0	€ 0.0	€ 0	€ 0.0	€ 0	€ 0.0	€ 556.0
						Total Benefits		€ 4,632.8				Total Costs		-€ 1,364.0	
														NPV=	€ 3,268.8
														B/C=	3.39

Appendix F

Energy Consuming Systems Power Demands for Microgrid Modelling

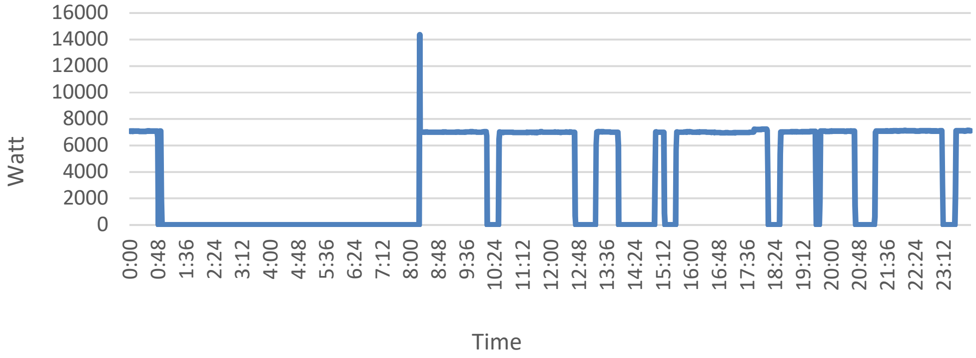


Figure F-1: Cooling Tower Pump Power Demand for a Typical Production Day

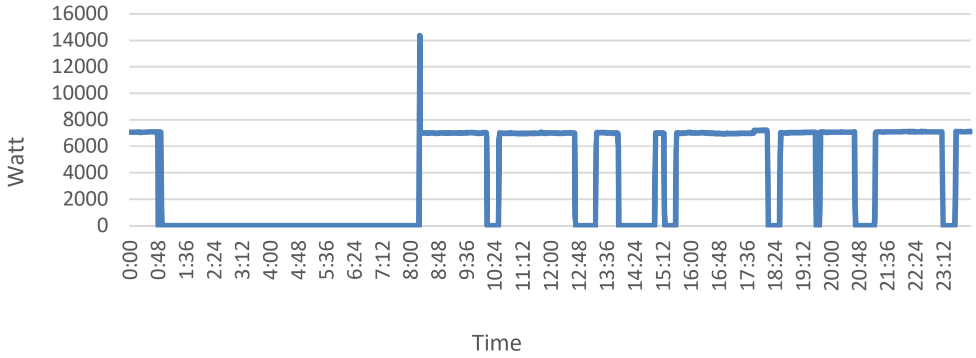


Figure F-2: Cooling Tower Pump Power Demand for a Typical Production Day

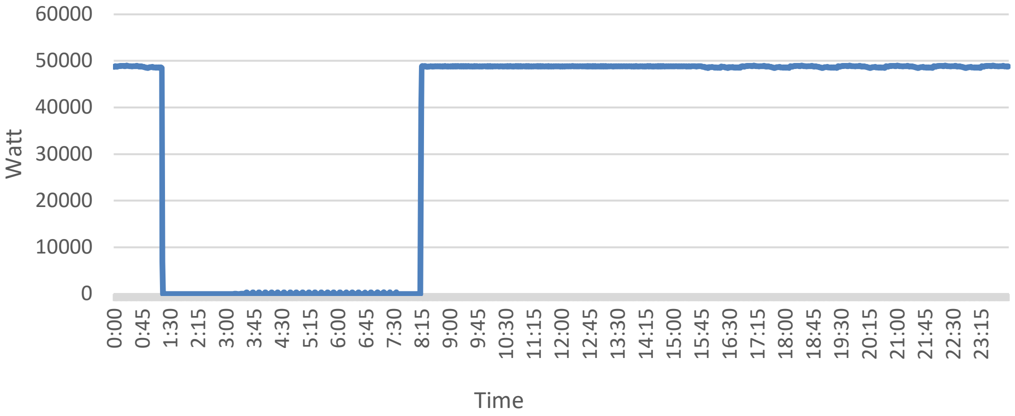


Figure F-3: Ventilation Fan Power Demand for a Typical Production Day

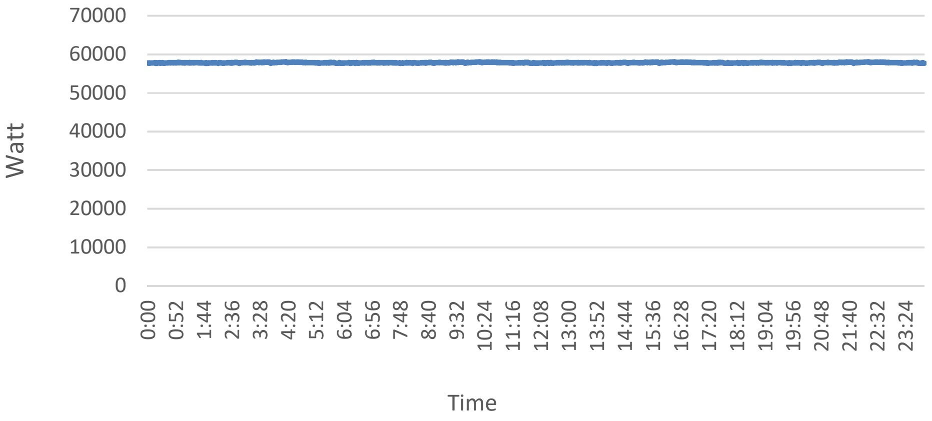


Figure F-4: Cooling Tower Power Demand for a Typical Production Day

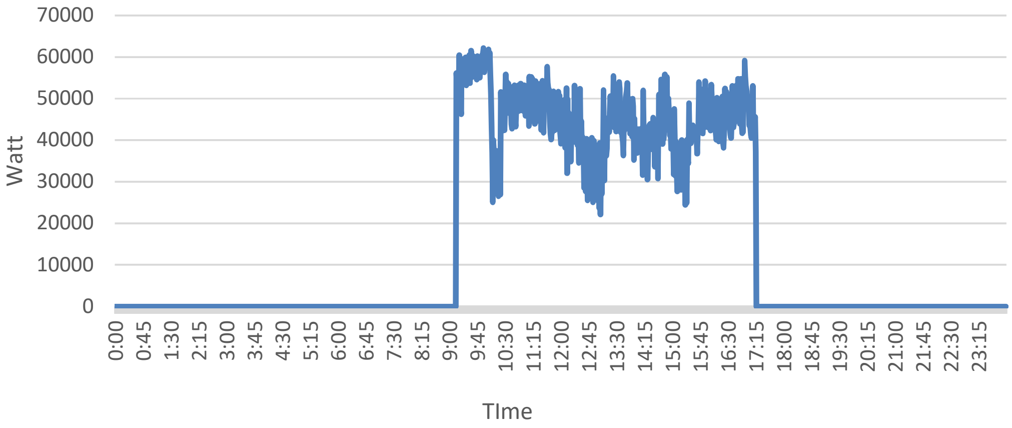


Figure F-5: Air Compressor 1 Power Demand for a Typical Production Day

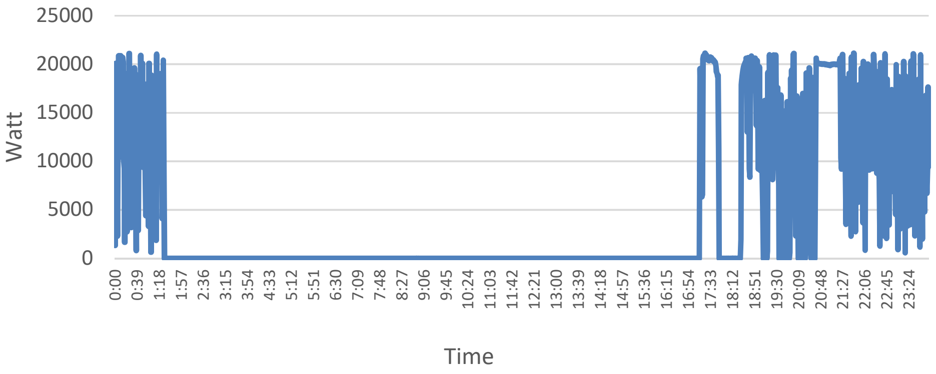


Figure F-6: Air Compressor 2 Power Demand for a Typical Production Day

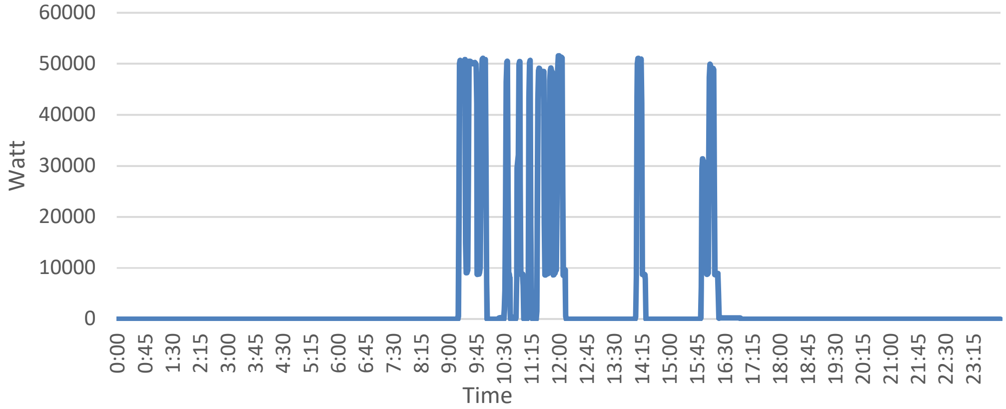


Figure F-7: Shot Blasting System Power Demand for a Typical Production Day

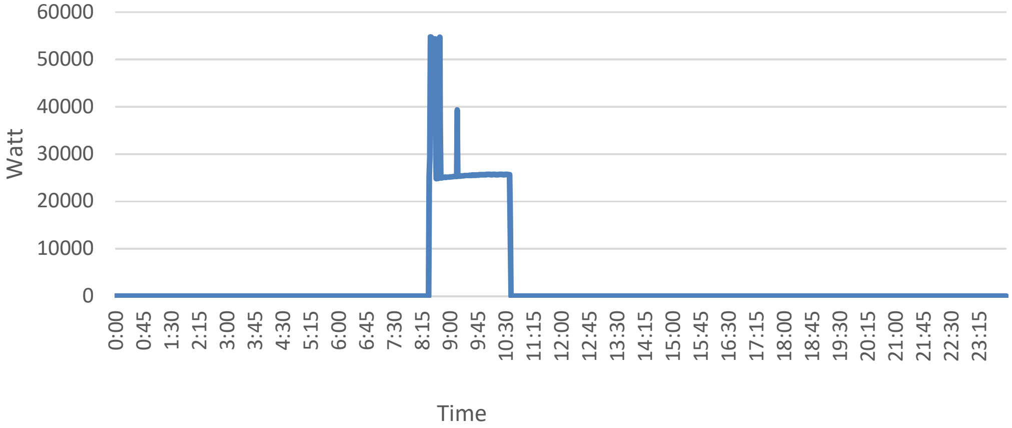


Figure F-8 Quenching Pool Pump and Agitator Power Demand for a Typical Production Day

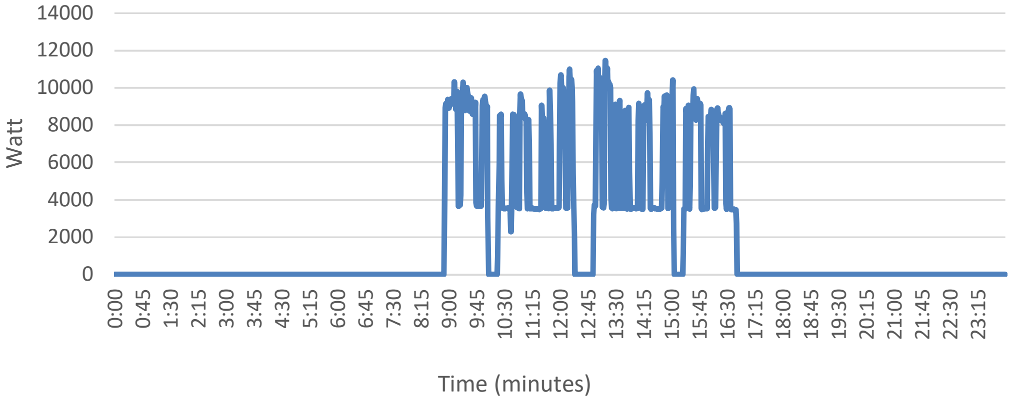


Figure F-9: Grinding Systems Power Demand for a Typical Production Day

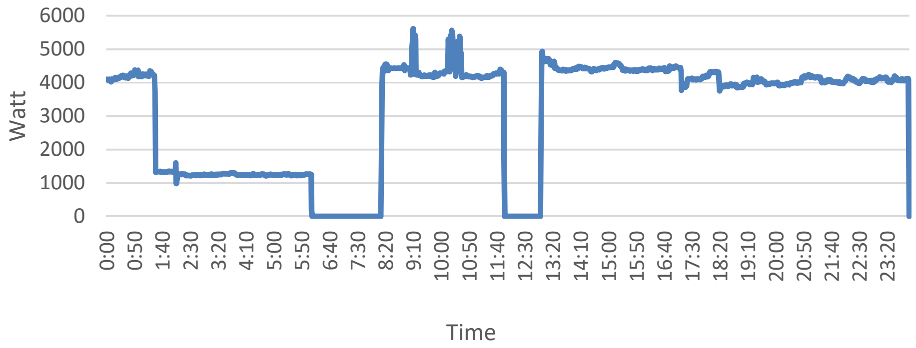


Figure F-10: : Foundry Floor 1 and Floor 2 Lighting System Power Demand for a Typical Production Day

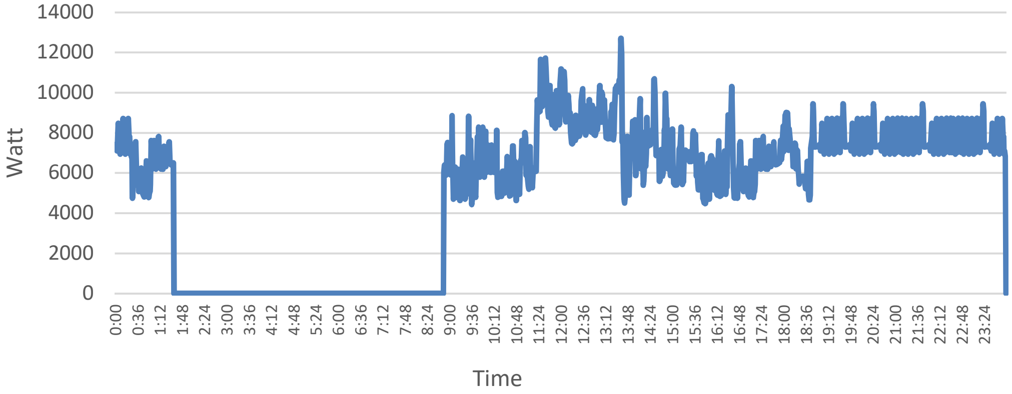


Figure F-11: Machine Shop Lighting System Power Demand for a Typical Production Day

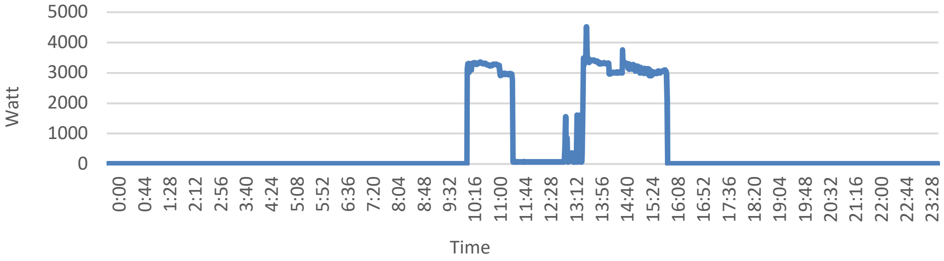


Figure F-12: Lathe Preheating Fans Power Demand for a Typical Production Day

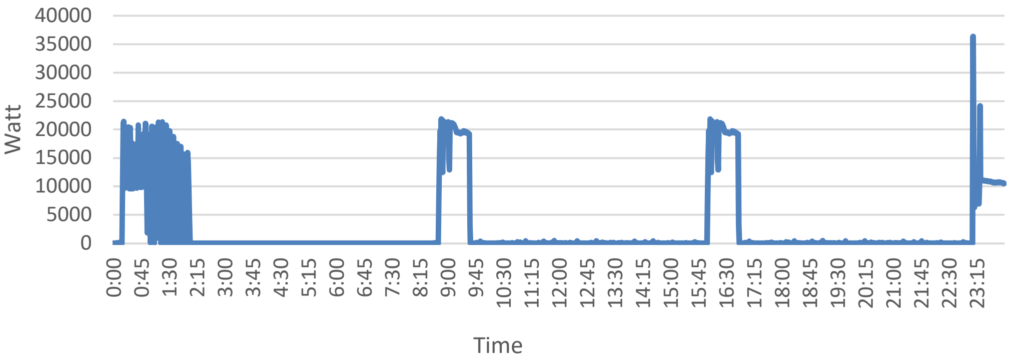


Figure F-13: Sand Mixing System 1 Power Demand for a Typical Production Day

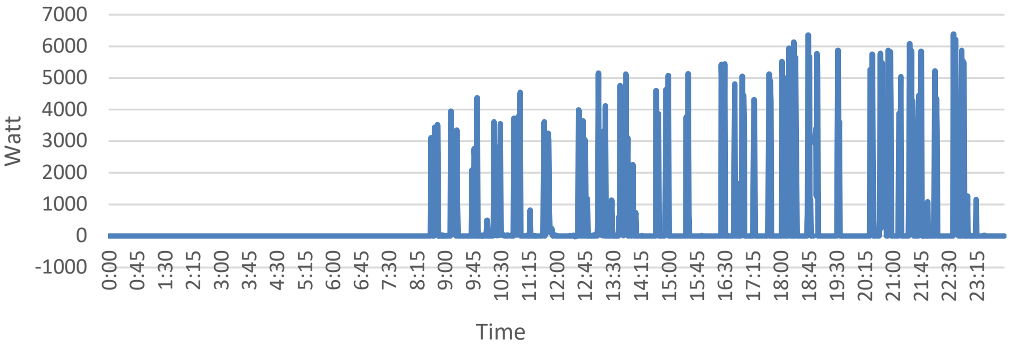


Figure F-14: Sand Mixing System 2 Power Demand for a Typical Production Day

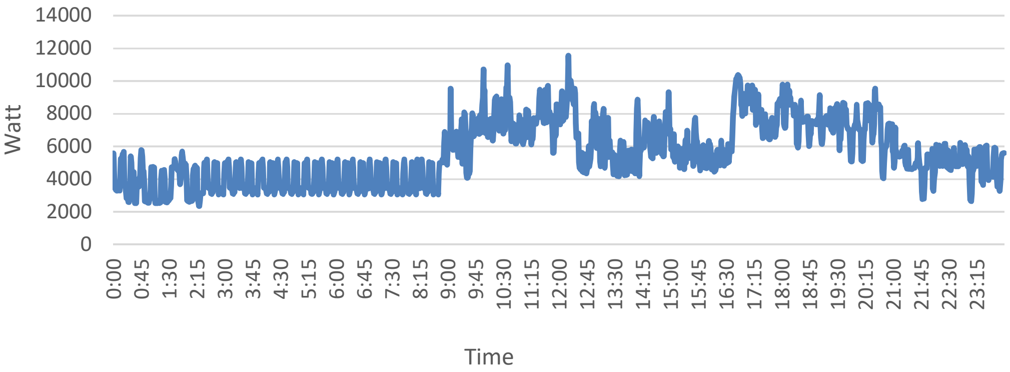


Figure F-15: Offices Power Demand for a Typical Production Day

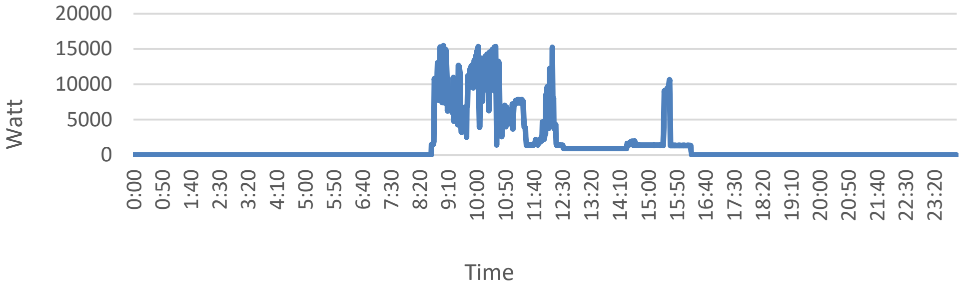


Figure F-16: CNC Lathe 1 for a Typical Production Day

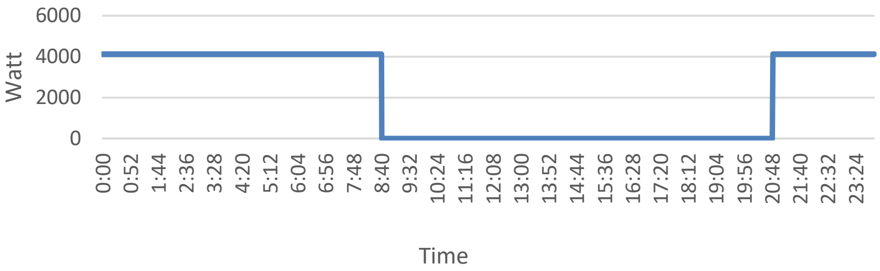
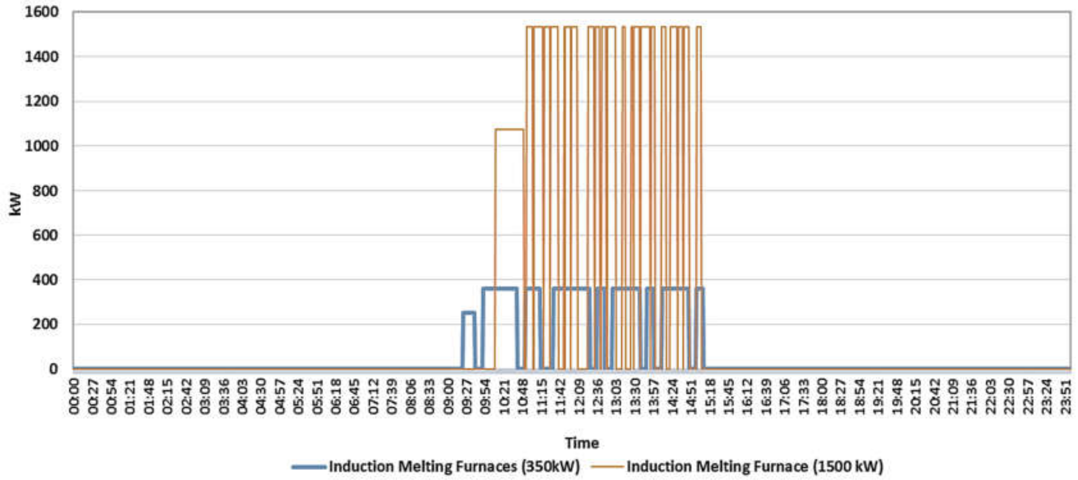


Figure F-17: Normalisation Furnace Fan Power Demand for a Typical Production Day



Figur F-18: Induction furnaces power demand over a 24 hours period

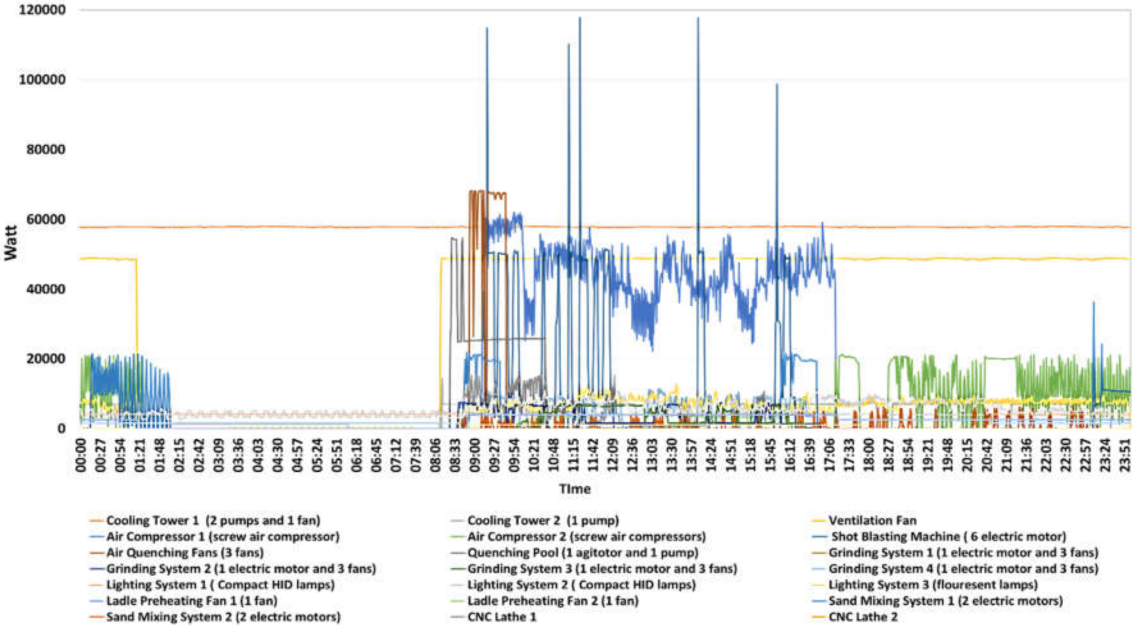


Figure F-19: Power demands of each energy using systems over a 24 hours period

Appendix G

Photos of Some Energy Consuming Systems in the Plant

Figure G-1: Compressor 1 and power measurement of it in the subject plant

Figure G-2: Compressor 2 in the subject plant

Figure G-3: Compressed air storage tank in the subject plant

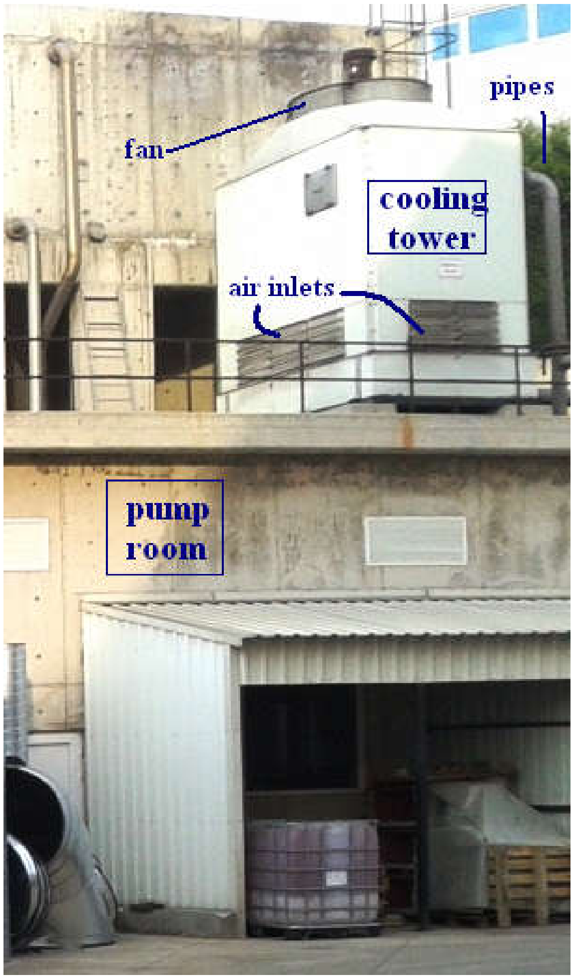


Figure G-4: Cooling Tower of the Induction Furnaces in the subject plant

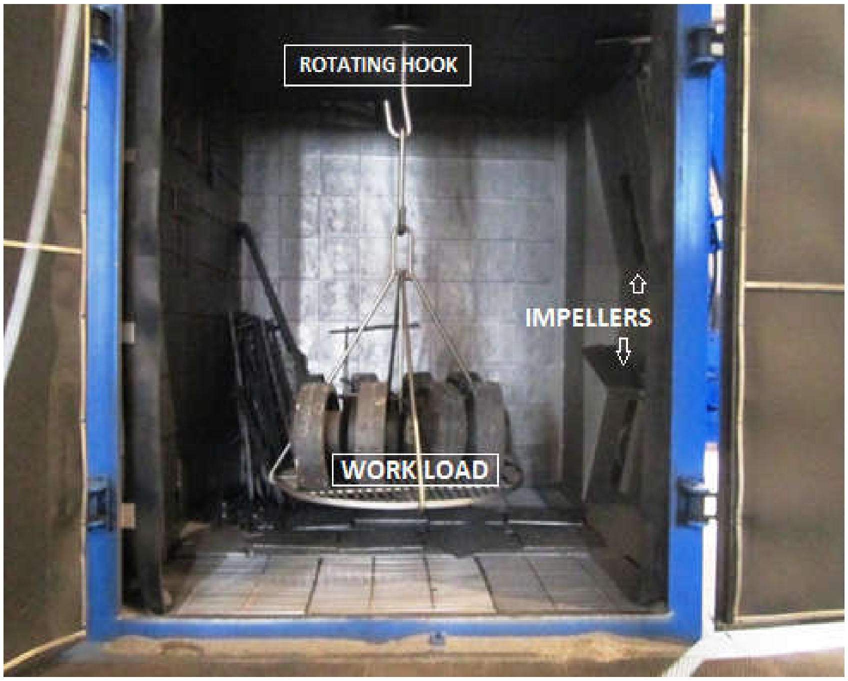


Figure G-5: Abrasive Blasting Machine in the subject plant

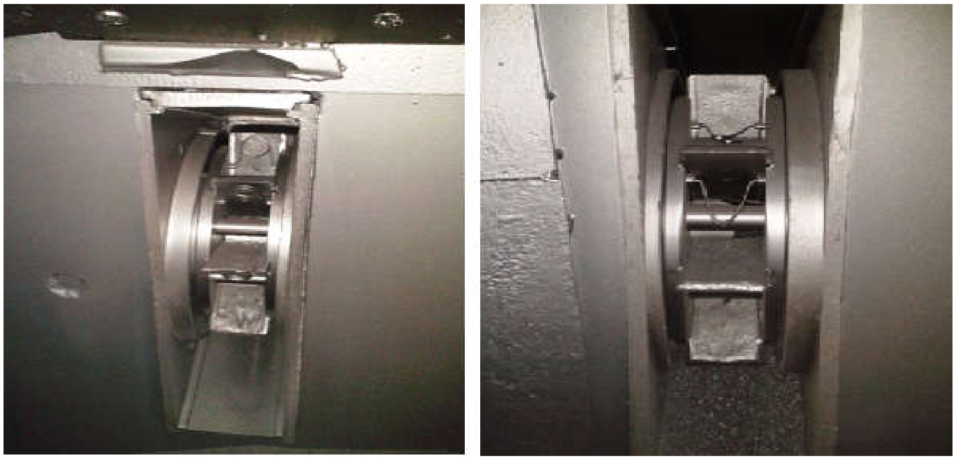


Figure G-6: Blast impellers of the abrasive blasting machine in the subject plant

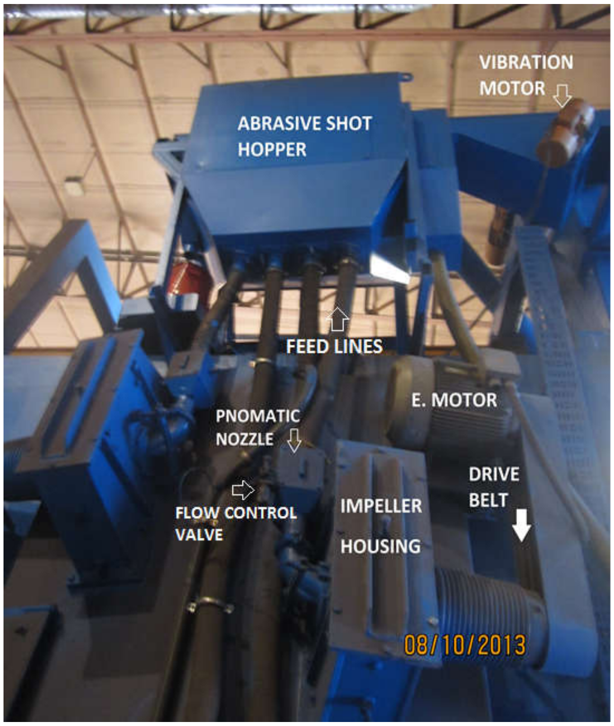


Figure G-7: Various components of the abrasive blasting system

Figure G-8: Dust collection unit of the abrasive basting system