TECHNISCHE UNIVERSITÄT DRESDEN

Developing a Decision Making Approach for District Cooling Systems Design using Multi-objective Optimization

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﴿يَا أَيُّهَا النَّاسُ إِنَّا خَلَقْنَاكُمْ مِنْ ذَكَرٍ وَأُنْثَى وَجَعَلْنَاكُمْ شُعُوباً وَقَبَائِلَ لِتَعَارَفُوا إِنَّ أَكْرَمَكُمْ عِنْدَ اللَّهِ أَتْقَاكُمْ إِنَّ اللَّهَ عَلِيمٌ خَبِيرٌ﴾

سورة الحجرات – الآية 13

"O people, we created you all out of a male and a female, and have made you into nations and tribes, so that you might come to know one another. Verily, the noblest of you in the sight of God is the one who is most deeply conscious of Him. Behold, God is all-knowing, all-aware"

Quran 49:13

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Dedication

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To my parents; my kind-hearted, understanding, sacrificing mother and my supporting, encouraging father.

To my loving brothers and beloved sister…

To my most precious in this life, my friends…

Abstract

Energy consumption rates have been dramatically increasing on a global scale within the last few decades. A significant role in this increase is subjected by the recent high temperature levels especially at summer time which caused a rapid increase in the air conditioning demands. Such phenomena can be clearly observed in developing countries, especially those in hot climate regions, where people depend mainly on conventional air conditioning systems. These systems often show poor performance and thus negatively impact the environment which in turn contributes to global warming phenomena. In recent years, the demand for urban or district cooling technologies and networks has been increasing significantly as an alternative to conventional systems due to their higher efficiency and improved ecological impact. However, to obtain an efficient design for district cooling systems is a complex task that requires considering a wide range of cooling technologies, various network layout configuration possibilities, and several energy resources to be integrated. Thus, critical decisions have to be made regarding a variety of opportunities, options and technologies.

The main objective of this thesis is to develop a tool to obtain preliminary design configurations and operation patterns for district cooling energy systems by performing roughly detailed optimizations and further, to introduce a decision-making approach to help decision makers in evaluating the economic aspects and environmental performance of urban cooling systems at an early design stage.

Different aspects of the subject have been investigated in the literature by several researchers. A brief survey of the state of the art was carried out and revealed that mathematical programming models were the most common and successful technique for configuring and designing cooling systems for urban areas. As an outcome of the survey, multi objective optimization models were decided to be utilized to support the decision-making process. Hence, a multi objective optimization model has been developed to address the complicated issue of decision-making when designing a cooling system for an urban area or district. The model aims to optimize several elements of a cooling system such as: cooling network, cooling technologies, capacity and location of system equipment. In addition, various energy resources have been taken into consideration as well as different solar technologies such as: trough solar concentrators, vacuum solar collectors and PV panels. The model was developed based on the mixed integer linear programming method (MILP) and implemented using GAMS language.

Two case studies were investigated using the developed model. The first case study consists of seven buildings representing a residential district while the second case study was a university campus district dominated by non-residential buildings. The study was carried out for several groups of scenarios investigating certain design parameters and operation conditions such as: Available area, production plant location, cold storage location constraints, piping prices, investment cost, constant and variable electricity tariffs, solar energy integration policy, waste heat availability, load shifting strategies, and the effect of outdoor temperature in hot regions on the district cooling system performance. The investigation consisted of three stages, with total annual cost and CO_2 emissions being the first and second single objective optimization stages. The third stage was a multi objective optimization combining the earlier two single objectives. Later on, non-dominated solutions, i.e. Pareto solutions, were generated by obtaining several multi objective optimization scenarios based on the decision-makers' preferences. Eventually, a decision-making approach was developed to help decision-makers in selecting a specific solution that best fits the designers' or decision makers' desires, based on the difference between the Utopia and Nadir values, i.e. total annual cost and CO_2 emissions obtained at the single optimization stages.

Zusammenfassung

Die Energieverbrauchsraten haben in den letzten Jahrzehnten auf globaler Ebene dramatisch zugenommen. Diese Erhöhung ist zu einem großen Teil in den jüngst hohen Temperaturniveaus, vor allem in der Sommerzeit, begründet, die einen starken Anstieg der Nachfrage nach Klimaanlagen verursachen. Solche Ereignisse sind deutlich in Entwicklungsländern zu beobachten, vor allem in heißen Klimaregionen, wo Menschen vor allem konventionelle Klimaanlagensysteme benutzen. Diese Systeme verfügen meist über eine ineffiziente Leistungsfähigkeit und wirken sich somit negativ auf die Umwelt aus, was wiederum zur globalen Erwärmung beiträgt. In den letzten Jahren ist die Nachfrage nach Stadt- oder Fernkältetechnologien und -Netzwerken als Alternative zu konventionellen Systemen aufgrund ihrer höheren Effizienz und besseren ökologischen Verträglichkeit satrk gestiegen. Ein effizientes Design für Fernkühlsysteme zu erhalten, ist allerdings eine komplexe Aufgabe, die die Integration einer breite Palette von Kühltechnologien, verschiedener Konfigurationsmöglichkeiten von Netzwerk-Layouts und unterschiedlicher Energiequellen erfordert. Hierfür ist das Treffen kritischer Entscheidungen hinsichtlich einer Vielzahl von Möglichkeiten, Optionen und Technologien unabdingbar.

Das Hauptziel dieser Arbeit ist es, ein Werkzeug zu entwickeln, das vorläufige Design-Konfigurationen und Betriebsmuster für Fernkälteenergiesysteme liefert, indem aureichend detaillierte Optimierungen durchgeführt werden. Zudem soll auch ein Ansatz zur Entscheidungsfindung vorgestellt werden, der Entscheidungsträger in einem frühen Planungsstadium bei der Bewertung städtischer Kühlungssysteme hinsichtlich der wirtschaftlichen Aspekte und Umweltleistung unterstützen soll.

Unterschiedliche Aspekte dieser Problemstellung wurden in der Literatur von verschiedenen Forschern untersucht. Eine kurze Analyse des derzeitigen Stands der Technik ergab, dass mathematische Programmiermodelle die am weitesten verbreitete und erfolgreichste Methode für die Konfiguration und Gestaltung von Kühlsystemen für städtische Gebiete sind. Ein weiteres Ergebnis der Analyse war die Festlegung von Mehrzieloptimierungs-Modelles für die Unterstützung des Entscheidungsprozesses. Darauf basierend wurde im Rahmen der vorliegenden Arbeit ein Mehrzieloptimierungs-Modell für die Lösung des komplexen Entscheidungsfindungsprozesses bei der Gestaltung eines Kühlsystems für ein Stadtgebiet oder einen Bezirk entwickelt. Das Modell zielt darauf ab, mehrere Elemente des Kühlsystems zu optimieren, wie beispielsweise Kühlnetzwerke, Kühltechnologien sowie Kapazität und Lage der Systemtechnik. Zusätzlich werden verschiedene Energiequellen, auch solare wie Solarkonzentratoren, Vakuum-Solarkollektoren und PV-Module, berücksichtigt. Das Modell wurde auf Basis der gemischt-ganzzahlig linearen Optimierung (MILP) entwickelt und in GAMS Sprache implementiert.

Zwei Fallstudien wurden mit dem entwickelten Modell untersucht. Die erste Fallstudie besteht aus sieben Gebäuden, die ein Wohnviertel darstellen, während die zweite Fallstudie einen Universitätscampus dominiert von Nichtwohngebäuden repräsentiert. Die Untersuchung wurde für mehrere Gruppen von Szenarien durchgeführt, wobei bestimmte Designparameter und Betriebsbedingungen überprüft werden, wie zum Beispiel die zur Verfügung stehende Fläche, Lage der Kühlanlage, örtliche Restriktionen der Kältespeicherung, Rohrpreise, Investitionskosten, konstante und variable Stromtarife, Strategie zur Einbindung der Solarenergie, Verfügbarkeit von Abwärme, Strategien der Lastenverschiebung, und die Wirkung der Außentemperatur in heißen Regionen auf die Leistung des Kühlsystems. Die Untersuchung bestand aus drei Stufen, wobei die jährlichen Gesamtkosten und die CO_2-Emissionen die erste und zweite Einzelzieloptimierungsstufe darstellen. Die dritte Stufe war ein Pareto-Optimierung, die die beiden ersten Ziele kombiniert. Im Anschluss wurden nicht-dominante Lösungen, also Pareto-Lösungen, erzeugt, indem mehrere Pareto-Optimierungs-Szenarien basierend auf den Präferenzen der Entscheidungsträger abgebildet wurden. Schließlich wurde ein Ansatz zur Entscheidungsfindung entwickelt, um Entscheidungsträger bei der Auswahl einer bestimmten Lösung zu unterstützen, die am besten den Präferenzen des Planers oder des Entscheidungsträgers enstpricht, basierend auf der Differenz der Utopia und Nadir Werte, d.h. der jährlichen Gesamtkosten und CO_2-Emissionen, die Ergebnis der einzelnen Optimierungsstufen sind.

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Nomenclature

Z	Objective function	
W	Normalization factors	
U	Importance weights assigned by decision makers	
C	Cost	€ / yr
PC	Plant cost	€ / yr
NC	Network cost	€ / yr
EC	Electricity cost	€ / yr
FC	Fuel cost	€ / yr
Co2E	CO2 emissions due to electricity consumption	Ton / yr
Co2F	CO2 emissions due to fuel consumption	Ton / yr
Co2Equ	CO2 emissions due to installing certain system equipment	Ton / yr
Co2Net	CO2 emissions due to installing certain system pipeline	Ton / yr
O2	Co2 conversion factor	g / kWh_{el}
PrmE	Primary energy consumption due to electricity consumption	kWh_{pr} / yr
PrmF	Primary energy consumption due to fuel consumption	kWh_{pr} / yr
PrmEqu	Primary energy consumption due to installing certain system equipment	kWh_{pr} / yr
PemNet	Primary energy consumption due to installing certain system pipeline	kWh_{pr} / yr
pr	Primary energy conversion factor	kWh_{pr}/kWh_{el}
Q	Cooling energy flow rate among units	kW
CAP	Nominal unit capacity of equipment	kW
FLpip	Cooling energy flow rate among nodes via pipelines	kWh / h
NFLpip	Nominal energy flow rate through pipeline	kW
H	The amount of cooling energy stored at certain time step	kwh
E	Electrical energy	kWh_{el}
Ep	Electrical energy purchased to operate the compression chiller	kWh_{el}/h
Epv	Electricity produced by PV panels and consumed locally	kWh_{el}
Ce	Electricity purchase cost	€/kWh_{el}
Cpv	Price of selling surplus PV panel electricity	€/kWh_{el}
Gfl	Fuel consumption rate at the boiler	N m^3/h
Cf	Cost of purchased fuel	€/N m^3
HVg	Low heating value of fuel	kWh/N m^3

LCD	Local Cooling Demand	kW
SRad	Solar radiation on a horizontal surface	kW/m^2
η	efficiency	
COP	Coefficient of performance of chillers	
f	Annuity Factor	
n	Unit Life Time	yr
r	Investment Factor / Opportunity Cost Factor	
t	Duration of time step	hour
y	Binary variable defines the existence of a unit	
CCv	Capacity related investment cost	€ / kW
CCf	Fixed investment cost related to the existence of a unit	€
OC	Operation and maintenance cost	€ / kWh
L	Length or arc connecting two nodes	m
A	Area	m^2
GA	ground	
M	Large arbitrary number or max. commercial limit for unit	
µ	Small arbitrary number or min. commercial limit for unit	
mCn	Annual Maintanance cost factor for the DC network pipes	
pf	Power factor for approximating power demand at the DC pumping stations in relative to the energy (cooling & heating) transferred throughout the pipes [	$kWh_{el}/(kW_{th}.m)$
Rdis	Ratio of consumed electricity to dissipated heat at the heat dissipater	kWh_{el}/kW_{th}
ar	conversion factor that relates the capacity of equipment to the required area for it to be installed at a certain site	kW/m^2

Indices

i. j, k	Nodes
(i,j)	Arc between nodes
t	time

Subscribts

C	cost
inv	Investment cost
opr	Operational cost

CO_2	Carbone Dioxide emissions
Pr	Primary energy
N	Nadir value for the objective function
U	Utopia value for the objective function
in	Energy entering equipment
o	Energy leaving equipment
D	Dissipated heat
p	plant
net	DC network
equ	equpment
pip	pipeline
comp	Compression chiller
abs	Absorption chiller
str1	Cold storage tank
str2	Hot storage tank
ex1	Heat exchanger for energy entering from DC network into location
ex2	Heat exchanger for energy leaving location into DC network
htr	Electrical heater
dis	Heat dissipater / cooling tower
pv	PV panels
sol1	Vacuum tube solar collector
sol2	Trough solar collector
blr	Boiler
usr	User-site unit

Chapter One

Introduction, Motivation and Objectives

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Introduction, Motivation and Objectives

1.1 Introduction

It is globally observed that annual electricity consumption is continuously increasing, especially in summer seasons, within the last few decades. A significant role in this increase is subjected by the recent high temperature levels at summer time which causes rapid increase in the air conditioning demands keeping in consideration that the vast majority of air conditioning and refrigeration systems are electrically powered systems. This can be clearly observed in developing countries, especially those in hot climate regions, where they depend mainly on conventional air conditioning systems. These systems have a huge negative impact on the environment which in turn amplifies the global warming phenomena. Meanwhile, it's widely believed nowadays that district energy systems have a great potential to confront the global warming phenomena by reducing the greenhouse gas emissions caused by the energy sector, mainly heating, electricity and increasingly cooling. Therefore, many developed countries have started since a decade or two to adopt and promote the use of centralized or decentralized district cooling systems as a result of several factors such as the uncertainty of the energy prices, the limitation of the existing energy resources and newly imposed environmental regulations. A great deal of focus is being paid specially to hybrid integrated systems using fossil fuels and renewable energy sources. These district cooling systems are offering an alternative solution due to their high-energy efficiency and more friendly impact towards the environment and thus an option for a more sustainable development.

However, these district systems involve a wide range of possible technologies to be integrated with several possible configurations to be adopted, and are supposed to provide energy to a certain range of users, i.e. buildings, with varying energy demand profiles depending on each user's type of application and purpose of use. All that makes it very difficult to obtain a design that offer the desired best economic and environmental benefits as much as possible. Therefore, designing such a system requires a sophisticated method or tool developed specifically to obtain an optimized system that meets the energy requirements of a certain district while achieving minimum possible cost and CO_2 emissions.

Many researchers in the literature have used various energy tools available in market or developed customized mathematical models to carry out the task of designing and evaluating district cooling systems. The aim of this work is to develop and introduce a new mathematical model to address the complicated issue of decision making when designing an optimized district cooling system (DCS) while considering various plant design options and possible DC network layouts as well as taking several energy resources into consideration to achieve the ultimate goals of meeting the cooling demands in a district with best possible energy conservation, economic effectiveness and environment preservation levels. In addition a special focus was paid to design of DCS in context of hot climate regions. This first chapter introduces the current status of the cooling market and the technologies utilized within both developed and developing countries. The potentials of the district cooling market in hot climate regions in the scope of the global campaign to address the climate warming challenges which represent the motivation of this work are presented. Finally, the objectives of the developed decision making model within this study are stated and explained. The second chapter presents an overview of the main ideas and techniques implemented in the commonly used energy evaluation tools a long with decision making algorithms and optimization models developed by other researchers to address similar design and optimization problems in the scope of district energy systems. The mathematical optimization model developed in this work and the optimization environment are described in chapter three alongside decision making approach adopted. The modelling of the different DC units and equipment are explained in details in the same chapter. Chapters four and five present detailed descriptions of two different case studies, with various buildings characteristics, investigated in this work using the developed optimization model and adopted decision making approach. The results obtained for both single objective optimizations, i.e. cost and CO2 emissions separately, and multi objective optimizations, i.e. cost and CO2 emissions combined, are discussed for each case study and for several scenarios regarding different design and operational conditions. At the end of this thesis, the general conclusions obtained during the investigation and future work recommendations are listed and discussed in chapter six.

1.2 Background

Since the first United Nations Conference regarding sustainable development that took place in Stockholm 1972, the notion of sustainability has been gradually gaining worldwide attention. Since then the United Nations has been assessing the link between climate change, sustainability and greenhouse gas emissions throughout the works of hundreds of researchers around the globe. Eventually, the Kyoto Protocol was adopted in 1997 and became effective in 2005. However, many measure and policies are still to be adopted and implemented in order to achieve a worldwide impact. The European Environment Agency has stated in 2002 that “addressing climate change and the activities causing climate change is a key challenge for the 21st century, for both developed and developing countries, if sustainable development is to be attained”. Thus, many laws, programs and action plans have been adopted on a worldwide level represented by UN as well as local levels represented by individual governments and private companies especially in developed countries. However, many developing countries are still falling short on this matter when compared to the measures implemented by developed countries.

The main sectors responsible of the greenhouse emissions are the building, industry and transportation sectors. According to the United Nations Environment Program (UNEP) the building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy [1]. In Europe, Buildings are responsible for 40% of energy consumption and 36% of CO2 emissions in the EU, states the European Commission. Two thirds of the energy consumption in buildings is used for heating and cooling. Although heating represent the major part of building energy consumption in Europe, cooling is becoming increasingly important in the recent years due to the rising ambient temperatures. The rapid growth of technologies and thus the increasing use of electric appliances in buildings, and the less space per capita in offices and commercial buildings, are other major factors that contribute in the increasing cooling demand in the building sector. Today cooling systems available in the cooling market can be categorized into five main types or configurations:

1) **Single-Zone AC systems**: Also known are room air conditioners (RAC). These are the most common used systems for single rooms or zones. There are two conventional arrangements of these systems. A) **Window-Type** air conditioner where all the components, i.e. compressor, condenser, expansion valve or coil, and evaporator are enclosed in a single box, Figure 1.1a. This unit is usually fitted in a slot made in the wall of the room, or more commonly a window sill. B) Ductless Split-Unit air conditioner where the components are split into two parts: the outdoor unit and the indoor unit, Figure 1.1b. The outdoor unit, fitted outside the room, contains components like the compressor, condenser and expansion valve. The indoor unit comprises the evaporator or cooling coil and the cooling fan. For this unit no slot in the wall or window of the room is needed. Sometimes one outdoor unit is connected to more than one indoor unit to serve multiple zones.

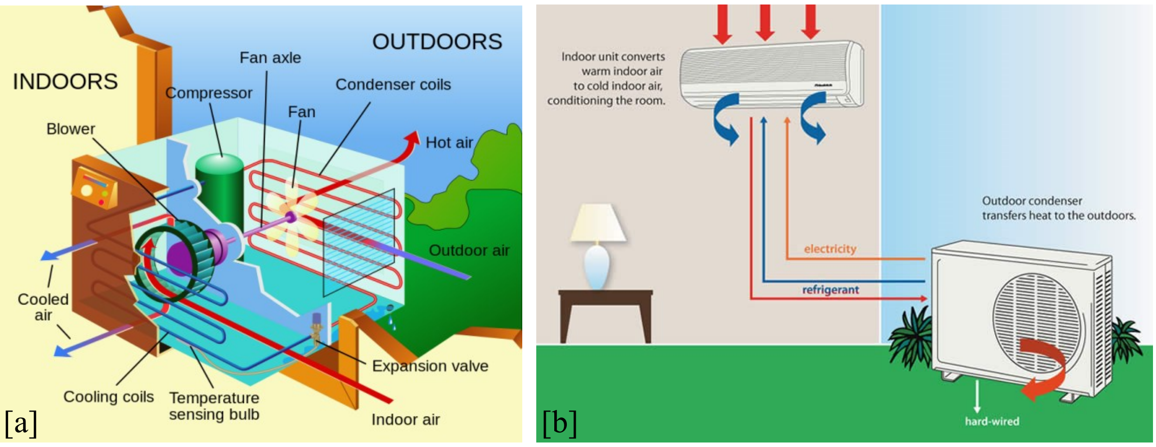

Figure 1.1: Single-Zone AC systems: a) Window-Type. b) Ductless Split-Unit. Source: http://www.n-m-services.eu

2) **Multi-Zone AC systems**: these are used to cool two or more zones/rooms within one building. The most common known examples of these systems are: A) **Packaged AC Systems** where all the components, namely the compressor, condenser (which can be air cooled or water cooled), expansion valve and evaporator are housed in a single box. This box is usually installed outside the building and often on top of the roof. Cooled air is thrown by the high capacity blower out of the evaporator, and it flows through the ducts laid through various rooms. B) **Ducted Split-Unit AC system** where the components of a packaged system are split into two units with the compressor and condenser in an outdoor casing and the expansion valve and cooling coil in an indoor casing and the compressed refrigerant being the energy transmitter between the two units however cooled air is transferred from the indoor units to multiple rooms via a duct network. C) **VRF** (Variable Refrigerant Flow) is another arrangement that is becoming very popular recently which is basically a ductless Split-Unit AC system style but with multiple indoor units. The compressed gas/refrigerant passes through several individual indoor units located in various rooms.

3) **Central Chillers or Stand-Alone AC systems** where the cooling energy is produced locally in each individual location or building. The cooling energy is then distributed throughout the various zones within the building either by cold air via ducts or cold water via pipeline. The prominent element in these systems is the chiller unit that comprises all the four major components of an AC system. Cold storage tanks are also a common unit to be used within these systems.

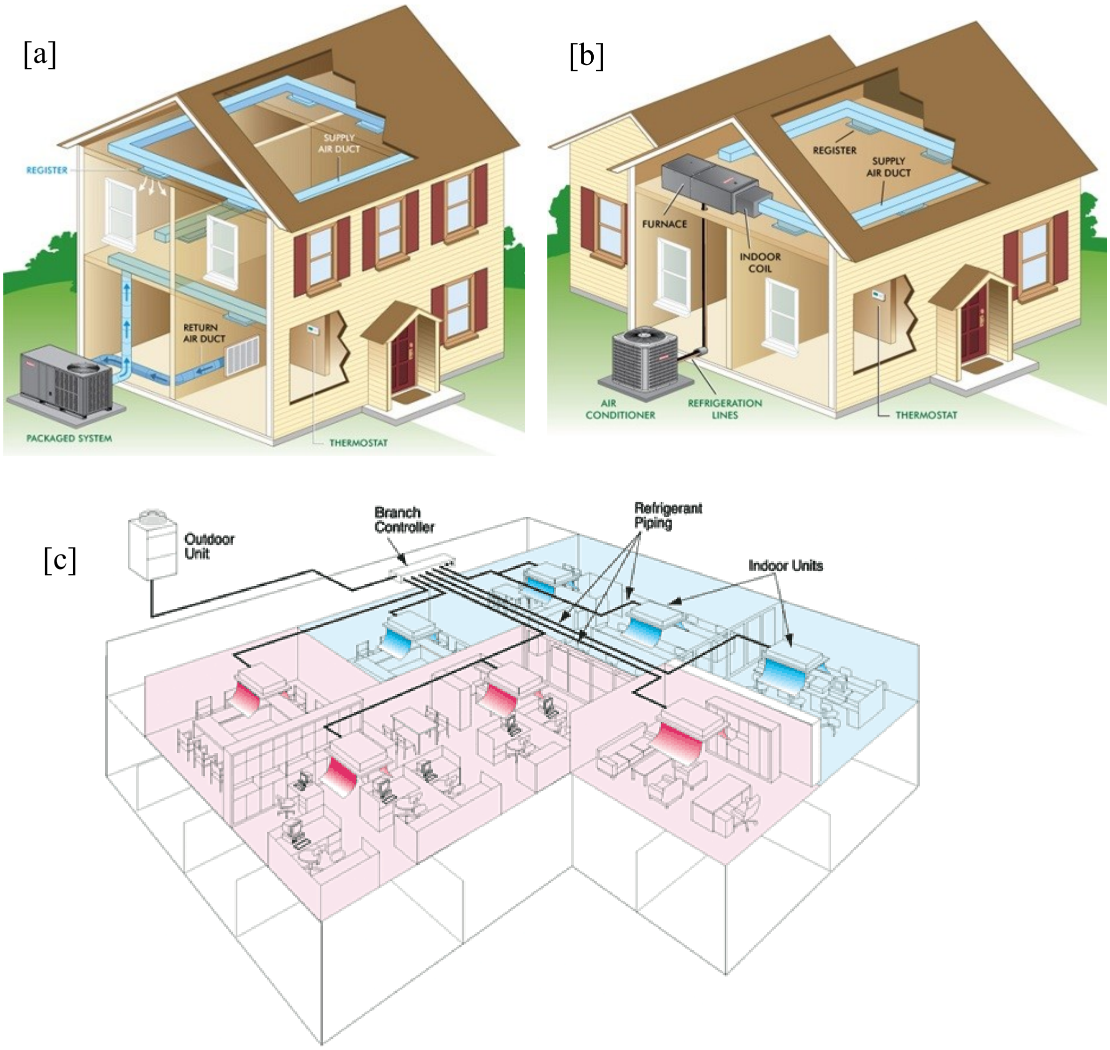

Figure 1.2: Multi-Zone AC systems: a) Packaged AC, b) Ducted Split-Unit AC, and c) VRF (Variable Refrigerant Flow). Source: http://www.carrier-comfort.com & http://ceu.construction.com

4) **Centralized District Cooling systems** these systems are used to serve more than one buildings where the cooling energy is produced at a central plant and then distributed to the distanced locations or buildings, also known as consumers, through a cold water pipelines networks. Multiple production plants, i.e. chillers units, and multiple storage tanks can occurs in these systems at different location.

5) **Distributed/De-Centralized District Cooling systems** where the cooling energy can be produced in multiple locations and distributed through several relatively small pipelines networks that might or might not be interconnected for support and reliability purposes. Certain buildings might have their own Stand-Alone Chillers where cooling energy is produced and consumed locally.

1.3 District Cooling

District Cooling (DC) is one of the main cooling trends that offer a promising solution with much better energy efficiency and environmental impact than conventional cooling technologies. In general, the term District cooling (DC) is widely associated with systems where mass production and distribution of cooling energy is the main theme. The basic idea of such systems is that the production of cooling energy, often in the form of chilled water, takes place in a central plant installed at one location and then distributed to the consumers throughout a network of pipelines. Such a district cooling system is named as **Centralized DCS** in this work. In many modern cases the single production plant is replaced by few distanced plants each serving a group of final consumers connected to its sub-network. The sub-networks might be interconnected themselves for backup concerns. This kind of systems is named **De-centralized DCS** in this work. The location of the production plants, in both centralized and de-centralized systems, is dependent of several factors most importantly is the availability of free or cheap primary energy within or near by the served region. The geographical distribution between the served consumers can play an important role as well. In fact, this later factor has a major role in the decision making between a centralized or decentralized DC system. Cold storage tanks can interfere in the distribution network with the purpose of enhancing performance. They might be installed at the production plants, consumer buildings, or intermediate stations with in the DC network. If the chilled water, or any other cooling agent, is designed to return back to the production plant using a return line, then the system is known as a closed circuit or loop. Other systems might consist of an open circuit network where the cooling agent is not returned back. Free or Natural cooling is a good example of that where cold water is taken from a cold source nearby, e.g. ground water or lakes …etc., and pumped into a building for cooling purposes then returned back to the ground or lake. F demonstrates a general example of District Cooling systems and their work concept.

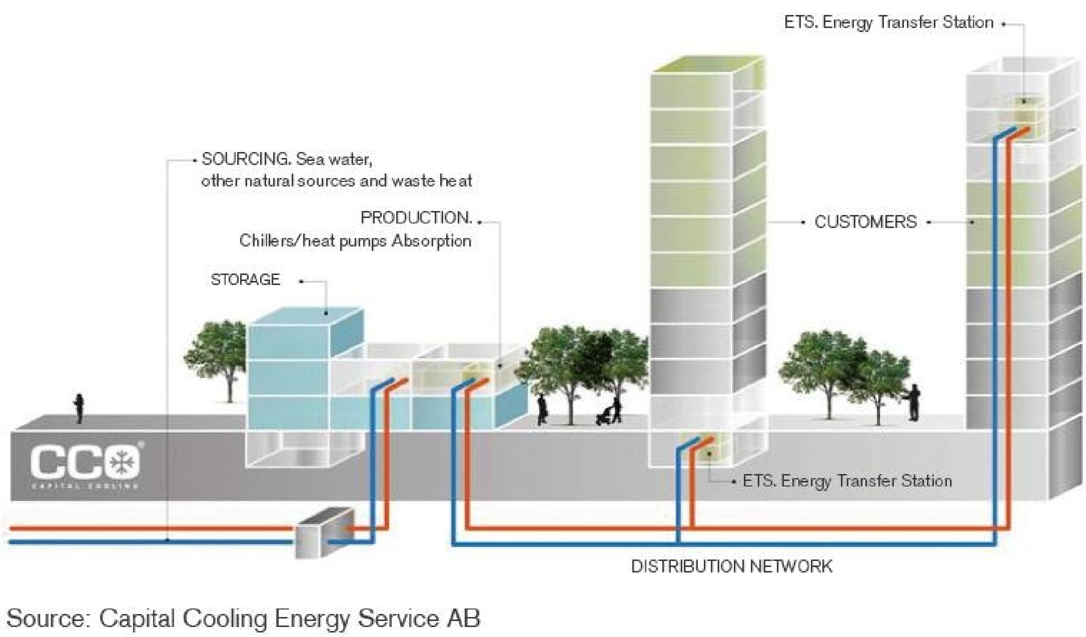

Figure 1.3: District Cooling System general scheme and main work concept [2].

1.3.1 District Cooling advantages

From a cooling perspective, primary energy consumption and CO_2 emissions are the two essential indicators of how environmental friendly a cooling system is. Many studies view district cooling technology as a key player in the struggle against global warming phenomena. This is due to the fact that the maximum cooling capacity requirement in DCS is less than the maximum cooling capacity requirements of all individual separated, i.e. stand alone, cooling systems replaced by that DC system and thus less primary energy consumption and eventually less CO_2 emissions. The final report of the Renewable Smart Cooling in Urban Europe (RESCUE) project [2] states that, in general, DC needs around 15% less capacity for the same cooling loads than separated cooling systems. According to the same project, if district cooling would cover 25% of the cooling market in Europe, CO_2 emissions could be reduced by 42 to 50 million tons per year which is equivalent to the average annual emissions from 9,500,000 passenger vehicles. Another major environmental advantage of DC systems is their large potential of using resources that are not aggravating the environment such as energy from different kinds of renewable energy resources as well as energy from low temperature of subsoil, surface and underground water. In addition, DCS have high ability to combine different kinds of these energy resources in the same time which offers a high flexibility in selecting most effective and economic production of chilled water which in turn represents an advance level of environmental consciousness. Other environmental advantages of DC systems involve contributing in reducing the urban island effect as the cooling energy production plant can be installed in a location where it will not thermally overload the urban region and also reducing the noise level by eliminating noise created by the stand alone air-conditioning units.

On top of these environmental advantages, DC systems offer great help in reducing electricity consumption and peak shaving. Meeting peak loads of electricity demand profiles represent a significant challenge for many cities, countries and regions especially in summer. Such a challenge can be rationally dealt with by DC systems due to their high full-load COPs which allows reducing overall electricity consumption and to their high potential of adapting storage technologies in peak shaving. RESCUE project stated that if DC would cover 25% of cooling market in Europe, electricity consumption could be reduced by 50 to 60 TWh per year which is equivalent to the average consumption of 10 million citizens [2]. Such benefit can be much greater in hot climate regions where the greater part of the electrical demand occur in the summer period due to cooling purposes.

On municipality level, district cooling systems provide significant benefits through the significant amount of infrastructure that will be added to the municipality where DCS is built. Such infrastructure gives those municipalities advantages in attracting new development in comparison to other communities where district energy systems are not available. DCS also provide an ability to capture cash flows that were previously leaving the community to pay for the natural gas and electricity that is imported. The opportunities of using local energy sources like combined heat and power and renewables within DC serves the goal of keeping more of the money used to import energy circulating within the community.

On property owner level, DC systems offer a better rational management ability of cooling energy production, if any, in comparison with lots of scattered stand-alone systems and reduce the amount of non-beneficial space in buildings such as boiler and chiller space which can be used for other beneficial uses instead once a DC system is adopted. This contributes in reducing the overall capital costs in newly constructed buildings due the elimination of chiller rooms or the reallocation of that space into a revenue generating space which is a significant benefit for commercial and industrial buildings. In addition, building owners can expect more stability in energy consumption costs due to the higher efficiencies of DCS and their ability to combine different primary energy resources. District cooling systems are often designed with standby cooling capacity and their distribution networks are usually built with backup measures. Such measures provide DCS with greater reliability than most buildings can achieve with stand-alone systems. This eventually results in reduced insurance costs due to lower risks.

1.3.2 DC Resources and Technologies

When planning a district cooling system, two major elements of the system have to be designed or chosen with great consideration. These are cooling energy production (cooling source and technology) and the distribution system, i.e. DC network. The aim is to plan an optimized DC system with performance and economics in mind in addition to environmental aspects.

Typically, there are three common ways to produce chilled water, i.e. cooling energy, at district cooling plant: Compressor driven chillers with high efficiencies, absorption chillers benefiting from surplus heat, or other sources like "Free Cooling" from nearby water resources such as deep lakes, rivers, aquifers or oceans. The decision of which technology to adopt for certain DCS has to be made with deep consideration of the local conditions residing in that district. The option of combining two or more of these technologies is also possible and should be made in a way to achieve most possible profit or better performance within the available energy resources, economic and environmental parameters. The following sections describe each one of these three technologies with brief details:

1. **Vapor Compression Chillers**

   It is the most common technology in air conditioning systems. Vapor-compression chillers are most often driven by electricity and in some other cases by turbines or reciprocating engines. Centrifugal or screw compressor-chillers are the most common in central chilled water applications. Coefficient of Performance (COP) of conventional mechanical vapor-compression chillers varies in the range of 3.0 to 8.0 [3]. District cooling systems are typically cooled with water from natural resources.

2. **Absorption Chillers**

   Absorption chillers are another type of heat pumps that work with a similar concept to that of vapor-compression chillers with the distinct that they use heat as a driving energy instead of electricity where they utilize an absorption cycle, consisting of a generator and absorber, instead of the electric driven compressor. According to the way the heat is used as a driving source, absorption chillers can be classified into indirect fired or direct fired chillers. Indirect fired absorption chillers are commonly used in chilled water production system for a district cooling network due to their ability to utilize waste or surplus heat available. Absorption chillers can be described by number of "effects" or number of "stages". Number of effects represents the number of times the heat input into the chiller is used internally. While number of stages in an absorption chiller refer to the number of evaporator/absorber pairs operating at different temperature levels within an absorption chiller. Typical COP's for commercially available absorption chillers range from 0.65 to 0.8 for single effect units and 0.9 to 1.2 for double effect units. In addition to the cold water cycle, a source of cooling water is required to reject heat from the unit condenser. The higher investment cost of absorption chillers and their lower COPs in compare to vapor-compression chillers make it very difficult to justify the use of absorption chillers in district cooling applications on economic basis without a source of surplus or low cost waste heat energy being available. A good example would be the use of absorption chillers in combination with district heating systems using the over-capacity of CHP units during summer periods. Sometimes specific technical reasons or local regulations require the use of absorption chillers.

3. **Free Cooling**
   Free cooling or ‘Natural Cooling’ is a term used to describe utilizing the available natural resources of cold energy in the surroundings such as air, underground water, lakes, rivers, oceans, snow and ice. In this technology there are no expenses of producing the cooling energy other than the electricity consumed by fans or pumps to circulate the cooling medium, e.g. air or water. Using air as a free cooling source is limited to regions where it’s cold outside for most of the year. The most common source for free cooling is the cold water from lakes and oceans. In the northern regions the temperature of water at or near the surface of a lake or stream will be variable with ambient temperature. If the lake or stream is deep enough, the temperature of the water will at a minimum temperature that is almost constant throughout the year. Thus, deep levels of lakes, rivers, or oceans can be used as a source of chilled water. The chilled deep water may be employed directly in cooling systems, or indirectly by providing cooling energy through a heat exchanger to a circulating network of chilled water. Another possible source for free cooling is snow or ice where a large amount of one of them can be stored during the winter season to be used later as a source of cooling energy during the summer. This kind of applications is available for example in Sundsvall, Sweden.

A very important element in rational planning for district cooling systems is the use of cold storages. Thermal storages are often integrated in the systems to reduce the chillers’ equipment requirements and lower operating costs by shifting peak load to off-peak times. Their concept of work is to produce cooling energy during the non-peak periods, especially if electricity prices were lower than peak load periods, store it and then use it later at peak load periods.

1.4 Cooling Market

The relatively new regulations adopted by several developed countries and international organizations which have put enormous restrictions on conventional cooling technologies along with the rapid increase in cooling load demands resulting from the global warming phenomenon have created a market situation that is thriving for new environmentally friendly cooling technologies. On the other hand, developing countries has been falling short on environmental regulation which left the introduced environmentally friendly technologies in an open market competition against the conventional cooling systems and technologies. This has left design engineers with various competing technologies and design options to select from in addition to a great deal of uncertainty regarding the claimed performance of the new technologies and their suitability to certain applications and regions. Hence, the task of deciding for which cooling system to invest in has become a complicated process that requires taking many aspects into consideration such as performance and economics in addition to the environmental aspects of each of these systems and their sub options and technologies. Therefore, it is useful to have an overview to the cooling market in developed and developing countries.

1.4.1 Cooling in developed countries: Europe as an example

At the end of 2006, Euroheat & Power, in cooperation with 13 partners across Europe and with support from the Intelligent Energy Europe programme, has concluded a two years project known as the ECOHEATCOOL project. The project covered 32 countries including EU 27 Member States, two accession and three EFTA countries. The main objective was to assess the heating and cooling markets, to look for possibilities for more district heating and district cooling in Europe, to provide recommendations for policy makers and develop a tool for assessing the efficiency of heating and cooling options [4]. The project results report has stated that the largest slice of the primary energy consumption in Europe is used for heating and that cooling seems to be catching up. The project has observed a strong cooling market expansion during the previous decade due to the fact that the standard of living has made this type of equipment affordable and that peoples comfort standard requirements have increased. The second work package final report has predicted that with saturation rate of 60% for the service sector and 40% for the residential sector the cooling market will show a four fold increase between 2000 and 2018, corresponding to 500 TWh_c for the EU-15 and 660 TWh_c for all 32 countries [5]. The project has concluded that a fast and wide implementation of energy efficient District Cooling has a major role to play in order to meet the challenges for Europe, in order to provide a robust and environmentally sound framework for future energy solutions.

Figure 1.4 published in a report on the economic and market analysis of air conditioning products, carried out for the European Commission (DG ENTR) by a group of contractors including Armines (lead contractor), BRE and VHK [6], shows the market shares, by cooling capacity, for different air conditioning systems. The term ‘Rooftop’ in this figure represent the packaged systems and the term ‘Chiller’ include all three central cooling systems. The figure indicates that 59% of the European cooling demand is met with Central chillers, i.e. Stand-Alone Chillers, Centralized, or De-Centralized District cooling systems. However, official statistics of DC in the EU27 countries show that the district cooling market corresponds only to 1% of the present of the cooling market in EU27 countries [7].

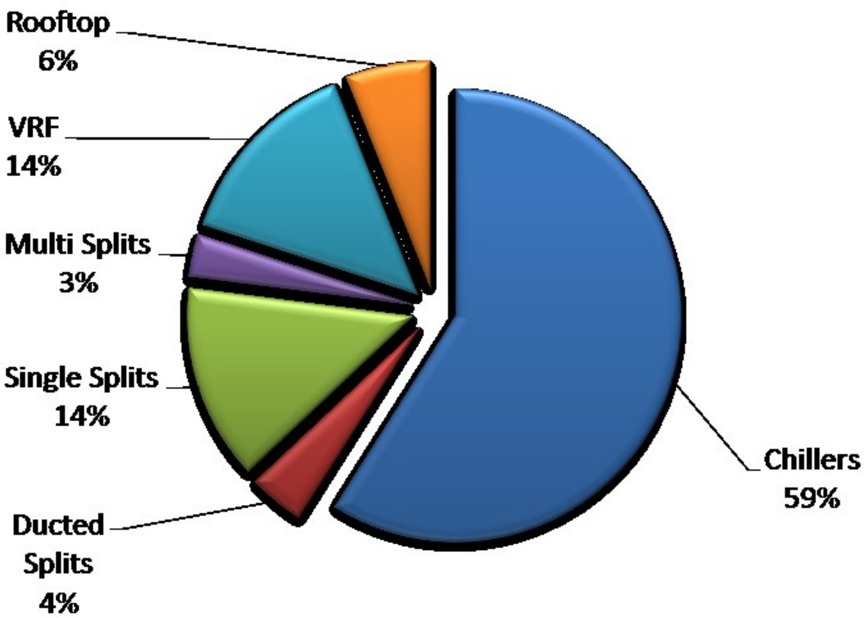

Figure 1.4: Estimated market share of Air Conditioning Systems by Type in Europe in 2008 (Shares by Cooling Capacity) [6].

In order to handle the climate change challenges, the European Union has adopted an Energy policy with environmental targets to be met by 2020 for EU-27. The targets are to reduce Greenhouse gas emissions by 20%, reach a share of 20% of renewable energy and reduce primary energy consumption by 20% in 2020. Many legal definitions, quantifications and legislations have been put forward to achieve these targets. Regarding achieving the energy efficiency target of reducing primary energy, the Energy Efficiency Directive (EED) 2012 has recognized District Cooling as one of the potential solutions and set forward several obligations for the EU-27 member states to comply with such as carrying out comprehensive assessment of the potential high efficiency cogeneration and efficient district heating and cooling application, to be updated every 5 years, and taking adequate measures for efficient district heating and cooling infrastructure to be developed.

With the background of the potential contribution of district cooling in achieving the EU 2020 environmental targets, the RESCUE project was conducted from June 2012 to May 2015. The aims of the project were to address the key challenges for the further development and implementation of district cooling using low and zero carbon emitting sources and to enable local communities to reap the environmental and economic benefits of this energy efficiency and mature technology [2].

Based on above, it can be concluded that the European cooling market is witnessing a rapid growth which will eventually lead into a higher use of primary energy and thus increasing the greenhouse gas emissions if no energy efficient solutions were adopted. The potential of District cooling to reduce the use of primary energy and the substantial CO2-emissions is recognized by the European Union and therefore some legislation were adopted and implemented to promote district cooling investments within European local authorities and municipalities.

1.4.2 Cooling in developing countries: Middle East as an example

The status of cooling market in Middle East differs extremely from that in Europe. However, the underlying problems and challenges to be face are surprisingly similar. For a region that holds around 49% of the world's oil reserve, it's hard to believe most of the Middle East countries are face domestic power concerns. The region is known for its high, and increasing, electricity consumption rates especially during the summer season when temperature reaches levels about 50^{o}C. Frost and Sullivan's recent research suggests that the demand for power, water & energy in the Middle East could triple over the next 25 years. Abhay Bhargava, Associate Director and Regional Head – MENA, Energy & Environment, Frost & Sullivan has stated: "Some of the highest per capita energy intensive countries, globally, are based in the Middle East and North Africa (MENA) region. This drives growth in demand for power in the region, which is expected to increase by over 7.0 percent annually until 2018. This is expected to create substantial opportunities for power generation projects across the region, based on not just conventional sources (hyrdocarbons), but also alternate sources,"

Considering the climatic condition of the region cooling is an indispensable part of required living condition almost throughout the year. The hot climate of the region during the long summer period has made air conditioning the major power consuming sector. According to Frost & Sullivan, air conditioning consumes about 50% of the peak power load in Middle East [8]. What increases the energy crisis is that the cooling market is overwhelmingly dominated by conventional air conditioning systems. Single-Zone AC systems, e.g. window-type and split-unit systems represent the number one choice for consumers in Middle East especially in the residential sector. Although the same systems occur continuously in many non-residential areas, e.g. office building, packaged and VRF are the prominent choice in that sector.


Figure 1.5: A common seen in residential or office area in developing countries.

However, the recent years have witnessed a growing interest for the authorities in Middle East, especially the golf region, to invest more in environmentally friendly air conditioning systems. The governments' efforts to bring down energy consumption have paved the way for District cooling to enter the cooling market in Middle East. District Cooling industry was growing in the region since late 90s, however growth between 2003 and 2008 has reached staggering rates of more than 60% [8]. Thus, the regions hot climate, the authorities desire to reduce energy consumption, and the increased construction activities have set a great potential for district cooling in the Middle East cooling market.

Today, Middle East continues to offer promising opportunities for District Cooling industry as it develops large green-field site and build new residential and commercial districts and cities. Prospering markets exist in most golf countries such as Saudi Arabia, Bahrain and Qatar with United Arab Emirates (UAE) being a leading robust market. Other regions in Middle East such as the Kurdistan region in northern of Iraq has also growing construction activities and plans for expanding Urban areas.

From the above, is can be concluded that due to the energy crisis in the region and the current conventional status of the cooling market in Middle East along with the urban expansion going on in the region, district cooling will be the preferred technology for new buildings coming up in the Middle East. However, significant efforts need to be spent on informing local authorities on the advantages and benefits of this energy efficiency and mature technology.

1.5 Cooling in hot climate regions

Operating a cooling system in a hot climate region usually face many obstacles. One of the main obstacles is the high ambient temperature which has a negative impact on the COP values of the compression chillers. Most of the chillers produced and offered in the market are designed to work within a range of 30-35°C. However, ambient temperatures in many areas, e.g. sub-tropical regions, exceed the designed ambient temperature. In some cases it reaches up to 55 °C. Such high ambient temperatures can reduce the compression chiller COP sufficiently. More details on the impact of the hot climate effect on the chillers performance is to be presented in the case studies in this work. Investigating this phenomenon within this study has the aim of projecting some attention on the problem and providing some general recommendations for decision makers when designing a cooling system in hot climate regions.

1.6 Motivation

The current status of the energy sector and it dependence on fossil fuel clearly has a huge role in the global warming phenomenon. Cooling being one of the prominent sectors of energy consumption market has attracted great attention in recent years to attempts to enhancing the energy performance of cooling systems. The wide range of cooling technologies and design options has left decision makers in what can be described as blind spot regarding what is the best option to investing in in terms of not only economics but environmental aspects as well.

Moreover, decision makers in developing countries seem to lack the informative background regarding total life cycle economics and efficient performance of cooling technologies. This can be clearly observed in the high rates of decisions made to invest in single-zone cooling systems which are mainly due to these systems low first investment costs and ease of installation.

This background was the main motive of this work. Thus, a multi-objective, both total cost and greenhouse gas emissions, optimization model was developed to assist decision makers at early design stages to decide what the best technologies or design options to be adopted are in terms of economics and ecological aspects.

1.7 Work Objectives

Considering the wide range of networking options, cooling energy producing technologies and energy resources integrating possibilities, optimal design and operation of the system comes out as an essential aspect in designing DCS especially when limited information is available such as at the first stages of the decision making process. The main objective of this thesis is to develop a methodology, approach, or tool to help decision makers evaluating the economic viability, potential energy savings and thus potential greenhouse gas emission reduction at the very early design stage. The tool has to include modellings for different energy conservation unit that can be included in cooling system. It also has to be flexible enough to consider different cooling technologies and various design configurations.

Considering the main objective of this thesis, the following specific sub-objectives are adopted:

- To carry out a comprehensive literature review regarding the main energy tools and methodologies currently available. This review will include energy evaluation, system simulation as well as mathematical optimization models for cooling systems. Based on this review, the type and methodology to be adopted in this thesis will be decided.

- To develop a methodology, tool, or model to assist decision makers at early design stage.

- To validate the developed tool or model on several small examples to assure results accuracy.

- To implement the use of the developed methodology, tool, or model in investigating two different case studies with different categorization of buildings to be considered. The case studies will be taken from a hot climate region.

- To generate estimated cooling load profiles for case study buildings to be investigated using the developed decision making assisting tool or model.

- To develop a method to select representative days for buildings based on their estimated or measured cooling load profiles and function of use.

- To investigate the performance of urban cooling systems in hot climate regions.

- To attempt to obtain general conclusions and design recommendation from the two investigated case studies.

Chapter Two

Literature Review

Chapter Two

Literature Review

2.1 Introduction

Each city district or urban area has its energy supply systems which often include cooling energy supply system. Cooling systems can be consisting of centralized, de-centralized or stand-alone, completely separated, units. In order to design, synthesize and evaluate these systems and to analyze or enhance their performances often energy tools, decision making algorithms and optimization models are used. The selection of these tools, algorithms or models must not only fit the requirements of the user but also be compatible with the input data available such as cooling energy demand profiles, energy prices, cost of cooling technologies, building characteristic, available areas to be utilized and the local legal restrictions.

This chapter represents an overview of the main ideas and techniques implemented in the energy evaluation tools, decision making algorithms and optimization models, been reviewed with in this research, which are used very commonly in the literature for the purpose of design, evaluation and optimization of cooling energy supply systems. It also represents an investigation of the suitability of these tools and models for different case studies and scenarios evaluated in the literature. The main simulation and energy evaluation tools used to analyze the performance of the cooling energy systems in city districts or urban areas are reviewed in section 2.2. A brief overview of the common and recent decision making algorithms and criteria is presented in section 2.3. Optimization models and their implemented methodologies and techniques are presented in section 2.4 where different optimization approaches were reviewed for different application. Many investigated case studies found in the literature are presented in this section as well. Tools and models dealing with the topic of multi objective optimization are reviewed in section 2.5.

The objective of the chapter is to define the scope of application of these tools and models and compare them in terms of applicability, usability and performance in order to come out with the suitable methodology or approach that serves the ultimate objectives of this work.

2.2 Energy System Evaluation for District Cooling

Since that energy performance analysis of an urban area often embrace a high scale investigation due to the technologies to be integrated and the amount of data to be processed, most researchers tend to perform such investigations using energy evaluation tools. These tools are used to simulate and analyze energy performance of pre-designed or pre-existing systems. Some researcher use these tools for design purposes by running several simulations after implementing certain design changes on a pre-designed systems to achieve a better overall performance. The type of energy tool to be selected usually depends on the geographical scale of the investigation, amount of input data, i.e. level of detail, and the time period to be investigated. It is observed that when investigating a case, where one of these three aspects is relatively big (i.e. big scale, highly detailed or long time), a simplification or reduction of complexity on the other two aspects is required in order to keep the simulation performable in a reasonable manner. In some cases, a simplified energy tool is chosen to evaluate a complicated case study which might lead to obtaining results that are not representative of the actual case. On the other hand, certain tools can be too complicated to use sometimes when the required level of detailed input data is not available. Therefore, it is up to the user to find the suitable tool for certain evaluation based on level of complexity of the case study in terms of scale, data and time.

A review of 37 different energy tools was presented by Connolly et al [9]. The possibility of integrating renewable energy resources was a major investigation goal in this review. The energy tools were classified into seven groups according to their function of purpose and approach as shown in Table 2.1. According to the Connelly different energy tools are not necessarily to be of one type but rather can be included in more than one group. The study also specifies the different types of analyses that can be completed with each of the tools investigated as well as the energy-sectors considered by each tool including renewable-energy resources. Moreover, each of the energy tools reviewed is discussed separately in a great level of detail. The classification obtained and details specified by Connelly can quickly reduce the number of tools that need to be considered for a specific investigation.

Table 2.1: Energy tools classification into seven groups by Connolly et al [9].

Type No.	Energy tool type	Functionality and approach
1	Simulation tool	Simulates the operation of a given energy-system to supply a given set of energy demands. Typically a simulation tool is operated in hourly time-steps over a one-year time-period.
2	Scenario tool	Usually combines a series of years into a long-term scenario. Typically scenario tools function in time-steps of 1 year and combine such annual results into a scenario of typically 20–50 years.
3	Equilibrium tool	Seeks to explain the behavior of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets. It is often assumed that agents are price takers and that equilibrium can be identified.
4	Top-down tool	is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands. Typically top-down tools are also equilibrium tools (Type 3).
5	Bottom-up tool	Identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives.
6	Operation optimization tools	Optimize the operation of a given energy-system. Typically operation optimization tools are also simulation tools (Type 1) optimizing the operation of a given system.
7	Investment optimization tools	Optimize the investments in an energy-system. Typically optimization tools are also scenario tools (Type 2) optimizing investments in new energy stations and technologies.

The energy tools reviewed by Connelly et al [9] and their classification into the seven types are shown in Table 2.2. One can notice directly some tools can be used to perform more than one approach or purpose while others can perform only one. As explained in Chapter 1, the aim of this study is to carry out both investment and operational optimizations to analyze a typical life cycle (approx. 20 years) for a cooling energy system while performing several scenarios where parameter such as: technology prices, energy prices, energy demand profiles, and operational constraints vary from one scenario to another. From that we conclude that only few tools, from those presented in Table 2.2, represent suitable candidates. These are the tools that can perform all three objectives desired in this work: Scenario analysis, investment and operation optimization. Those suitable candidates are marked with blue color within Table 2.2.

According to the reviews provided by Connelly BALMOREL and EnergyPLAN are tools that deal with design of large scale systems varying from regional to national to international scale. The first emphasis on electricity sector and CHP and can simulate some of the heat sector while the second assist the design of national or regional energy planning strategies by simulating the entire energy-system including heat and electricity supplies as well as the transport and industrial sectors and it simulate one year at a time. MESSAGE is a system engineering optimization tool used for the planning of medium to long-term energy-systems, analyzing climate change policies, and developing scenarios for national or global regions. However, the time step in MESSAGE is relatively big (5 - 10 years) to perform detailed operational optimization. The ORCED tool dispatches power-plants in a region to meet the electricity demands for any given year up to 2030 but simulates only the electricity sector and mainly for a US country at a regional to national level.

This leaves us with EnergyPRO and TRNSYS16 which are similar tools regarding the scale of the analysis. EnergyPRO is specifically designed for a single thermal or CHP power-plant investigation. It can model all types of thermal generation except nuclear, all renewable generation, and all energy storage units to complete the analysis. Similar to EnergyPro, TRNSYS16 is primarily used to analyze single project, local community, or island energy systems and it also can simulate most thermal and renewable energy generation. While EnergyPRO carries the analysis out using a one-minute time-step for a maximum duration of 40 years, TRNSYS16 allows the user to define the time-step within a range of 0.1 second to 1 hour and it can analyze a time-horizon of multiple years. The use of TRNSYS16 has been quite extended to simulate thermal systems, including renewable energy sources such as solar energy applications and biological processes. However, these two tools are designed to simulate energy systems with a high level of details. And since the ultimate aim of this study is: to provide assistance to decision makers through presenting preliminary systems based on rough detailed optimization to ease the process of selection between the wide technological, environmental and economic options where these preliminary systems are to be subjected into further investigation through detailed simulation, it has been concluded that these two tools are too detailed for the purpose of this work. Besides the investment (design) optimization of the system is often carried out with these tools as selection process among limited number of design options which is not the exact understanding of optimization within this work. However, TRNSYS17 was used to generate the cooling load profile of the buildings in the case studies investigated within this work as it will be explained in the following chapters.

Table 2.2: Classification of energy tools reviewed by Connelly et al [9].

Reviewed Tools	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimization	Investment optimization
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
EnergyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMax	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
Invert	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

2.3 Multi Criteria Decision Making for DCS

Traditionally, cooling systems used to be designed based on single criteria decision making where the main aim normally would be maximization of benefits and/or minimization of costs. Increasing awareness toward environmental aspects during the 1970s directed the energy planning efforts towards energy models aimed at exploring the energy–economy relationships established in the energy sector [10]. Particularly, ore focus was given for energy conservation and energy substitution after the oil crisis in 1973. Thus, multi-criteria approaches became widely adopted due to the increasing public demand to incorporate environmental and social in energy planning.

Today, designing a district cooling system requires making decisions among a variety of opportunities, options and technologies. A decision making process include choosing among quantifiable or non-quantifiable and multiple criteria. And because many objectives usually conflict each other, decisions made are highly dependent on the preferences of the decision-maker and often a result of a long process of study, analysis and compromise. Such a decision making rule is not merely the responsibility of design engineers anymore. In fact, it's more often to be carried out in cooperation with local governments (e.g. municipalities), investors, city planners, company managers, feasibility analyzers … etc. Many different methods have been developed to assist the decision makers such as weighted averages, priority setting, outranking, fuzzy averages and their combinations.

Generally, more and more attention from economic/thermo-economic, technical, and environmental aspects is being paid for evaluation of cooling system systems. Traditional economic analysis was applied to virtually, if not actually, all cooling projects. Thermo-economic analysis is an additional supplement method that applies the laws of thermodynamics to economic theories [11, 12]. While technical analysis is related to the feasibility of cooling systems besides to their economic performance. Terms such as: Primary energy consumption, primary energy ratio, primary energy saving, fuel energy saving ratio and energy-efficiency are often employed to evaluate the technical performance of cooling systems [13, 14, 15, 16], and [17]. In addition to the economic and technical analysis, many researchers evaluated and analyzed cooling systems environmentally [18, 19].

Such focus on different aspects of evaluation is increasingly presented in Multi criteria approaches. Wang et al. [20, 21] employed grey relational method and fuzzy analytical hierarchy process method to compare five Tri-generation schemes for a building in Shanghai, China, from technical, economic, environmental and social aspects, respectively. Cho et al. [22] used operational cost, primary energy consumption and CO_2 emission to evaluate the operation modes of Tri-generation systems for different cities. Jiang-Jiang et al. [23] employed three relative criteria: 1) primary energy saving, 2) CO_2 emission reduction, and 3) Annual total cost saving, to evaluate the respective performances of CCHP systems for a hypothetical building in five different climate zones from the technical, environmental and economic aspects following two main operation modes: Thermal demand management mode and electrical demand management mode.

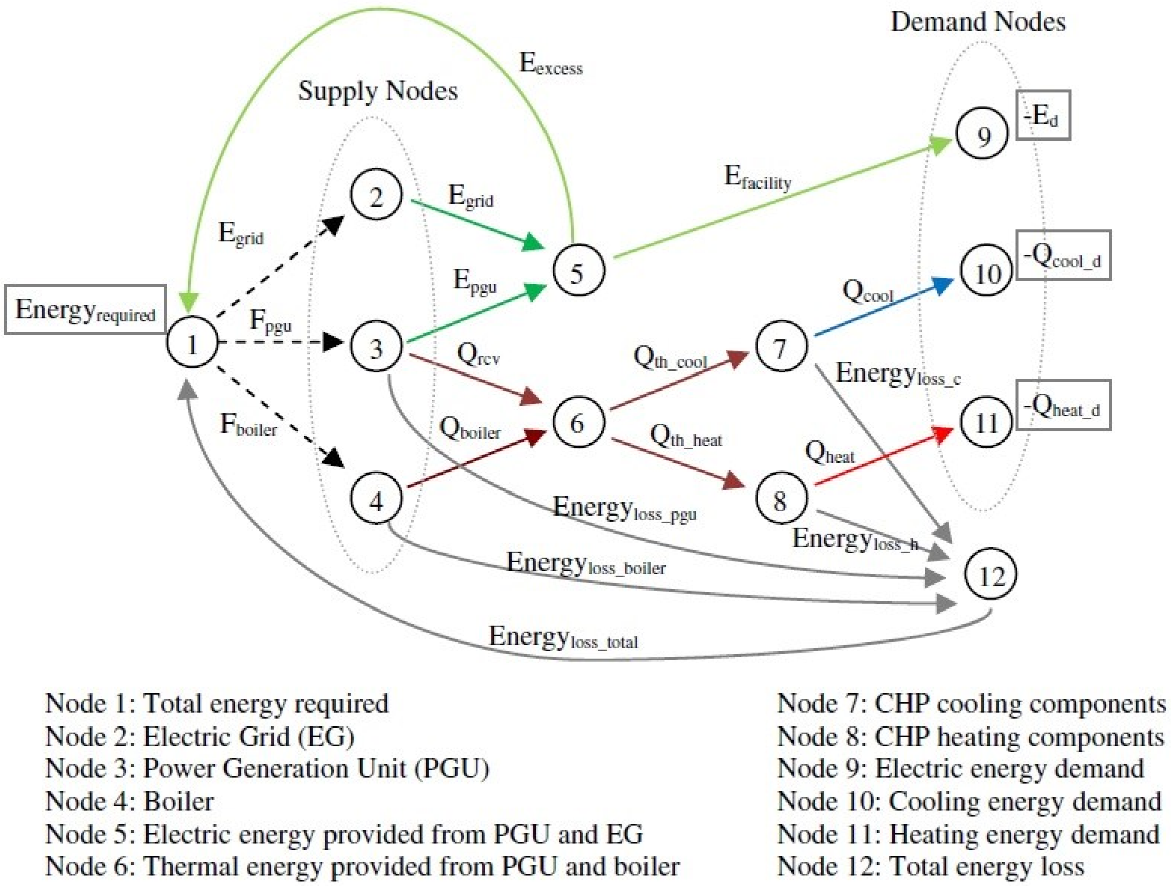

Figure 2.1: Network flow model of a typical CHP system presented by Cho et al. [22]

Pohekar and Ramachandran [24] presented a review of more than 90 published articles in order to analyze several methods commonly used in multi criteria decision making and their applicability. A classification based on application areas of these methods was presented as well. Moreover, the methods were classified into two major groups based on approach of decision making:

- Multiple Attribute Decision Making: Where a small number of alternatives are to be evaluated against a set of attributes which are often hard to quantify. The best alternative is usually selected by making comparisons between alternatives with respect to each attribute.

- Multiple Objective Decision Making: Where alternatives are not predetermined but instead a set of objective functions is optimized subject to a set of constraints. The most satisfactory and efficient solution is to be determined by the optimization model.

Many decision making methods have been briefly explained within their review, however they found that commonly applied methods are multi-objective optimization, AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS). The review also classified the application areas in which these methods are commonly, yet not exclusively, used. As shown in Table 2.3.

Table 2.3: Classification of methods reviewed by Pohekar and Ramachandran based on their common area of application [24].

Method of Decision Making		Renewable energy planning	Energy resource allocation	Building energy management	Transporta-tion energy systems	Project planning	Electric utility planning
Multi-Objective		X	X	X	–	–	X
Multi-Attribute	MAUT	X	–	–	–	–	X
	AHP	X	X	–	X	X	X
	PROMETHEE	X	–	X	X	X	–
	ELECTRE	X	–	X	X	X	–
	Others	X	X	–	X	–	X

The survey observed that Analytical Hierarchy Process (AHP) is most popular for prioritizing alternatives and suggested that this might be due to provisions of converting a complex problem into a simple hierarchy, flexibility, intuitive appeal, its ability to mix qualitative as well as quantitative criteria in the same decision framework. In contrary to the Multi Attribute Utility Theory, outranking methods belonging to PROMETHEE and ELECTRE techniques are extensively used in energy planning. Other miscellaneous methods including DSS, genetic algorithms and fuzzy approaches were found to be used in a verity of applications such as electric utility planning, renewable resources and building energy management.

However, efforts to develop new methods to assist decision making are still present. Haiwen Shu et al.[25] stated that techno-economic evaluation method, which is traditionally used in evaluating different DCH schemes and select among alternatives throughout quantitative comparison, is actually only from the investor’s point of view, so it does have limitations in multi-attribute decision-making problems such as the DCH scheme selection. For instance, the differences of the energy-saving and environmental protection properties between each DCH scheme cannot be fully displayed in the techno-economic evaluation method. Therefore, the value engineering method was adopted in his work to help make the final decision on the DCH scheme selection problem for the first seawater source heat pump DCH project in China. The function analysis of different DCS source scheme options was done by using the AHP method to evaluate the degree of importance for 10 function factors for each scheme: Occupied area of equipment plant (F1), system adjustability (F2), effectiveness of system control (F3), safety and protection performance (F4), plant noise level (F5), equipment service life (F6), equipment failure rate (F7), energy-saving property (F8), environment protection performance (F9) and privileges of policy (F10). A judgment matrix was created through comparing and scoring each pair of function factors by consulting experts as shown in Figure 2.2. Each function factor of every scheme was evaluated and scored separately by the same invited experts. Later on, an engineering cost analysis was used. Ultimately, the value coefficient of each DCH source scheme is calculated after the function coefficient and total cost coefficient are obtained through above process. The scheme that has the highest value coefficient is the best one from value engineering perspective.

Although the approach adopted by Shu et al. take many economic, operational and environmental factors into consideration, however the weight of every function factor (F1–F10) has to be dependent on experts' experience which makes the criterion of scheme comparison seems to be subjective more or less. Therefore, a generalization for the use of a certain judgment matrix created by a certain group of experts will always remain a point of debate. Moreover, decision making by using the adopted Value engineering method is limited among a group of predetermined schemes.

Function Factor	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
F1	1	1/4	1/3	1/5	1/3	1/5	1/6	1/7	1/6	1/4
F2	4	1	1	1/3	2	1/2	1/3	1/5	1/4	1/3
F3	3	1	1	1/3	2	1/3	1/4	1/6	1/5	1/4
F4	5	3	3	1	3	2	1	1/4	1/3	1/2
F5	3	1/2	1/2	1/3	1	1/3	1/5	1/7	1/6	1/4
F6	5	2	3	1/2	3	1	1	1/5	1/4	1/2
F7	6	3	4	1	5	1	1	1/4	1/3	1/2
F8	7	5	6	4	7	5	4	1	1	4
F9	6	4	5	3	6	4	3	1	1	3
F10	4	3	4	2	4	2	2	1/4	1/3	1

Figure 2.2: Judgment matrix adopted by Shu et al. as comparative degree of importance of function factors [25].

It is important to keep in mind that many of the Multi criteria approaches presented by the researchers mentioned above are Multi Attribute methods, i.e. they do not create or suggest solutions but rather select among a number of predefined alternatives. While Multi Objective programing is very wildly used in formulating new alternative solution.

2.4 Optimization Tools and Models

The design of district cooling system requires several input data and parameters such as cooling load profiles, investment and operation costs of different components of the system and time dependent energy prices… etc. In order to achieve a higher efficiency than that of a conventional system, an optimal matching between the cooling energy production and its consumption rates is required, especially in residential districts which are normally characterized by highly variable cooling demand profiles, which makes an optimal design of the cooling energy supply system highly essential. Optimization methodologies have and are still being used extensively for obtaining optimal design and operation of district cooling energy systems in the literature. However, the methodologies adopted to obtain such system are different from one researcher to another. Some example of the optimization models adopted for investigating district cooling, cogeneration, tri-generation or poly-generation systems are presented in this section while examples of multi-objective optimization models are presented in the next section (2.5).

Chicco et al [26] outlined the main aspects of the district energy systems, or what they called distributed multi-generation (DMG), framework, illustrated its characteristics and presented a summary of optimization models for DMG systems classification where they classified the models as short-term and long-term according to their time scale and the type of objective to be optimized. Where short-term, considers the operational planning of the system in a given period (e.g., one year) while long-term, consistent with the formulation of the plant design problem over the plant useful life.

It can be observed in the literature that research efforts were focused on various fields of interests such as the effectiveness of district systems, the layout of the DC network, the technologies to be considered and the feasibility of their integration, and the mathematical programing methodology adopted in the optimization process. Weber [27] has pointed out that very few papers deal with the issue of the network configuration of district energy systems and suggested that researchers may not to be so interested in this topic due to the belief by some of them that the design of the distribution network is anyway solved by politicians and urban planners, without involving any quantitative support, and that it is therefore useless to include the design of the distribution network when studying the thermo-environomic (economic, energetic and environmental) optimization of district energy systems. However, Weber also believed that quantitative support tools, when and if available, can be very interesting for politicians and urban planners.

Regarding optimization methodologies, mathematical programming techniques were found to be the most extended methodology for optimization of cogeneration and poly-generation systems, and for a lesser degree of application, evolutionary algorithms such as genetic algorithms. Ortiga [28] have stated that the design of district energy systems is often carried out with the aid of mathematical models that are solved and optimized minimizing the investment and operational costs, but these optimization techniques are applied frequently for industrial applications and rarely for building or district heating and cooling (DHC) applications.

These mathematical programming techniques consist of a mathematical model for minimizing or maximizing an objective function which can represent total cost (investment and operational costs), environmental parameters (such as CO_2 emissions), or a mixture of both (i.e. multi-objective optimization). The model usually includes a multivariable objective function and a set of constraints as a consequence of the physical and operational limitations of the modelled system. Models found in the literature often developed common resolution algorithms such as: linear programming models (LP), mixed integer linear programming models (MILP), non-linear programming models (NLP), and mixed integer non-linear programming models (MINLP).

Kong et al [29] presented simple linear programming model (LP) to minimize the overall energy costs for a cogeneration system for combined cooling, heating and power production (CCHP) consisting of a gas turbine, an absorption chiller and a heat recovery boiler. They used several sets of fixed loads of the form of ratios respect to the turbine size. Figure 2.3 shows the configuration of the energy system considered. It was shown in their work that the optimal operation of such system is dependent upon load conditions to be satisfied and that when the electricto-gas cost ratio is very low, it may not be optimal to operate the gas-turbine in the view of energy cost.

Linear programming take advantage of that linear objective function is convex which means that a local minimum is the global minimum within the feasible region. However, the optimum is not necessarily unique where it is possible to have a set of optimal solutions covering an edge or face of the feasible region. In linear programming is relatively is easier and faster to solve however computational expense dependent mostly on the number of constraints and not so much on the number of variables. A major disadvantage is that there are some situations where no optimal solution can be found such as when the constraints contradicts between them (the feasible region is empty) or when the problem is unbounded in the direction of the objective function.

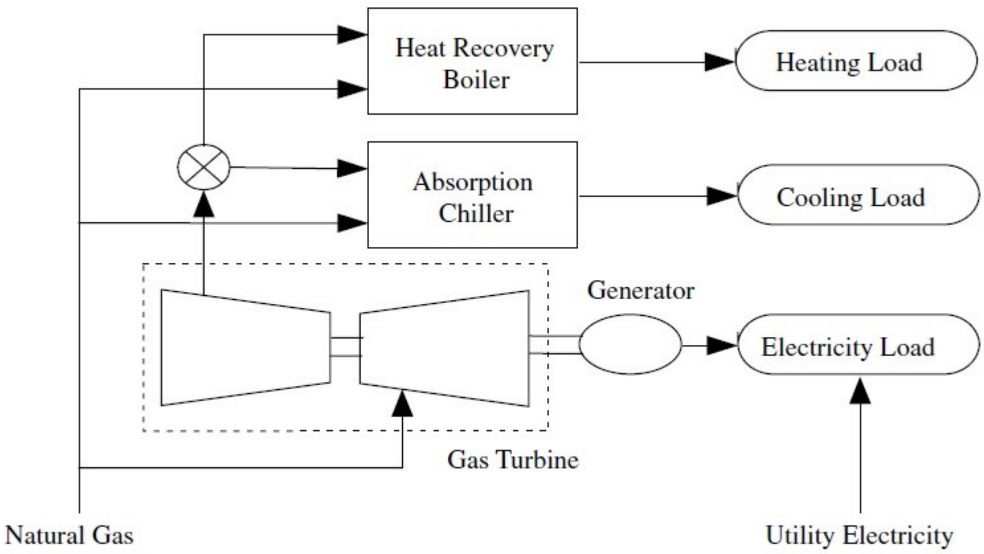

Figure 2.3: Energy flow layout of a gas turbine based CCHP scheme by Kong et al [29].

On the other hand, mixed integer linear programming models (MILP) is an extension of LP where a subset of the variables is restricted to integer values (usually 0-1). Here are several methods to solve MILP problem but the most common one is branch and bound method. The computational expense for this method tends to be proportional to the number of integer variables, constraints, and continuous variables, ordered by importance. This means, the more integer variables the more computational power and time will be required.

Piacentino et al [30] proposed some simplifications into the mixed integer linear programming (MILP) optimization of tri-generation systems like the exclusion of binary variables for the hour by hour unit commitment problem which significantly reduced the consumption of computational resources. They presented an hourly optimization model applied two large buildings in the civil sector where the optimization was carried out for several times considering different numbers of typical days to represent the whole year in order to estimate the minimum number of typical days that must be considered in such optimization model. Figure 2.4 shows the super-configuration and its energy supply system considered in comparison to the conventional, i.e. separate production, system. This work was only intended to offer a new perspective on the problem of the improvement of MILP techniques for district energy systems.

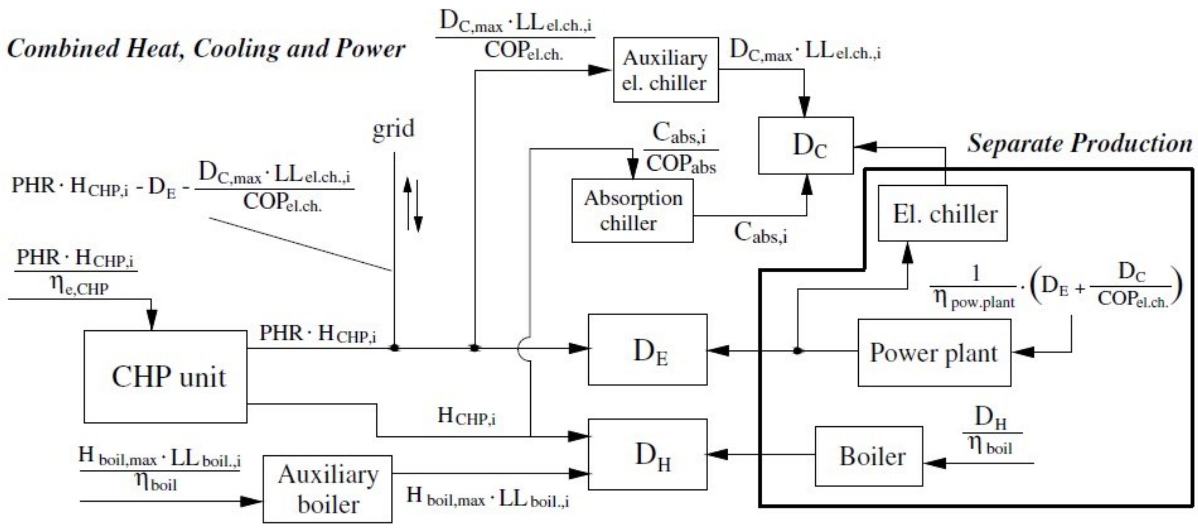

Figure 2.4: Super-configuration of Tri-generation system presented in Piacentino et al [30] compared to a conventional system.

In general, it has been found in the literature that MILP models are the most common used ones between other mathematical models when optimizing the design and operation of district energy systems [31, 32, 33, 34, 35]. The following are some of the works reviewed which are very close to the approach and aim of the work presented in this thesis.

Lozano et Al. [36] have developed an optimization model, using mixed integer linear programming (MILP), to determine the preliminary design of CHCP systems with thermal storage. The objective function is the minimization of the total annual cost taking into account the legal constraints imposed on cogeneration systems in Spain: minimum equivalent electrical efficiency and minimum electrical self-consumption. In this model cogeneration, absorption chillers, thermal storage tanks and the option of distributed boilers and cooling towers were considered as shown in Figure 2.5. However, the model was only concerned with design and operation of the production plant itself but not the energy distribution pipeline network.

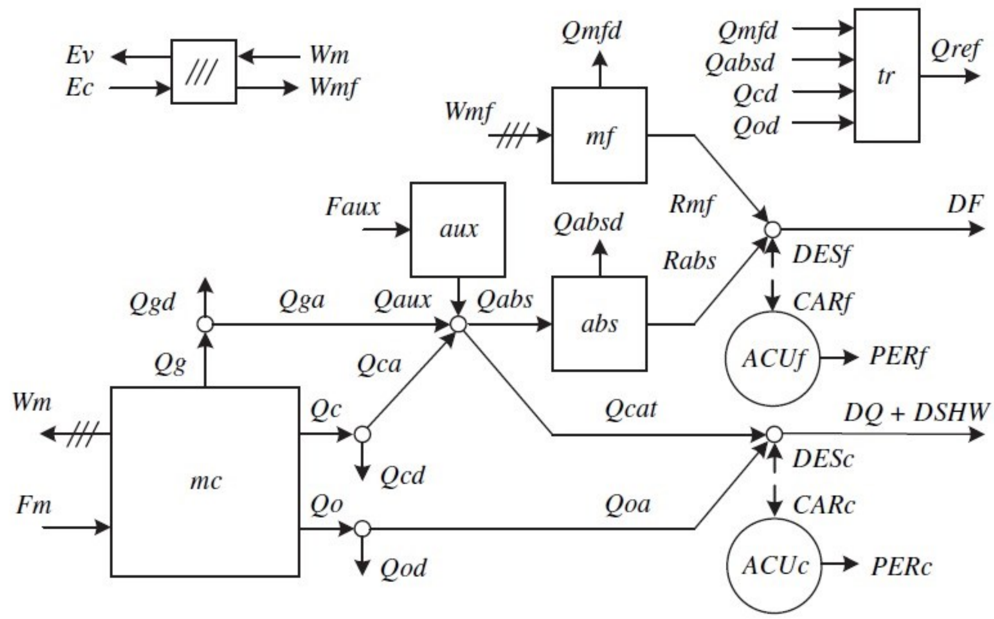

Figure 2.5: Superstructure of the Tri-generation energy supply system presented by Lozano et al [36] including: (1) cogeneration modules (mc), consisting of natural gas engines and heat recovery equipment, (2) auxiliary boilers (aux), (3) vapor compression refrigerators (mf), (4) single effect absorption refrigerators (abs), (5) cooling towers (tr), (6) heat storage (ACUc), and (7) cold storage (ACUf).

Söderman [37, 38] presented overall cost optimization models that include the number and location of possible production sites, the number of possible district pipeline routes and the number of possible energy storage sites. In these models, the possible locations of the generation plants, storages and the main pipelines are to be predefined and the optimization model curries the task of choosing the best possibilities of those locations. In addition, the model assist the decision of which costumers are to be connected to the predefined main network routes and which ones are to be left with individual separated systems. However, only conventional compression cooling machines were considered in this work. Figure 2.6 presents both the predefined main routes network and the optimal layout obtained by the model.

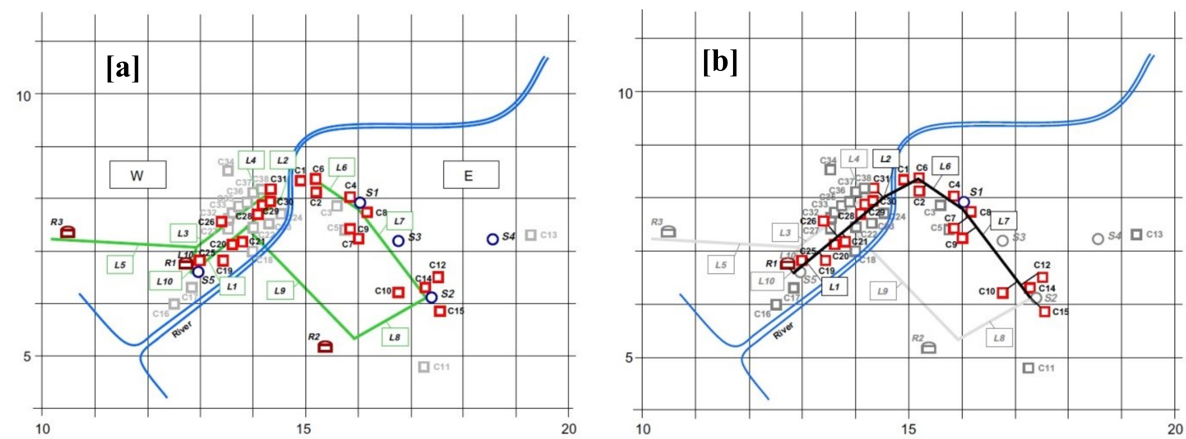

Figure 2.6: Optimization results obtained by Söderman [38]: a) predefined main routes network and locations of plant and storages and b) optimal layout obtained.

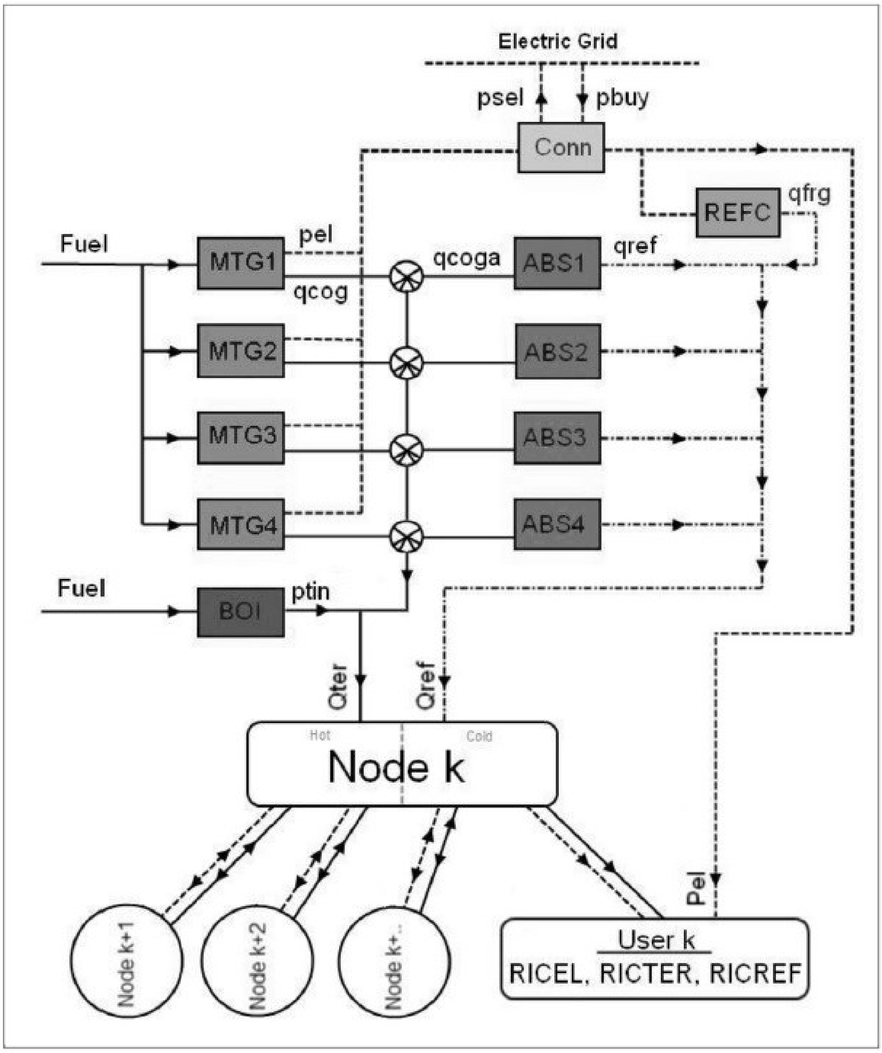

Figure 2.7: Superstructure of the tri-generation system at Node (k) developed by Buoro [39].

Buoro et al. [39] developed a tri-generation model based on MILP that includes micro-cogeneration gas turbines, absorption chillers, boilers and compression chillers. The optimization model specifies the kind, number and location of the cogeneration equipment and the absorption devices, the size and position of the network pipelines. The investment costs of boilers and compression chillers have not been taken into consideration, because in the case under study of this work users were already equipped with one boiler and one compression chiller. In each building up to 4 micro-turbines and up to 4 absorption chillers can be chosen by the optimization procedure. All these devices are size pre-defined. As shown in the scheme of the single user in Figure 2.7, each absorption chiller is directly connected to a corresponding micro-turbine, so that a specific absorption chiller cannot be adopted if the related micro-turbine does not exist, inside the optimal solution.

Chinese [40] has stated that the issue of designing new district cooling and heating systems from the beginning has hardly been addressed in operations research literature up to now. A mixed integer programming model (MILP) was developed for decentralized DHCSs design optimization combining and comparing central and distributed production of heat and cooling under consideration of network costs. Figure 2.8 represent the superstructure of developed model. Both compression and absorption cooling machines were considered however thermal storage technologies and alternative energy resources were not considered in the model. The objective function to be minimized was representing the annual equivalent system cost combining components for capital and operational costs and revenues. The smart grid (tri-generation) model was applied to two real case studies. The study concluded that Distributed generation solutions may lead to better economic performances than centralized solutions.

A more realistic, however less present in the literature, approach to implement and optimize district energy systems is non-linear programming modelling (NLP). More specifically, mixed integer non-linear programming (MINLP), due to the synthesis of district energy systems which requires a large number of integer and continuous variables to be involved particularly when taking design layout optimization into consideration. MINLP problems are usually the hardest to solve, mathematically, unless a special structure can be exploited. However, several researchers have developed models using MINLP [41, 42, 43, 44].

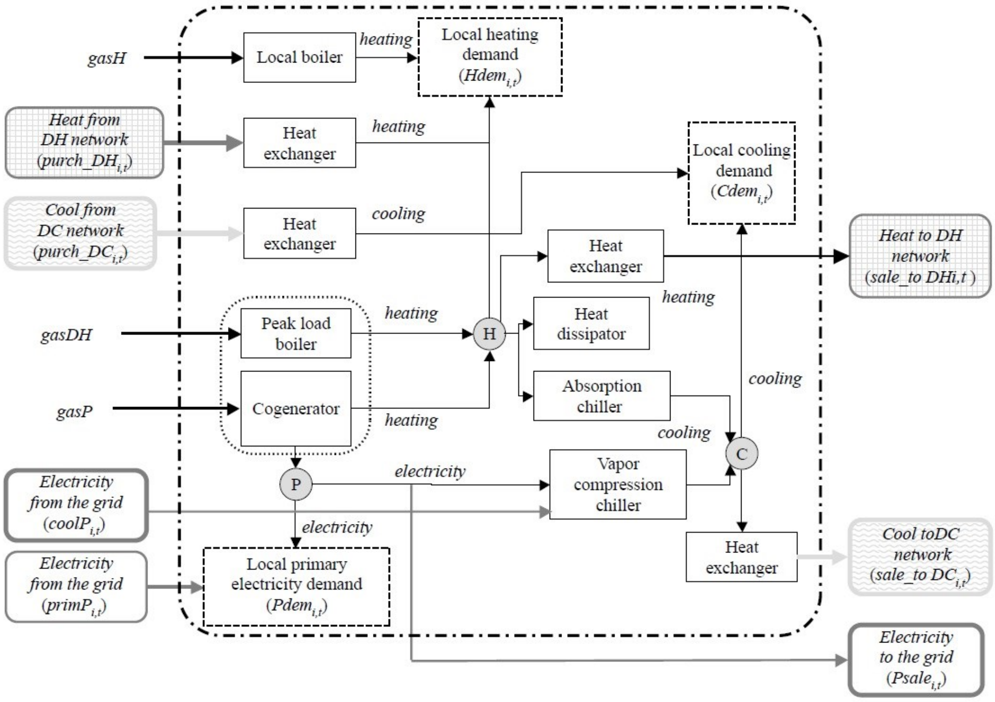

Figure 2.8: Superstructure of the energy subsystem at each node (i) presented by Chinese [40].

Weber et al. [27, 45] have developed a new method to design district energy systems, by decomposing a multi-objective MINLP optimization problem into two sub-problems: 1) A master optimization problem, a multi-objective optimization minimizing CO2 production and total costs, responsible of the selection of the technologies to be used and their design size, the temperature of the fluid in the ongoing-piping of the network, the temperature difference between the ongoing-pipe and the return-pipe of the district network and finally the thickness of the insulation around the pipes. 2) A slave optimization problem, a mono-objective optimization minimizing the costs, defining the optimal network design and operation from the solutions obtained from the master optimization problem. Evolutionary algorithm was adopted to optimize the master problem by computing the trade-offs between the multiple objectives while the slave problem was solved by using MILP model. The resolution method developed comprises three processing phases as shown in Figure 2.9. The study has observed that the results of the optimization were very dependent on the input parameters provided by the model user such as equipment prices.

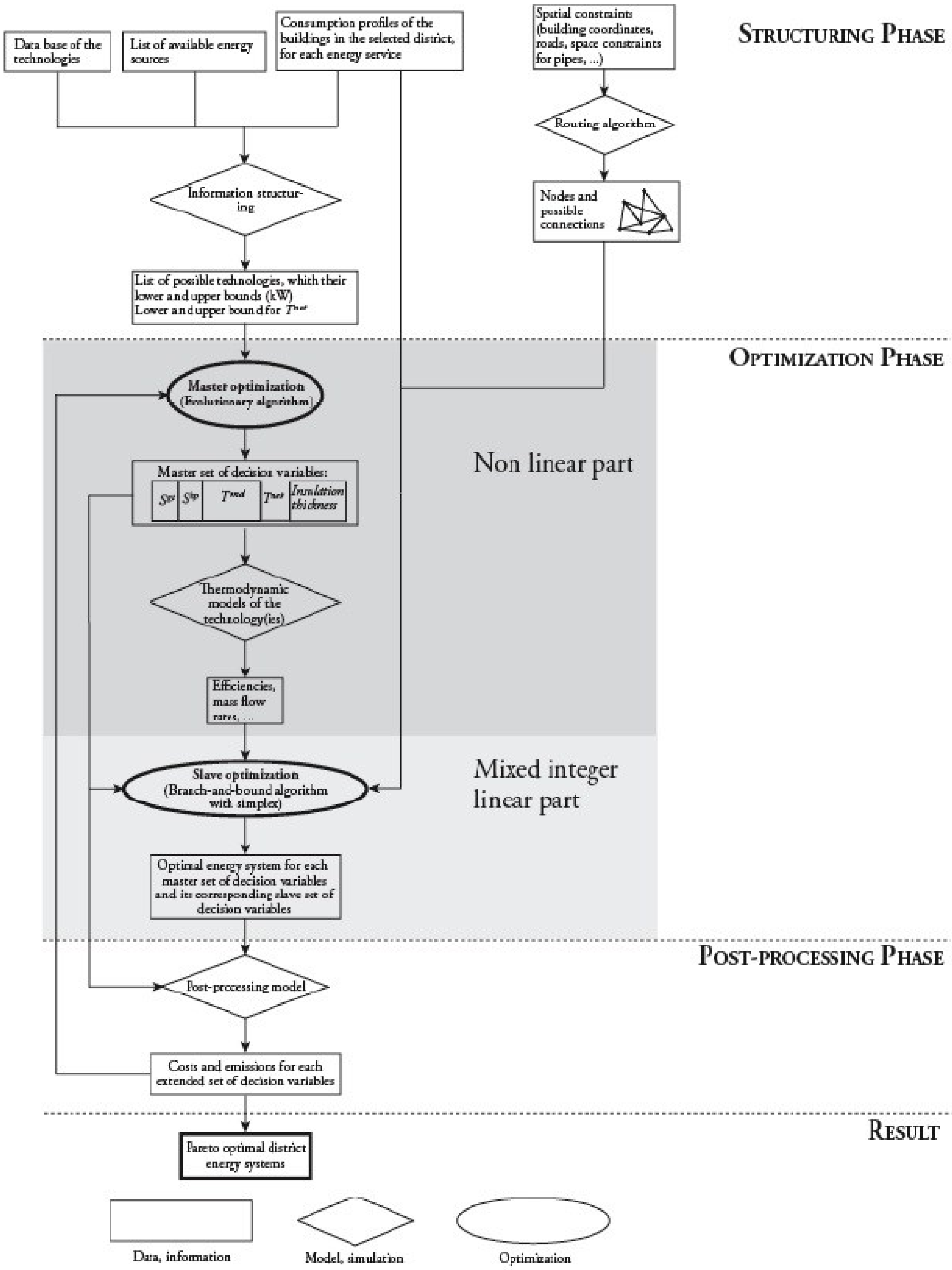

Figure 2.9: Multi-objective decomposition resolution strategy adopted by weber [45].

Coronas and Bruno [46] developed a mathematical model to propose an initial size and analyze the operational conditions and economic analysis of a poly-generation plant. Both linear programming (LP) and non-linear programming (NLP) equations were used to implement the different units and technologies considered in the optimization. The optimal size and operation of each technology is optimized by minimizing economic costs. A simplified block diagram for the complete energy supply system is shown in Figure 2.10. The obtained nominal size of the cogeneration units were almost the same in both LP and NLP models however the total cooling energy production was lower in the NLP case, for the same consumed energy. They suggested that this slight difference was due to the different variation of the COPs with ambient conditions between the two models.

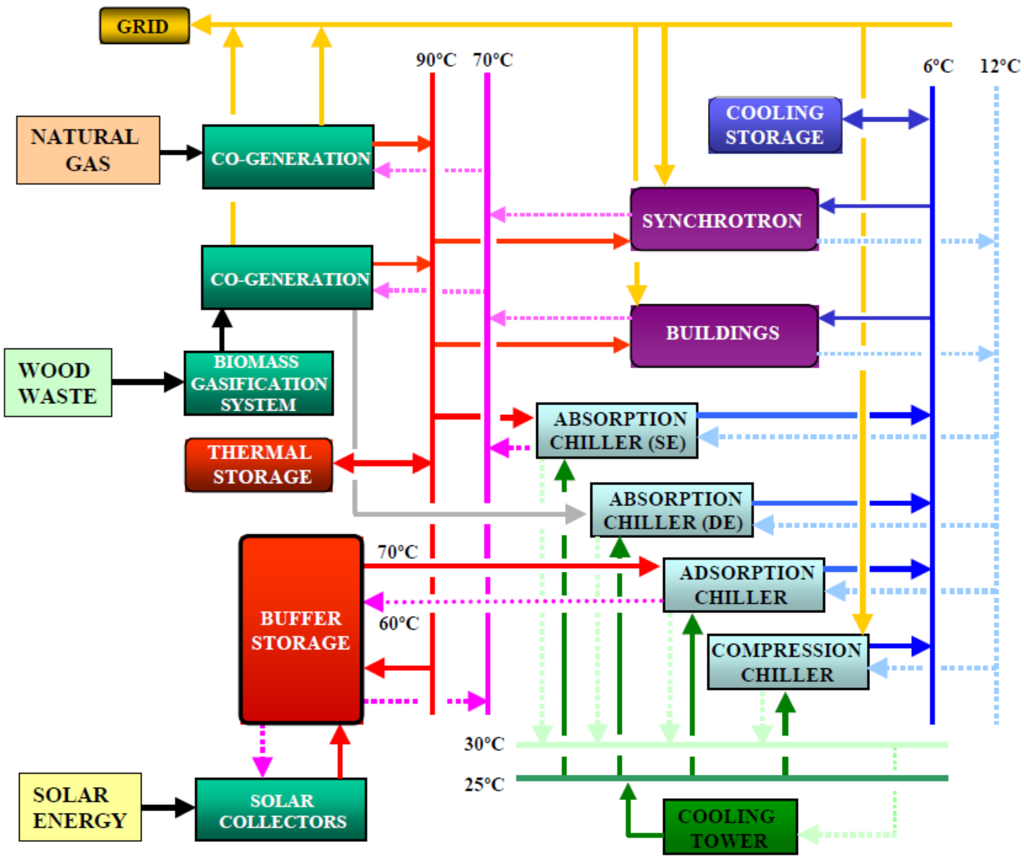

Figure 2.10: Superstructure of the energy supply system for poly-generation presented by Coronas and Bruno [46].

2.5 Multi Objective Optimization

The design of district cooling system also requires the consideration of various technical, economic and environmental aspects. Since that multi attribute methods does not provide decision makers with alternatives especially on design level, multi objective programing became the focus researchers who want to provide decision makers with new alternative solutions based on comprehensive comparisons not only between predetermined systems but also between different individual aspects, e.g. production technologies, within the one system itself.

In multi objective optimization two, or more, of conflicting and non-comparable objective functions are to be optimized. Cost objective function is usually one these objectives and often the first to be thought of. Another common objective is the environmental aspect which is usually represented in the CO_2 emissions resulted from the system. Other objectives, and to a lesser degree, include quality, flexibility, safety …etc. Multi objective solutions are usually generated by solving each single objective several times in respect to each singular solution obtained from the other objective. Thus a set of optimal solutions, each having a certain value for each objective, are found. These solutions are non-dominating points where no other pair can be considered a better solution when compared on all criteria. In other words, it’s not possible to improve one of the objectives of an optimal solution without worsening the other objective. These non-dominating optimal solutions are known as Pareto domain. Later on, it’s up to the decision maker to pick the most suitable solution within the Pareto domain based on their experience and knowledge.

Many mathematical methods have been developed as an attempt to substitute the role of decision makers, however most of them require some preferences input from the decision maker side either at the beginning of the optimization. It has been observed in the literature that there are two common techniques used extensively to address multi objective problems. Those are:

- Weighted sum method: which is basically the summation of the scalar objective functions after the normalizing them since they often are in different units. This is usually performed by adopting different normalizing weights for each objective function. These weights can also include representation for the relative importance between objectives. Defining the values of these weights is the most critical obstacle in this method.

- Normal constraint method: In which, one of the objectives is selected as objective function while the others are transformed into constraints. Here, defining the limits of the new constraints can be a challenge since these values are very critical in defining the optimal solution for modified problem.

By changing the values of the weights, in the first method, or the constraints values, in the second method, Pareto can be generated especially if the problem was convex. If the problem is non-convex then Pareto domain might still be generated but at a high time computational cost [47]. The advantages and drawbacks of these methods along with other proposed methods to solve multi objective problems are presented by Pohekar [24], Messac [47] and Martinez [48]. However, it has been observed throughout this survey that the normalized weighted sum and its modified versions is the most common adopted technique.

Multi-objective optimization applied to district energy systems, e.g. cogeneration, tri-generation or poly-generation systems, can be found in literature widely [49, 50]. Ren et al. [51] developed a multi-objective optimization model to analyze the optimal operating strategy of a district energy system while combining the minimization of energy cost with the minimization of environmental impact as shown in Figure 2.11. Aki et al [52] used the normal constraint method, where they adopted the annual cost as objective function and took the CO2 emissions into consideration in the form of constraints, in their investigation of three different energy service systems for urban areas. Another approach was presented by weber [27, 45], reviewed previously, to deal with multi objective MINLP optimization problem by decomposing it into a master and slave problems solve by two different techniques (Figure 2.9).

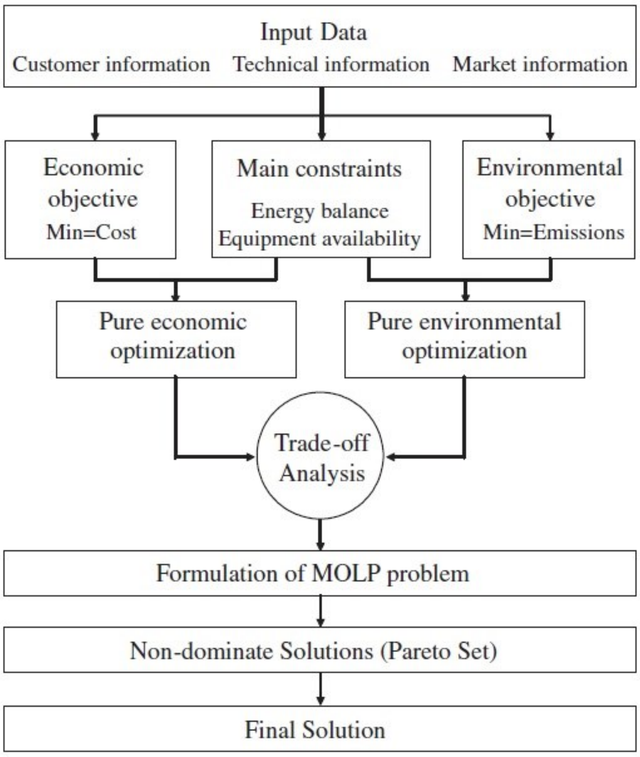

Figure 2.11: Flow chart of the multi-objective optimization model developed by Ren et al. [51].

Genetic Algorithms is another technique that has been adapted, but into a lesser degree, for multi-criteria problems. Kavvadias et al [53] used genetic algorithms to solve a multi objective model for tri-generation plants considering three objectives indicators: economic, energetic and environmental. The adaptation of genetic algorithm was due the non-linearity of equipment efficiency curves as well as the inclusion of economy of scales on the capital cost calculation. Both the energy and information flow diagrams of the multi objective model are shown in Figure 2.12.

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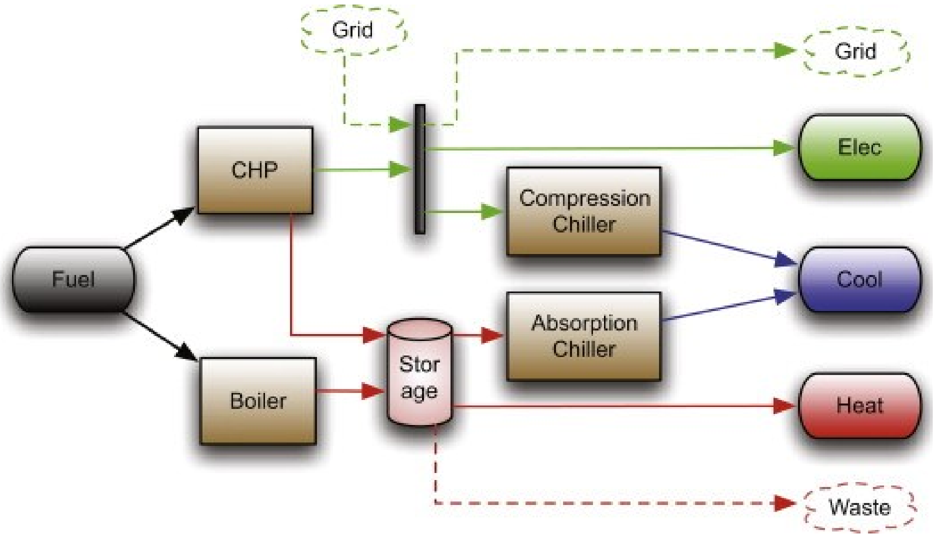

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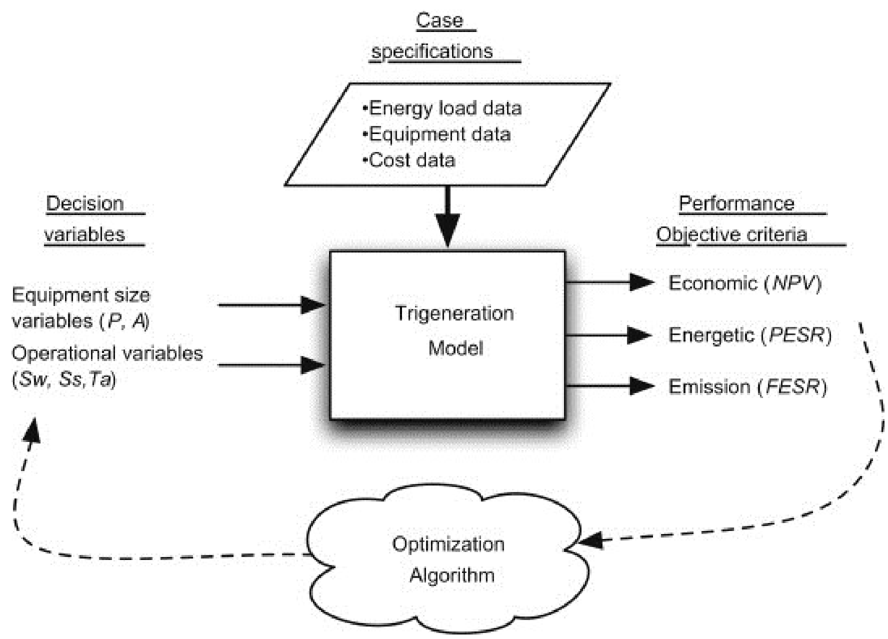


Figure 2.12: Multi-objective optimization model developed by Kavvadias et al [53]: a) Energy flow diagram, and b) information flow diagram.

2.6 Summary and Conclusion

The objective of this work is to develop a decision making tool or model and to use it in obtaining preliminary, i.e. roughly optimized, design configuration and operation strategies for district cooling energy systems while performing economic and performance comparison for different design, e.g. cooling technologies, options with in the process. It has been found in the literature that such assistance can be provided throughout different tools and methodologies depending on how detailed the suggested solutions are intended to be. Energy simulation tools such as TRNSYS and EnergyPro, for example, are supposed to be used to simulate and optimize energy supply systems with high level of details. Actually, the high complexity of the issue regarding the energy planning and management of district energy systems calls for powerful analysis tools at a certain stage in the design process. However, since the preliminary configurations aimed to be obtained in this work are intended to serve as preliminary suggestions for design engineers, urban planners and decision makers where extensive performance investigations are expected to be carried out later on by using scenario simulation tools, it came to our believe that a high detailed model is not a desired option especially at early stages of the design.

After carrying out a brief survey in the state of the art and reviewing several surveys presented by other researchers in the literature regarding different aspects of the subject, it has been concluded that multi objective optimization model can be a useful instrument to support the decision making process. Genetic algorithms and mathematical programming are widely used in the literature for the purpose of optimizing energy supply systems for their high flexibility when developing customized models for certain application or user. Usually adopting genetic algorithm technique requires developing the genetic algorithm to be used in solving the model, while mathematical programming requires only developing the model and not the solving algorithm, which is usually developed by mathematicians. Typically, optimizing the design and operation of a district cooling energy system using mathematical programming is a nonlinear problem with integer variables. Such models can be solved by using mathematical solvers. However, when the model is relatively complex, due to high number of decision variables with several time periods, the problem might not be possible to solve. Therefore reducing the complexity of the problem is essential in mathematical programming. One solution can be dividing the problem into sub-problems or farther reduction in the complexity of the model, e.g. reducing the number of technologies considered or the research space. The most reliable simplification, without having to drop some options out of consideration, is to linearize the non-linear equations in the model. Thus, a mixed integer linear programming MILP model was chosen to develop a multi objective optimization model to carry out the main aim of this work.

Chapter Three

Optimization Model and Environment

Chapter Three

Optimization Model and Environment

3.1 Introduction

Cooling Systems in urban areas are generally categorized into three main types or configurations: Centralized District Cooling Systems where the cooling energy is produced in a central plant and then distributed to the distanced locations, e.g. consumers, through pipelines networks; Separated, or Stand-Alone, Systems where the cooling energy is produced locally in each individual location; and Distributed, or De-centralized, District Cooling Systems where the cooling energy might be produced in multiple locations and distributed through several relatively small pipelines networks or consumed locally. The first and second categories represent the conventional systems in the market while the third category is a new trend which has been promoted, increasingly, throughout the last two decades due to its lower life time cost, higher control possibilities and better impact on the environment [40]. Considering the wide range of networking options, cooling energy producing technologies and energy resources integrating possibilities, optimal design and operation of the system comes out as an essential aspect in designing urban cooling systems especially when limited information is available such as at the first stages of the decision making process. The extensive literature survey has shown that mathematical programming is widely used for optimizing the design and operation of cooling systems for urbans under both economic and ecologic objectives. Hence, mathematical programming implemented in GAMS (General Algebraic Modeling System) language is used for developing the optimization model in this work.

The goal of this chapter is to present the different models for the cooling system units and equipment as well as the mathematical algorithm of the optimization model. The optimization environment is another integral part of this chapter. Section 3.2 investigates the cooling energy demands of the buildings and while the method used for selecting typical days for the simulation is presented in sub-section 3.2.1, the following sub-section presents the energy simulating technique used to model the residential and office building in the case studies. Section 3.3 provides a comprehensive overview to the optimization model through: Defining the problem of the urban cooling system to be optimized (sub-section 3.3.1); a super structure comprising all the equipment and technologies to be considered in the design process (sub-section 3.3.2); the energy balances controlling energy transaction throughout the superstructures of each location and the pipeline networks connecting them (sub-section 3.3.3); the cost objective function along with the pricing system (sub-section 3.3.4); units and equipment models and their governing equations and constraints (sub-section 3.3.5); CO2 emissions and primary energy consumption objectives (sub-section 3.3.6); multi objective model (sub-section 3.3.7). A general overview of the GAMS optimization environment and the mathematical solver are presented in section 3.4.

3.2 Cooling Energy Demand

Using an optimization model to design a cooling energy supply system requires many inputs such as weather data, locations characteristics, equipment prices, primary energy prices, etc. Cooling energy demand profiles are essential inputs for the optimization process. Therefore, these profiles have to be estimated at the very beginning based on a suitable methodology depending on the available information. Cooling energy demand profiles differ according to the type and use of the urban area. Residential districts are categorized with high variable cooling demand profiles while industrial or commercial districts have a more constant cooling demand profiles due to the nature of the use. Swan et al [54] presented a review of modelling energy demand where two main approaches were identified: 1) Top-down approach, where overall sectors are treated as an energy sink without distinguishing energy consumption due to individual end-uses. 2) Bottom-up approach, where the energy consumption of individual or group of houses are calculated and then extrapolated to represent a region or district. Since that the cooling energy demand profiles for each individual building is required in this work, only bottom-up approach will be considered.

Bottom-up approach can be conducted through statistical or simulation models. In statistical models the cooling energy demand is estimated based on historical information and measurements collected for each particular building type. In the simulation models buildings are simulated based on heat transfer and thermodynamic relationships. Simulation is the only approach that can estimate cooling load profiles for non-existing, i.e. planned to be built, buildings where no historical information are available.

3.2.1 Typical Days

When using optimization models to simultaneously optimize both configuration and operation many factors, parameters and variables are to be considered in the optimization process such as type and number of units, nominal capacities of technologies and pipelines, primary energy consumed, cooling energy produced, investment operation costs, …etc. Due to the large number of parameters, variables and the possible feasible combinations of equipment and networking, optimization models might require a very long run time to reach the optimal solution. In other words, the more detailed the model, the more complex and difficult it is to solve. One of the most important factors in an optimization process is the time periods. When the model is too complex, the time periods should be reduced and when the time periods considered are too high then the model should be simplified.

Ortiga J. [55] has stated that there are two main schemes for time steps according to type of the building or district being considered. 1) Multi-period or long time periods for industrial applications due to their constant cooling energy demands which depends on the production process where it tends to be constant at each time period and fairly independent of ambient conditions. 2) Hourly periods of representative days for residential applications which are, usually, highly influenced by the ambient conditions and occupation pattern.

Many researchers, in the literature, have used different approaches to select the typical days and their number to represent a full year or certain periods. Yokoyama et al [56], Renedo et al [57] and Chicco et al [17] presented three typical days demand profiles, one day for winter, one day for midseason and another day for summer. Each one of these days represents the common pattern of its season. Beihong et al [42], Seo et al [58] and Lozano et al [36] have used twelve typical days, one representing each month of the year. Yoshida et al [33] used two more days representing the heating and cooling peak-demand days in addition to the twelve typical days of the year. Ortiga J. [55] proposed selecting a minimum number of typical days where he found out that it is not necessary to distinguish between working and non-working days and that some variables could be more affected by the profiles of the selected typical days more than the number of days selected. However, he also stated that other criteria in the selection of typical days, such as one representative day for each month, should be used when considering variable tariff prices. Since that variable electricity and primary energy prices are in the consideration of this work, representative days for each month are used here. And because this work is concerned only with the cooling season, summer, only 6 typical days are chosen representing the months of April to September. The selection criteria and process of selecting these representative days are to be presented within each case study in the following chapters.

3.2.2 Estimating the Energy Demand for Buildings

Many simulation tools exist in the literature which can be used to simulate individual buildings or a whole district to estimate the cooling energy demand profile of that building or district. The use of these simulation tools requires the availability of some input data depending on the chosen tool, such as construction materials of the building, type and schedule of the occupancy pattern, weather data, and the number, sizes and/or capacities of equipment and devices located in the buildings.

In this work the cooling energy demand for each individual building was estimated using TRNSYS which is a transient simulation tool with an open modular structure that simulates different energy sectors of an energy system. Each equipment or unit in the energy system is represented by a TYPE (or block) that can be connected to other types (equipment) to create the energy system. Every single building investigated in this work was simulated using TRNSYS and thus the cooling demand profiles were generated. These profiles are essential inputs for the optimization model. Table 3.1 shows examples of input data required for two different buildings considered in this work. More details about the buildings are to be presented in the case studies which are to be presented in details in the following chapters. Figure 3.1 demonstrates the TRNSYS simulation model for a one zone building used to estimate the energy demand.

Table 3.1: Examples of the main input data to the TRNSYS simulation.

Building type / data	Residential Building (from CS1)	Office building (from CS2)
Building name/code	N1a1	N1 (Mech.)
Area	675 m^2	1380 m^2
Height	9.5 m	14 m
Orientation	S-N	SE-NW (45º)
Glass area percentage of the front outside surface area	22 %	26 %
Max. number of occupants	36 Persons	1000 Persons
Occupancy schedule at a week day	12 Persons (7am - 2pm) 36 Persons (2pm - 7am)	1000 Persons (7am - 3pm) 0 Persons (3pm - 7am)
Occupancy schedule at a weekend day	36 P (24 hours)	0 (24 hours)
Ventilation	0.5 Air-ch/hr (24 hours)	0.5 Air-ch/hr (7am - 3pm)
Average lightening	5 W/m^2	5 W/m^2
Infiltration	0.5 Ach/hr	0.5 Ach/hr
Computers /Equipment /Printers	60 Units (7 am - 12 am) 12 Units (12 am - 7 am)	300 Units (7 am - 3 pm)
Cooling set temperature	24ºC (24 hours)	24ºC (7am - 3pm)

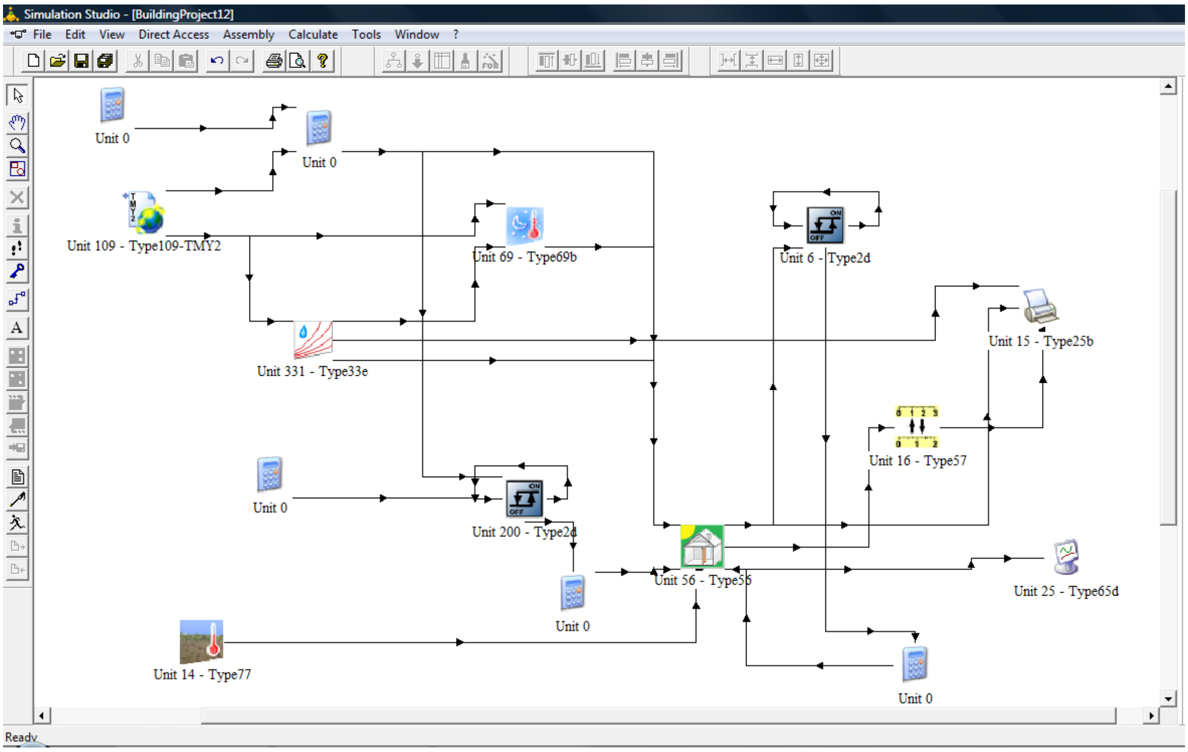
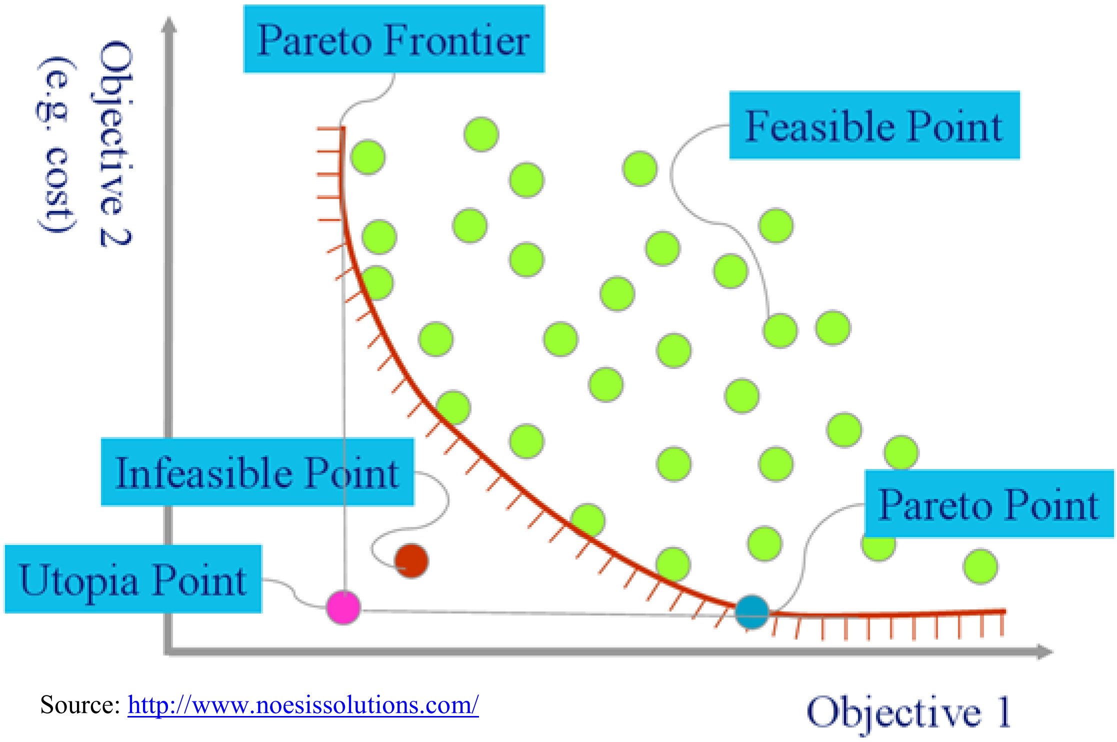


Figure 3.1: TRNSYS model for one zone building using type 56.

3.3 Optimization Model

The literature survey carried out in this work, i.e. chapter two, has concluded that multi objective optimization model can be a useful instrument to support the decision making process especially after taking into consideration that the different objectives in consideration are conflicting. Total annual cost and CO_2 emissions, which are the focus of this work, are conflicting objectives. It was also observed that simplification of the a complex mathematical model, such as optimizing the design and operation of a district cooling energy system, is essential to obtain solutions in a reasonable time frame especially that this model is support to support early stage decision making process. Considering the wide range of possible network structures and capacity planning options, it becomes extremely essential to compare and analyze the trade-off between the scale economies in centralized solutions and those in the decentralized solutions in order to reach optimal solutions. This can be achieved by using binary variables accounting for fixed cost components [40]. Mixed integer linear programming MILP techniques have been applied in the optimization of cogeneration and tri-generation systems by several authors [36].

Therefore, linearizing the complex model into a MILP model was adopted as an approach to address the aims of this work which is obtaining DC solutions that fulfill the conflicting objectives in a satisfactory manner for the decision makers. Furthermore, the choice of using MILP in urban cooling systems was driven by the necessity of producing a realistic comparison of centralized and decentralized solutions. Thus, Pareto Frontier is to be generated by obtaining several solutions based on the decision makers' preferences. Figure 3.2 presents a simplified demonstration of Pareto Frontier. A Pareto solution is basically defined as a solution that no further enhancement to any of the objectives is possible without harming at least one of the other objective. Enhancement on all objectives beyond the Pareto Frontier is mathematically infeasible.



Source: http://www.noesissolutions.com/

Figure 3.2: Pareto Frontier distinguishing between feasible and infeasible solutions in multi-objective optimization.

3.3.1 Problem Definition

A typical urban cooling system consists of several cooling consumption locations, i.e. buildings, which are usually different in application type and occupation pattern and therefore, different cooling load profiles. It comprises also one, or more, cooling energy production plants. The pipelines network is a common element in the DC system to distribute the cold water among the production, storage and consumption sites. A very important component in the UC system would be the cold water storages and their locations. These locations are used to store the circulation water during low consumption periods and re-supply the cold water into the network during high consumption periods.

The decision of integrating solar technologies into urban cooling, especially in sub-tropical regions, is a technically feasible way to replace the electric refrigeration machines, minimize the consumption of fossil fuels, subsequently reduce the greenhouse gas emission and eventually reduce the effect of climate change and global warming [59, 60].

In this work, two cooling technologies to produce cooling energy have been considered: a) Compression chillers powered by electricity grid, PV-panels or both. b) Absorption chillers connected to a boiler powered by natural gas supply line or to solar energy technologies, e.g. vacuum tube collectors and/or trough solar concentrators. Figures 3.3 and 3.4 represent the possible constructions of the cooling energy generation unit to be installed at each site including all the technologies integrated to the model.

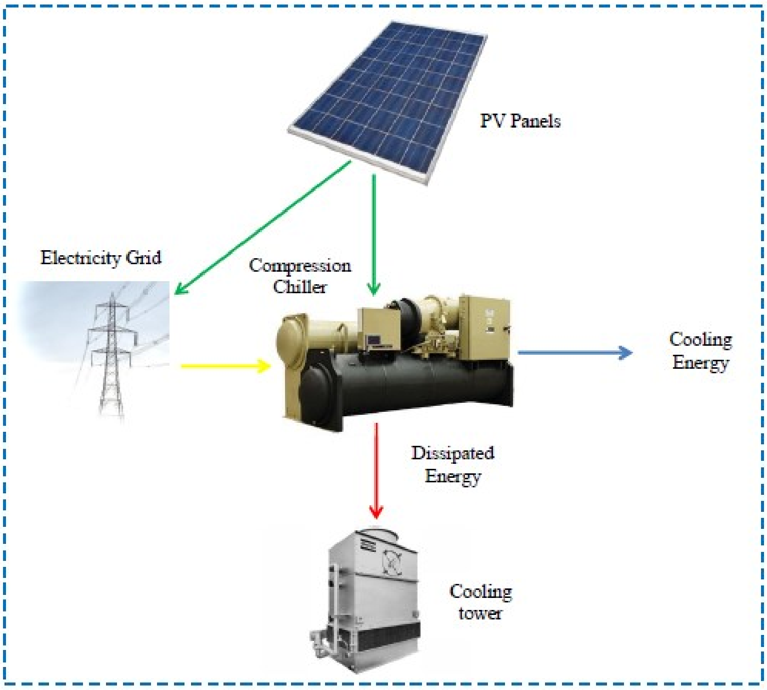


Figure 3.3: First configuration option for the cooling energy generation plant on site (i).

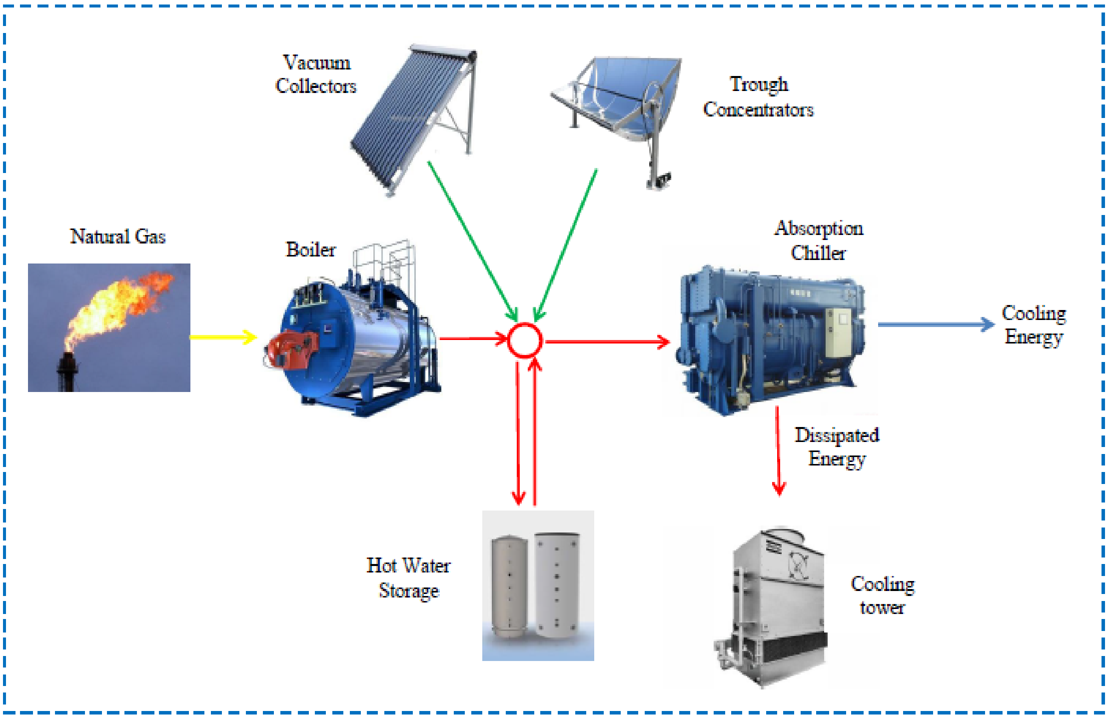


Figure 3.4: Second configuration option for the cooling energy generation plant on site (i).

3.3.2 Super Structure and Energy Balances

A MILP model was developed, considering local energy balances and overall network configuration, to optimize the structural design and operational parameters of the cooling system. That includes the size and location of each equipment in the system, the size and location of the each distribution pipeline, the energy flow rates in those pipelines and how the production and storage units should be hourly operated to cover the hourly cooling load of each building in the district. The model comprises a group of sets:

1) Site or Node Set (i) representing all possible locations for cooling plant sites, cold storages or consumers.
2) Equipment set (equ) representing all possible units to be installed at site (i) i.e. compression chiller (comp), absorption chiller (abs), boiler (blr), cold storage tank (str1), hot storage tank (str2), heat dissipater (dis), heat exchangers (ex1 & ex2), PV-panels (pv), vacuum tube collectors (sol1), trough solar concentrators (sol2) and user-site unit (usr).
3) Time set (t) containing a number of representative days of the year with each day having a number of time steps or periods.

In this model, each location is a possible plant, storage, consumer or all three together. It's up to the optimization model to decide which type of technology is to be installed in each site. If a certain location has a cooling demand profile, then a consumer (user) unit is to be installed there. Later the model is to decide how the cooling demand of this user is to be covered. Basically a costumer would have one of three options. The first one is to have its own separated or stand-alone cooling system. The second is to be connected to a full district network known as centralized district cooling system where everyone else is connected to it. The third option is to be combined with few other costumers in a small district network other than the main network which known in this work as de-centralized district cooling systems.

Each location also has the possibility to serve as a cooling energy production plant as long as it has the free space required to install such plant. Thus there are no pre-defined possible plant locations. Figure 3.5 shows, schematically, the basic energy flow structure of the cooling network. The nodes (i, j and k) represent the physical locations where the cooling energy can be offered or requested, e.g. buildings, storages, or plants. The nodes can also be a pure network connection point of few or several network branches. The lines, arrows, represent the possible network branches connecting one node to another as well as the energy flow direction.

Figure 3.6 shows a superstructure at any location (i), comprising all equipment and technologies which are possible to be installed at this site. The blue arrows represent the cooling energy flow direction among the equipment. The red arrows represent the hot energy flow direction. While the yellow and green arrows represent the flow direction of the electrical and fuel energies respectively. Each site (i) has the possibility to receive cooling from the DC network through the heat exchanger (ex1) and also to provide cooling energy to the DC network through heat exchanger (ex2). It is logical that in most cases only one of these scenarios is going to be chosen depending on whether this site is going to serve as a consumer or as a provider. When the location is to serve as both consumer and provider, the heat exchanger (ex1) might not be needed because the local cooling demand will more likely be covered by the cooling energy produced in the same location. Regardless of the cases explained above the optimization model is still designed so that it allows any location to be connected to the network through ex1 or ex2 or even both of them together. The reason of that is that to take a very special case into consideration. When a certain site is serving as production plant but with a limited capacity or time-depended capacity (such a case is highly expected to be faced when including the solar energy as a driving power of the absorption chillers), extra cooling energy might be imported from the DC network at the high cooling load hours while the same location might still serves as a provider to the network in the low cooling load hours.

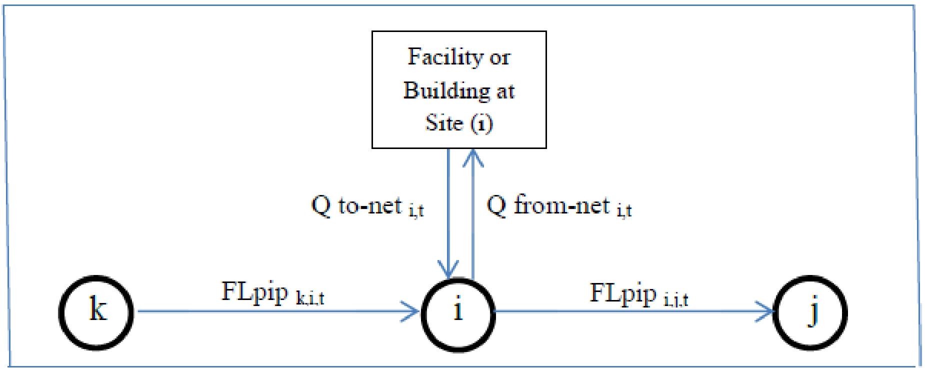


Figure 3.5: Energy-flow structure of the UC network at site (i).

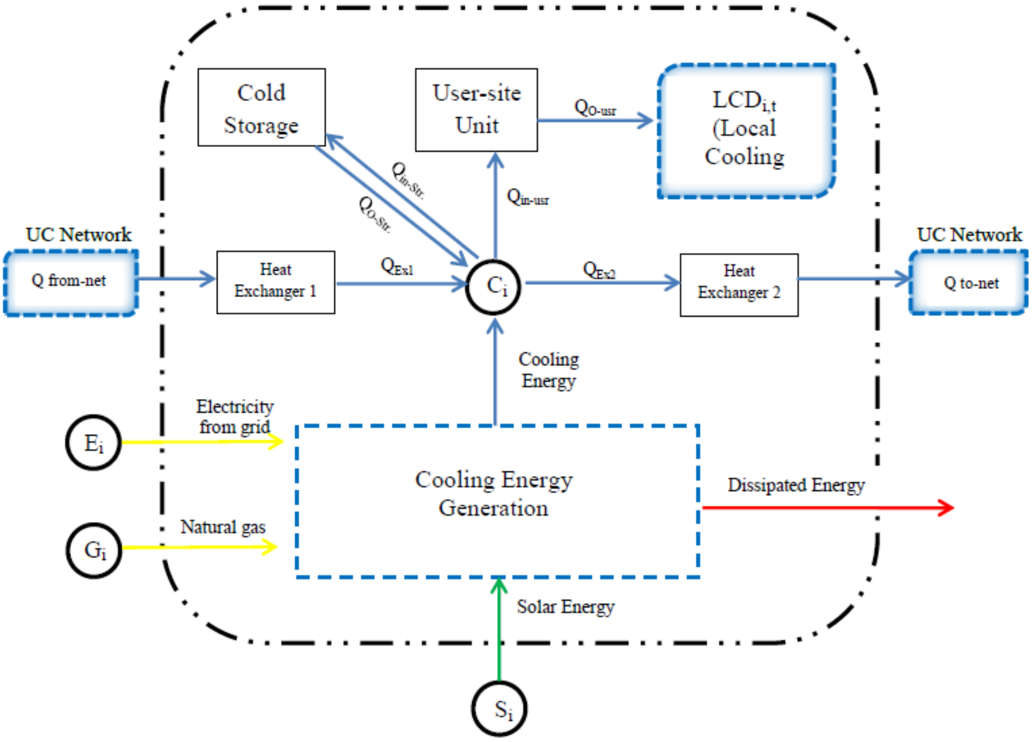


Figure 3.6: Local Cooling Energy System (Superstructure) at site (i). Where: G_i represents the local fuel (Gas) supply system, E_i represents the local electricity supply grid and C_i represents the local cooling supply piping system.

Looking back to the overall problem, an optimal structure can only be reached when considering the optimal operation of the system's different components on an hour-by-hour basis throughout the year, which in turn depends on energy market prices [36]. In this study, an hourly local cooling demand (LCD) is presented for each location, as shown in Figure 3.6, which is expected to have a great influence on the optimization process.

3.3.3 Energy Balances

A local system cooling energy balance at site i (at point *Ci* in Figure 3.6) have been obtained, eq. (3.1). This equation is essential to assure that the cooling demand at each location is being satisfied either by costumers own cooling device or from the DC network. By considering a network cooling energy balance at each node, e.g. node i in Figure 3.5, it is observed that the sum of all flows entering the node i equals the sum of all flows exiting that node, i.e. eq. (3.2). An overall energy balance for the network can be obtained by considering that the sum of cooling energy quantities entering the DC network from various substations should equal in every time period (t) the sum of cooling energy quantities leaving the DC network to the substations, i.e. eq. (3.3).

$$Q_{O_{"ex1",i,t}} + Q_{O_{"Comp",i,t}} + Q_{O_{"Abs",i,t}} + Q_{O_{"Str1",i,t}} = Q_{in_{"ex1",i,t}} + Q_{in_{"usr",i,t}} + Q_{in_{"Str1",i,t}} \quad \forall i, \forall t \tag{3.1}$$

$$Q_{to-net_{i,t}} + \sum_{k,i:k\neq i} FL_{pip_{k,i,t}} = Q_{from-net_{i,t}} + \sum_{i,j:i\neq j} FL_{pip_{i,j,t}} \quad \forall i, \forall t \tag{3.2}$$

$$\sum_i Q_{to-net_{i,t}} = \sum_i Q_{from-net_{i,t}} \quad \forall t \tag{3.3}$$

3.3.4 Cost Objective Function

The optimization was defined, at first stages, as to minimize the overall annual cost of the cooling system. As presented in eq. (3.4), the objective function considers both the investment and operational costs of all equipment and network of the DC system.

$$\text{min. } Z_C = \{C_{inv} + C_{opr}\} \tag{3.4}$$

The MILP model for the multi-period, i.e. multiple time steps, design and operational planning problem is characterized by integer variables which determines the location and number of units installed, and also by continuous variables for the representation of nominal capacities and energy flows.

3.3.4.1 Pricing System

The investment cost of each equipment (e.g. chillers, storage tanks, boilers, heat exchangers, PV-panels, solar collectors, … etc.) or pipeline is defined using the annuity method as presented in equation (3.5), which represents also the linearized price function of the equipment or pipeline. It consists of two main parts:

- A size-depended price coefficient (*CCv*) multiplied by a continuous variable representing the nominal capacity of the equipment at site *i* (CAP_i). For the network pipelines, the nominal energy flow rate ($NFLpip_{i,j}$) is used.

- A fixed price coefficient (*CCf*) multiplied by a binary variable (Y_i) representing the existence of the equipment. The binary variable gets a value of (1) only in the case of equipment existence (a positive value for the capacity variable), otherwise it obtains the value of (zero).

$$C_{inv} = f_{equ} \cdot \left[CCv_{equ}.CAP_i + CCf_{equ}.Y_i\right] \tag{3.5}$$

The annuity is obtained using an annuity factor (*f*), which is calculated as presented in equation (3.6). Where (n) is the unit (equipment or pipeline) life time in years and (r) is the Investment factor. The values of n for each equipment and pipeline in this work are assumed to be 20 and 50 years, respectively, and r is 5%. Different annuity factors for different equipment can be obtained using different life time investment factors.

$$f_{equ} = \frac{(r+1)^n.r}{(r+1)^n-1} \tag{3.6}$$

Figure 3.7 shows an example of linearized cost function of a single-stage absorption chiller. The values of the size-dependent and fixed cost (price) coefficients of various equipment are listed in Table (3.2).

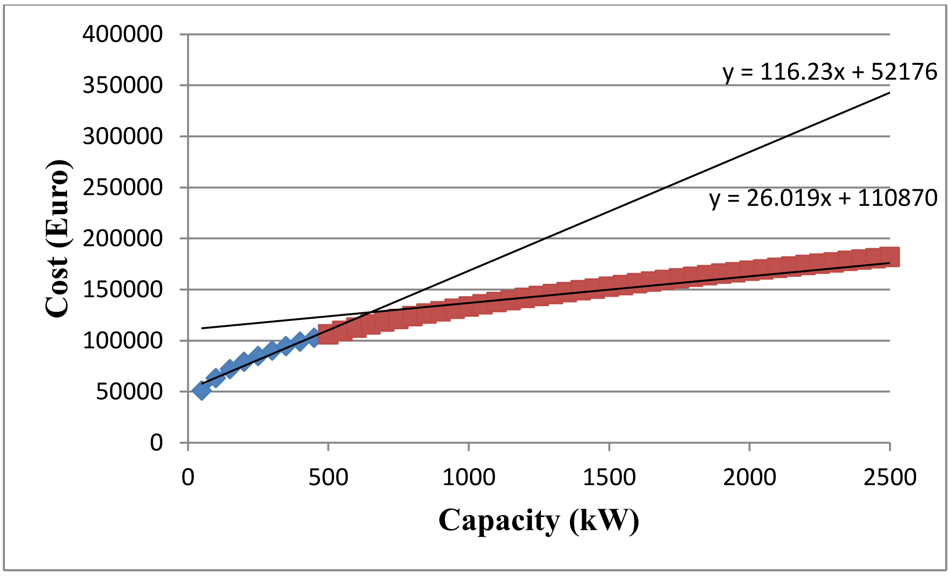


Figure 3.7: Linearized costs function of a single-stage absorption chiller. Original function being: [$C_{inv.} = (14740*X^{-0.6849}+3.3)*X$]. Where, X represents the Nominal Capacity in (kW).

Table 3.2: Size-dependent and fixed cost coefficients of cooling system equipment.

Equipment	*CCv* (Euro/kW)	*CCf* (Euro)	Price Function [7] [61]
Compression Chiller	112.14	27679	$=(4732*X^{-0.7382}+109.3)*X$
Absorption Chiller (Single Stage)	116.230 [1] 26.019 [2]	52176 [1] 110870 [2]	$= (14740*X^{-0.6849}+3.3)*X$
Heat Dissipater (Cooling Tower)	37.42	312.93	$= 37.42*X+312.93$
Network Pipes (Digging+supply+ return)	0.2487 [3]	1432.3 [3]	$=[21.4*D^2+201.36*D+163.89]$ $+ 2 * [2775*D+207.9]$ $D= X^{0.5}/183.43$
User-end Utility	56.335	17093	----- [8]
Cold storage	23.817 [4]	4781.1	$=[59.656\ X^{-0.1051}]*X$
Hot Storage	19.259 [4]	1279.5	$= 18.179\ V^{0.6347}$
Heat Exchanger	7.8401	3010.2	$=198.93 * A^{0.8641} + 524.92$
Boiler	30.776	15525	$=F *[4521.33+675.3492*X^{0.5753}]$ $F= 1.1706$
Electrical heater	8.1714	269.29	[62]
PV-panels	1751 [5]	0.0	$= 1751 * X_{peak}$ [63]
Solar 1 (V. tube)	519.95 [6]	2600	[62]
Solar 2 (Trough)	200 [6]	0.0	[64]

1 For X below 500 kW

2 For X above 500 kW

3 The units for the pipelines are per (m) of length

4 The units for the storage tanks are (Euro/kW. h)

5 The units for the PV panels are (Euro/kW peak)

6 The units for the solar collectors are in (Euro/m2 of gross area)

7 X= Nominal Capacity (kW) [except for the Cold Storage (kWh)], V= Volume (m3), A= surface area (m2), D= Diameter (m)

8 Assumed based on the Author's best knowledge

3.3.4.2 Investment Cost:

The total investment cost is the sum of the investment costs of equipment and network pipelines, i.e. eq. (3.7). The annuity method has been used to calculate the investment cost of the equipment units as shown in eq. (3.8). For the network investment cost, i.e. eq. (3.9), the annuity method was also used where the size-dependent cost coefficient was related to the nominal energy flow rate through the pipeline (*NFLpipi,j*) and not to the diameter. This simplification was intended to avoid the complexity of considering the pipeline diameters and the forthcoming need to meet the acceptable commercial diameter sizes in markets. This equation comprises also the network maintenance costs, expressed as a fraction (*mCn*) of the capital cost. In fact, maintenance costs for network pipelines are mainly attributed to inspection and preventive activities and can be approximated as a fixed yearly amount [40].

$$C_{inv} = PC_{inv} + NC_{inv} \quad (3.7)$$

$$PC_{inv} = \sum_i \sum_{equ} f_{equ} \cdot \left[CCv_{equ} \cdot CAP_{equ,i} + CCf_{equ} \cdot Y_{equ,i}\right] \quad (3.8)$$

$$NC_{inv} = \sum_{i,j:i \neq j} \left[f_{pip} + mCn\right] \cdot \left[CCv_{pip} \cdot NFL_{pip_{i,j}} + CCf_{pip} \cdot Y_{pip_{i,j}}\right] \cdot L_{i,j} \quad (3.9)$$

The nominal capacity variable ($CAP_{equ,i}$), in kW, was used to calculate the investment cost of most equipment. However this variable was replaced with the nominal cooling energy storage capacity, in kW.h, for the Cold- and Hot-Storage tanks and with the surface area, in m2, for PV-panels and both thermal solar collectors (Vacuum collectors and Trough concentrators).

3.3.4.3 Operation Cost:

While the annuity method has been used to calculate the investment cost of the equipment units and the network pipes, the annual operational costs were calculated as the sum of operational costs in all time periods as presented in eq. (3.10). Equations (3.11) to (3.16) represent the operational costs which are proportional to operation hours and the instantly outputs (i.e. generated, stored, consumed or distributed cooling effects) [38]. Operation costs taken into account in this model are:

- Equipment operation costs: eq. (3.11).
- Electricity cost for water pumping throughout the network: eq. (3.12).
- Cost of purchased electricity to operate the compression chillers, heat dissipation fans at the cooling towers and electrical heaters after considering PV panels electricity production: eq. (3.13) to (3.15).
- Cost of fuel used to operate the absorption chillers: eq. (3.16).

$$C_{opr} = PC_{opr} + EC_{net-opr} + EC_{p-opr} + FC_{opr} \quad (3.10)$$

$$PC_{opr} = \sum_i \sum_{equ} \sum_t \left[OC_{equ} \cdot Q_{O_{equ,i,t}} \cdot \Delta t\right] \quad (3.11)$$

$$EC_{net-opr} = \sum_{i,j:i \neq j} \sum_t \left[Ce_t \cdot pf \cdot FL_{pip_{i,j,t}} \cdot L_{i,j} \cdot \Delta t\right] \quad (3.12)$$

$$EC_{p-opr} = EC_{purch} - EC_{sold} \quad (3.13)$$

$$EC_{purch} = \sum_i \sum_t Ce_t \left(Ep_{i,t} + R_{dis} \cdot Q_{O"dis",i,t} + Q_{in"htr",i,t} - Epv_{i,t}\right) \cdot \Delta t \quad (3.14)$$

$$EC_{sold} = \sum_i \sum_t Cpv \left(extraEpv_{i,t}\right) \cdot \Delta t \quad (3.15)$$

$$FC_{opr} = \sum_i \sum_t Cf_i \cdot Q_{in"blr",i,t} \cdot \Delta t \quad (3.16)$$

Both electricity and fuel (natural gas) prices are time dependent in this model. Thus a time related purchase tariff including various prices of electricity (depending on the hour of the day) and fuel (depending on the time of the year) can be easily adopted. Table 3.3 shows the energy prices and the running cost coefficients for different equipment of the cooling system. The model was designed so that the electricity production of PV panels would be consumed in the system instantly, at each time step, otherwise sold to the national grid as demonstrated in eq. (3.15).

The annual demand is expressed considering a number of representative days throughout the summer season (e.g. one representative day for each month from April to September) divided into 24 periods of 1 hour each. However, although only representative days have been included in the time set of the model, the operational costs were calculated for the full period considered by assuming similar operational costs at similar time periods.

Table 3.3: Energy prices and the running cost coefficients of cooling system equipment.

Equipment	Coefficient	Value	Units	Ref.
Compression Chiller	OC_{Comp}	0.015	€/kWh	[38]
Absorption Chiller (Single Stage)	OC_{Abs}	0.01	€/kWh	[39]
Heat Dissipater (Cooling Tower)	OC_{Dis}	0.015	€/kWh	[38]
Boiler	OC_{Blr}	0.001	€/kWh	[40]
User-end Utility	OC_{Usr}	0.0004	€/kWh	*
Cold storage	OC_{Str}	0.0023	€/kWh	[38]
Heat Exchanger	OC_{Ex1}& OC_{Ex2}	0.0004	€/kWh	*
Network Pipes (maintenance)	mCn	4.4 %	-----	[40]
Selling price of PV panel electricity to the national grid	Cpv	0.16	€/kWh$_{el}$	[65]
Electricity Price	Ce_{t8-t17} (Load hours)	0.26	€/kWh$_{el}$	[66]
	$Ce_{t1-t7\ \&\ t18-t24}$ (Off-load hours)	0.194		
Fuel price	Cf	0.067	€/kWh$_{th}$	
electricity consumption ratio at the heat dissipater	$Rdis$	4.5 %	kWh$_{el}$ / kWh$_{th}$	*
pumping stations power factor	pf	0.0000095	kWh$_{el}$ / m.kWh$_{th}$	*
Electrical heater	OC_{htr}	0.0	€/kWh	*
PV-panels	OC_{PV}	0.0	€/kWh	*
Solar 1 (V. tube)	OC_{Sol1}	0.0001	€/kWh	*
Solar 2 (Trough)	OC_{Sol2}	0.0001	€/kWh	*

* Assumed based on the Author's best knowledge

3.3.5 Constraints

The objective function is subjected into several constraints regarding energy balances, capacity limits, consistency bounds and available area constraint. All of which were applied on the local equipment and the pipeline network.

3.3.5.1 General Equipment Capacity and Consistency Constraints

There are some logical capacity limits and consistency bounds which have to be satisfied in the optimization model. For example, equipment's output should not exceed, at any location of time, the nominal capacity of that equipment which is expressed in eq. (3.17). An input-output balance has been applied for each equipment unit, stating that the output of energy conversion equipment is the product of the process input and the equipment COP, presented in eq. (3.18). For non-cooling generation equipment (e.g. Boilers, cooling towers, heat exchangers … etc.), COP was substituted with that equipment's efficiency. However, equations (3.17) till (3.19) are not to be applied to the storage tanks, solar thermal collectors nor to the PV panels as it is going to be presented in the following segments. Table (3.4) shows the equipment parameters used within this work.

$$Qo_{equ,i,t} \leq CAP_{equ,i} \qquad \forall i, \forall t \qquad (3.17)$$

$$Qo_{equ,i,t} = Qin_{equ,i,t} \,.\, COP_{equ} \qquad \forall i, \forall t \qquad (3.18)$$

$$\mu_{equ} . Y_{equ,i} \leq CAP_{equ,i} \leq M_{equ} \cdot Y_{equ,i} \qquad \forall i \qquad (3.19)$$

Where M_{equ} & μ_{equ} can be defined as a large and small arbitrary numbers, respectively, or as the max. and min. commercial limits for that equipment.

Equation (3.19) is a consistency bound, basically stating that if a certain type of equipment was not installed at site i then the nominal capacity of that equipment should be set to zero. And vice versa, if the capacity has been set to zero by the optimization model then the binary variable, representing the existence of that equipment, should be set to zero as well.

3.3.5.2 Cooling energy production units (Chillers)

Implementing the constraints presented in equations (3.17) to (3.19) to the compression chillers, their capacity and consistency constraints will lead to:

$$Qo_{"comp",i,t} \leq CAP_{"comp",i} \qquad \forall i, \forall t \qquad (3.20)$$

$$Qo_{"comp",i,t} = Qin_{"comp",i,t} \,.\, COP_{"comp"} \qquad \forall i, \forall t \qquad (3.21)$$

$$\mu_{"comp"} . Y_{"comp",i} \leq CAP_{"comp",i} \leq M_{"comp"} \cdot Y_{"comp",i} \qquad \forall i \qquad (3.22)$$

While for absorption chillers:

$$Qo_{"abs",i,t} \leq CAP_{"abs",i} \qquad \forall i, \forall t \qquad (3.23)$$

$$Qo_{"abs",i,t} = Qin_{"abs",i,t} \,.\, COP_{"abs"} \qquad \forall i, \forall t \qquad (3.24)$$

$$\mu_{"abs"} . Y_{"abs",i} \leq CAP_{"abs",i} \leq M_{"abs"} \cdot Y_{"abs",i} \qquad \forall i \qquad (3.25)$$

Where M_{comp} , M_{abs} , μ_{comp} & μ_{abs} represent the max. and min. commercial limits for the compression and absorption chillers, respectively .

Table 3.4: Technical parameters of DC equipment.

Equipment	*COP*	*η*
Compression Chiller	4 , 5.5 or 7	---
Absorption Chiller	0.8	---
Heat Dissipater (Cooling Tower)	---	100 %
User-end Utility	---	100 %
Cold storage	---	100 %
Hot storage	---	100 %
Heat Exchanger	---	100 %
Boiler	---	90 %
Electrical heater	---	95 %
PV-panels	---	14 %
Solar 1 (V. tube)	---	100 %
Solar 2 (Trough)	---	100 %

As shown in Figure 3.3, the energy input of the compression chiller ($Q_{in"comp",i,t}$) is actually the electricity consumed by the chiller ($Ep_{i,t}$). On the other hand, the energy input of the absorption chiller ($Q_{in"abs",i,t}$) can be obtained through an energy balance over the connection point in Figure 3.4:

$$Q_{in"comp",i,t} = Ep_{i,t} \qquad \forall i , \forall t \qquad (3.26)$$

$$Q_{in"abs",i,t} = Q_{O"str2",i,t} - Q_{in"str2",i,t} + Q_{O"blr",i,t} + Q_{O"htr",i,t} + Q_{O"sol1",i,t} + Q_{O"sol2",i,t} \qquad \forall i , \forall t \qquad (3.27)$$

3.3.5.3 Heat dissipaters / Cooling towers

The total heat dissipated at each energy production location is the sum of heat dissipated from the cooling energy production units, chillers, in that location:

$$Q_{in"dis",i,t} = Q_{d"comp",i,t} + Q_{d"abs",i,t} \qquad \forall i, \forall t \qquad (3.28)$$

Where:

$$Q_{d"comp",i,t} = Q_{in"comp",i,t} + Q_{O"comp",i,t} \qquad \forall i, \forall t \qquad (3.29)$$

$$Q_{d"abs",i,t} = Q_{in"abs",i,t} + Q_{O"abs",i,t} \qquad \forall i, \forall t \qquad (3.30)$$

3.3.5.4 Storage Tanks

Logically, equations (3.17) and (3.18) do not apply to the cold and hot storage tanks. Instead, equations (3.31) to (3.34) were used in a way that the capacity constraints are applied in terms of the amount of cooling energy stored in the Cold- and Hot-Storages, $H_{Str1_{i,t}}$ and $H_{Str2_{i,t}}$, respectively. The constraints for cold storage tanks were presented as:

$$H_{Str1_{i,t}} \leq CAP_{"Str1",i} \qquad \forall i, \forall t \qquad (3.31)$$

$$H_{Str1_{i,t}} - H_{Str1_{i,t-1}} = \left(Q_{in"Str1",i,t} - Q_{O"Str1",i,t}\right) \cdot t \qquad \forall i, \forall t \qquad (3.32)$$

Similar equations were introduced for the hot storage tanks:

$$H_{Str2_{i,t}} \leq CAP_{"Str2",i} \qquad \forall i, \forall t \qquad (3.33)$$

$$H_{Str2_{i,t}} - H_{Str2_{i,t-1}} = \left(Q_{in"Str2",i,t} - Q_{O"Str2",i,t}\right) \cdot t \qquad \forall i, \forall t \qquad (3.34)$$

The efficiencies of the storage tanks were assumed to be (100 %) as shown in equations (3.32) and (3.34), i.e. energy loses through storage tank walls were neglected. Moreover, storage tanks were allowed to have initial stored energy value at each representative day. However, they were required to compensate those initial values by the end of the optimization, i.e. the final stored energy value at each representative day should be equal to the initial value on that day, as presented in equations (3.35) and (3.36).

$$H_{Str1_{i,t_{int}}} = H_{Str1_{i,t_{end}}} \qquad \forall i, \forall t, \forall d \qquad (3.35)$$

$$H_{Str2_{i,t_{int}}} = H_{Str2_{i,t_{end}}} \qquad \forall i, \forall t, \forall d \qquad (3.36)$$

Extra constraints were applied to the storages also. For example, storages were not allowed to store or discharge more than 25% of their nominal storage capacities in each time step, which is one hour. In other words they need minimum 4 hours to charge from zero-energy storage level to a full-energy storage level or the other way around.

$$\left|Q_{in"Str1",i,t} - Q_{O"Str1",i,t}\right| = 0.25 * CAP_{"Str1",i} \qquad \forall i, \forall t \qquad (3.37)$$

$$\left|Q_{in"Str2",i,t} - Q_{O"Str2",i,t}\right| = 0.25 * CAP_{"Str2",i} \qquad \forall i, \forall t \qquad (3.38)$$

3.3.5.5 Boilers

The boiler is, usually, the main driver of the absorption chiller. The energy input of the boiler ($Q_{in"blr",i,t}$) represent the primary fuel, e.g. Natural Gas, energy consumed by the system. Equation (3.18) was adapted to serve as control equation for the energy flow and heat production through the boiler where the COP parameter, shown in the equation, was replaced with a boiler efficiency of 90% as presented in equation (3.39).

$$Q_{O"blr",i,t} = Q_{in"blr",i,t} \cdot \eta_{"blr"} \qquad \forall i, \forall t \qquad (3.39)$$

3.3.5.6 Heat exchangers

The heat exchangers represent the energy transaction units between the production units or the local energy handling units from one side and the cooling network from the other side. Where the energy flow rate entering each location *i* from the DC network represents the energy input of heat exchanger ex1 and the energy output of heat exchanger ex2 represents the energy flow rate leaving each location *i* to the DC network.

$$Q_{from-net_{i,t}} = Q_{in"ex1",i,t} \qquad \forall i, \forall t \qquad (3.40)$$

$$Q_{O"ex2",i,t} = Q_{to-net_{i,t}} \qquad \forall i, \forall t \qquad (3.41)$$

3.3.5.7 User-site unit

This unit represents the local cooling energy handling unit for each consumer. It is to be installed only when there is a cooling demand on that location where the energy output of the user-unit ($Q_{O"usr",i,t}$) must meet the instant local cooling demand ($LCD_{i,t}$) at each location and time step as shown in equation (3.42). The input energy to the user-site unit is controlled by the energy balance at site *i* in Figure 3.6 represented by equation (3.1).

$$Q_{O"usr",i,t} = LCD_{i,t} \qquad \forall i, \forall t \qquad (3.42)$$

Equation (3.43) indicate that the model should not install a user-site unit in a certain location if the there was no cooling demand at all time periods on that location.

$$\mu_{"usr"} . Y_{"usr",i} \leq \sum_t LCD_{i,t} \qquad \forall i \qquad (3.43)$$

3.3.5.8 Electrical heaters

An electrical heater is to be equipped inside the hot storage tank to be used at high demand periods to operate the absorption chiller. This is a supplement considered so often in solar energy driven cooling systems in the market. The efficiency of the electrical heater is assumed to be 95%. Equations (3.45) and (3.46) are constraints to avoid the option of installing an independent electrical heater or to exceed the nominal storage capacity of the hot storage tank.

$$Q_{O"htr",i,t} = Q_{in"htr",i,t} \cdot \eta_{"htr"} \qquad \forall i, \forall t \qquad (3.44)$$

$$Y_{"htr",i} \leq Y_{"str2",i} \qquad \forall i \qquad (3.45)$$

$$H_{Str2_{i,t-1}} + Q_{O"htr",i,t} + Q_{in"str2",i,t} \leq CAP_{"Str2",i} \qquad \forall i, \forall t \qquad (3.46)$$

3.3.5.9 Thermal solar units

Two different solar thermal technologies are considered in this work: Vacuum Solar Collectors (sol1) and Trough Solar Concentrators (sol2). The investment costs of these units were based on the surface area of the collectors installed in the locations.

$$PC_{"sol1"} = \sum_i f_{"sol1"} \cdot \left[CCv_{"sol1"} \cdot A_{"sol1",i} + CCf_{"sol1"} \cdot Y_{"sol1",i}\right] \quad (3.47)$$

$$PC_{"sol2"} = \sum_i f_{"sol2"} \cdot \left[CCv_{"sol2"} \cdot A_{"sol2",i} + CCf_{"sol2"} \cdot Y_{"sol2",i}\right] \quad (3.48)$$

The capacity constraints of the thermal solar units were also based on the surface area along with nominal solar radiation available. Equations (3.49) to (3.54) show the capacity constraints of these units in relation to their surface area and efficiencies.

$$Q_{in"sol1",i,t} \leq SRad_t \cdot A_{"sol1",i} \qquad \forall i, \forall t \quad (3.49)$$

$$Q_{in"sol2",i,t} \leq SRad_t \cdot A_{"sol2",i} \qquad \forall i, \forall t \quad (3.50)$$

$$Q_{O"sol1",i,t} = Q_{in"sol1",i,t} \cdot \eta_{"sol1",t} \qquad \forall i, \forall t \quad (3.51)$$

$$Q_{O"sol2",i,t} = Q_{in"sol2",i,t} \cdot \eta_{"sol2",t} \qquad \forall i, \forall t \quad (3.52)$$

$$\mu_{"sol1"} \cdot Y_{"sol1",i} \leq \cdot A_{"sol1",i} \leq M \cdot Y_{"sol1",i} \qquad \forall i \quad (3.53)$$

$$\mu_{"sol2"} \cdot Y_{"sol2",i} \leq \cdot A_{"sol2",i} \leq M \cdot Y_{"sol2",i} \qquad \forall i \quad (3.54)$$

Where μ_{sol1} & μ_{sol2} represent the minimum commercial limits available in the market for a single unit for both technologies, respectively. On the other hand, *M* represents an arbitrary large number.

3.3.5.10 PV panels

Similar to the thermal solar units, investment cost and capacity constraints for PV panels were calculated based on the surface area, solar radiation and PV efficiencies. The efficiency of the PV panels was assumed to be 14% while the efficiency of inverter used to transfer DC electricity from PV to AC was assumed to be 92%.

$$PC_{"pv"} = \sum_i f_{"pv"} \cdot \left[CCv_{"pv"} \cdot A_{"pv",i} + CCf_{"pv"} \cdot Y_{"pv",i}\right] \quad (3.55)$$

$$Q_{in"pv",i,t} \leq SRad_t \cdot A_{"pv",i} \qquad \forall i, \forall t \quad (3.56)$$

$$Q_{O"pv",i,t} = Q_{in"pv",i,t} \cdot \eta_{"pv",t} \qquad \forall i, \forall t \quad (3.57)$$

$$Epv_{i,t} = Q_{O"sol1",i,t} \cdot\cdot RE_{pv} \cdot \eta_{inv} \qquad \forall i, \forall t \quad (3.58)$$

$$\mu_{"pv"} \cdot Y_{"pv",i} \leq \cdot A_{"pv",i} \leq M \cdot Y_{"pv",i} \qquad \forall i \quad (3.59)$$

Where: RE_{pv} represents the ratio of PV electricity allowed to be sold to the national grid, μ_{pv} is the minimum commercial limits available in the market for PV panels and *M* is an arbitrary large number.

3.3.5.11 Available Area Constraints

Each location has a free available area inside the building which is to be utilized to install cooling system equipment. The amount of this area can be entered into the model by the user (e.g. decision maker, design engineer or feasibility analyzer) according to reality characteristics of the location in consideration. Each main DC unit has a required area to be installed at a certain location that is related to its capacity. The sum of areas required for the equipment to be installed at site (i) should not exceed the maximum available area at that site as shown in equation (3.61). Heat exchangers, electrical heaters and user-site units were not included in equation (3.61) due to their relatively small required areas. However, heat dissipater (cooling tower) was also not included under the assumption that there will be enough area for it on the roof or right beside the location (i).

$$A_{equ,i} = CAP_{equ,i} / ar_{equ} \qquad \forall i \tag{3.60}$$

$$A_{"Comp",i} + A_{"Abs",i} + A_{"Blr",i} + A_{"Str1",i} + A_{"Str2",i} \leq Amax_i \qquad \forall i \tag{3.61}$$

3.3.5.12 Roof Area Constraints

The available roof area is essential for the solar energy technologies (Vacuum Tube Collectors, Trough Concentrators and PV panels). Since that these technologies are to share the same roof area for each site (i), some governing constraints were required. First the surface areas of these units were transferred into a ground area, i.e. the actual roof area to be occupied by each one of these units, by using the area ratio factor (ar_{equ}).

$$GA_{"sol1",i} = ar_{"sol1"} \,.\, A_{"sol1",i} \qquad \forall i \tag{3.62}$$

$$GA_{"sol2",i} = ar_{"sol2"} \,.\, A_{"sol2",i} \qquad \forall i \tag{3.63}$$

$$GA_{"pv",i} = ar_{"pv"} \,.\, A_{"pv",i} \qquad \forall i \tag{3.64}$$

The governing constraint adopted in this work was that the total ground area used to install solar technologies should not exceed 75% of the whole available roof area at each location as shown in equation (3.65). Another constraint was developed to control the mount of roof area to be invested for installing PV panels in case such limitation is required, i.e. equation (3.66). Where ($RA_{"pv"}$) is ratio of area allowed to be used for installing PV panels.

$$GA_{"sol1",i} + GA_{"sol2",i} + GA_{"pv",i} \leq 0.75 * Aroof(i) \qquad \forall i \tag{3.65}$$

$$GA_{"pv",i} \leq RA_{"pv"} \,.\, Aroof(i) \qquad \forall i \tag{3.66}$$

3.3.5.13 Other logical and Consistency Constraints

By reviewing Figures 3.3, 3.4 and 3.6 some logical conclusions stand to reason. For example:

- Since that heating is not included in this study, if there was no absorption chiller installed at site (i) then no boiler, hot storage tank, electrical heater or thermal solar units are to be installed at that site:

$$Y_{"blr",i} + Y_{"str2",i} + Y_{"htr",i} + Y_{"sol1",i} + Y_{"sol2",i} \leq M \,.\, Y_{"abs",i} \qquad \forall i \qquad (3.67)$$

- It's not allowed to install a hot storage tank that works merely on electrical heaters:

$$Y_{"blr",i} \leq Y_{"str2",i} + Y_{"sol1",i} + Y_{"sol2",i} \qquad \forall i \qquad (3.68)$$

- A heat dissipater is to be installed at site (i) only if a compression or an absorption chiller is installed at that site:

$$Y_{"bis",i} \leq Y_{"abs",i} + Y_{"comp",i} \qquad \forall i \qquad (3.69)$$

3.3.5.14 Network Capacity and Consistency Constraints

In this work, we are concerned with the cooling energy flow throughout the DC network in order to meet the cooling demands with the lowest costs possible. The difference between the supply and return temperature has been assumed to be constant. Similar to the DC equipment, DC network pipeline have capacity limitations and consistency bounds. This was implemented by introducing Binary variables (Y_{pip}) for each possible pipeline, i.e. each arc connecting two nodes (i & j), representing the existence of that pipeline and continuous variables (NFL_{pip}) for each pipeline representing the nominal energy flow rate of that pipeline. The cooling energy flow rate (FL_{pip}) transmitted through a certain pipeline (*i,j*) at any time (*t*) should not exceed its nominal energy flow rate, i.e. eq. (3.70). If a certain arc was to be installed between two nodes, then the corresponding binary variable has to be set to 1 to allow a positive value for the nominal flow rate variable of that arc. Otherwise the both variables will be set to Zero. On the other hand, if the nominal flow rate has been set to zero by the optimizer, i.e. no energy transmit is needed between the two nodes, then the binary variable, representing the existence of the pipeline connecting those two nodes, should be set to zero as well, i.e. eq. (3.71). Another consistency bound is that if there was no instant (hourly) heat flow rate at every time period (*t*) then a pipeline should not be installed at (*i,j*), i.e. eq. (3.72). Where; (M) and (μ) represent large and small arbitrary numbers, respectively.

$$FL_{pip_{i,j,t}} \leq NFL_{pip_{i,j}} \qquad \forall (i,j) \;, \forall t \qquad (3.70)$$

$$\mu \,.\, Y_{pip_{i,j}} \leq NFL_{pip_{i,j}} \leq M \,.\, Y_{pip_{i,j}} \qquad \forall (i,j) \qquad (3.71)$$

$$\mu \,.\, Y_{pip_{i,j}} \leq \sum_t FL_{pip_{i,j,t}} \qquad \forall (i,j) \qquad (3.72)$$

In sake of simplification we assumed that if a pipeline, i.e. double pipe: both supply and return, is installed from i to j, then a pipeline from j to i is not to be installed as presented in equation (3.73). A bi-direction flow over the time periods might be considered in future work to obtain a more sophisticated operational optimization model.

$$Y_{pip_{i,j}} \leq 1 - Y_{pip_{j,i}} \qquad \forall (i,j) \qquad (3.73)$$

3.3.6 CO_2 emissions and primary energy consumption objectives

The model contained extra objective functions in addition to the cost reduction objective. Additional objectives into the multi objective optimization model were the reduction of the CO_2 emissions and the primary energy consumptions of the system. Since CO_2 emissions are, originally, related to the primary energy consumption, both objective functions were mostly depended on the operation pattern of the system as presented in equation (3.74). Where most of the CO_2 emitted is related to the amount of electricity and fuel consumed in the various units in the system and the amount of electricity consumed in the pipeline network to circulate the supply and return cooling water. Other sources of CO_2 emissions are the energy consumed at installing the pipelines and the various system units.

$$Z_{CO2} = Co2E + Co2F + Co2Equ + Co2Net \tag{3.74}$$

The amount of electricity consumed at the system can be calculated as the sum of consumption at the major electrical equipment, i.e. compression chiller, heat dissipater, electrical heater, and water pumps in the DC network, after subtracting the amount of electricity produced locally by the PV-panels.

$$Co2E = Co2E_{comp} + Co2E_{dis} + Co2E_{htr} + Co2E_{net} - Co2E_{pv} \tag{3.75}$$

$$Co2E_{comp} = \sum_i \sum_t \left[O2_E .\ Ep_{i,t} . \Delta t\right] \tag{3.76}$$

$$Co2E_{dis} = \sum_i \sum_t \left[O2_E .\ R_{dis} . Q_{O"dis",i,t} . \Delta t\right] \tag{3.77}$$

$$Co2E_{htr} = \sum_i \sum_t \left[O2_E .\ Q_{in"htr",i,t} . \Delta t\right] \tag{3.78}$$

$$Co2E_{net} = \sum_{i,j:i\neq j} \sum_t \left[O2_E . pf . FL_{pip_{i,j,t}} . L_{i,j} . \Delta t\right] \tag{3.79}$$

$$Co2E_{pv} = \sum_i \sum_t \left[O2_E .\ Epv_{i,t} . \Delta t\right] \tag{3.80}$$

Another major source for CO_2 emissions is the fuel consumed at the boiler in order to provide hot water to drive the absorption chillers. These emissions can be estimated as the sum of the thermal energies entering the boiler throughout its operation periods multiplied by a conversion factor, presented in Table 3.5.

$$Co2F = \sum_i \sum_t O2_f . Q_{in"blr",i,t} . \Delta t \tag{3.81}$$

The process of installing DC pipelines, chillers, boilers, storages and other system units also result, usually, in some CO_2 emissions which are mostly related to the size of the equipment or pipeline being installed. In order not to limit the CO_2 emission objective to the operation pattern only, some conversion factors that estimate the amount of CO_2 emitted at installing different DC system units and network pipelines were assumed.

$$Co2Equ = \sum_i \sum_{equ} \left[O2_{equ} .\ CAP_{equ,i} . \Delta t\right] \tag{3.82}$$

$$Co2Net = \sum_{i,j:i\neq j} \sum_t O2_{Net} .\ NFL_{pip_{i,j,t}} . L_{i,j} . \Delta t \tag{3.83}$$

Table 3.5: CO_2 emissions and primary energy conversion factors of electricity and natural gas.

Factors	Energy source	Factor symbol	Value	Units	Ref.
CO2 emissions factors	Electricity	$O2_E$	633	g_{co2} /kWh_{el}	[67]
	Fuel (natural gas)	$O2_f$	244	g_{co2} /kWh_{th}	[67]
Primary energy factors	Electricity	Pr_E	3.0	kWh_{pr}/kWh_{el}	[68]
	Fuel (natural gas)	Pr_f	1.1	kWh_{pr}/kWh_{th}	[68]

Similar to CO_2 emissions, the primary energy consumption was also calculated mostly depending on the operation pattern of the system. Thus, a similar estimation method of primary energy consumed at pipelines and equipment installation was adopted.

$$Z_{Pr} = PrmE + PrmF + PrmEqu + PrmNet \tag{3.84}$$

$$PrmE = PrmE_{comp} + PrmE_{dis} + PrmE_{htr} + PrmE_{net} - PrmE_{pv} \tag{3.85}$$

$$PrmE_{comp} = \sum_i \sum_t \left[Pr_E . Ep_{i,t} . \Delta t\right] \tag{3.86}$$

$$PrmE_{dis} = \sum_i \sum_t \left[Pr_E . R_{dis} . Q_{O"dis",i,t} . \Delta t\right] \tag{3.87}$$

$$PrmE_{htr} = \sum_i \sum_t \left[Pr_E . Q_{in"htr",i,t} . \Delta t\right] \tag{3.88}$$

$$PrmE_{net} = \sum_{i,j:i\neq j} \sum_t \left[Pr_E . pf . FL_{pip_{i,j,t}} . L_{i,j} . \Delta t\right] \tag{3.89}$$

$$PrmE_{pv} = \sum_i \sum_t \left[Pr_E . Epv_{i,t} . \Delta t\right] \tag{3.90}$$

$$PrmF = \sum_i \sum_t Pr_f . Q_{in"blr",i,t} . \Delta t \tag{3.91}$$

$$PrmEqu = \sum_i \sum_{equ} \left[Pr_{equ} . CAP_{equ,i} . \Delta t\right] \tag{3.92}$$

$$PrmNet = \sum_{i,j:i\neq j} \sum_t Pr_{Net} . NFL_{pip_{i,j,t}} . L_{i,j} . \Delta t \tag{3.93}$$

3.3.7 Multi objective optimization

The extensive literature survey has showed that there are different methods and theories to obtain the multi objective optimal solution [47, 69, 70, 71, 72]. Messac et. al. [47] has presented a concise comparison of the most notable methods for generating Pareto solutions. They importantly emphasized that generating Pareto solutions is an objective task while selecting a specific Pareto solution is a subjective task that depends extremely on the decision maker preferences. The earlier task, i.e. generating Pareto solutions, seeks to objectively generate Pareto points in the design space regardless of their desirability. One of the most common methods is the normalized weighted sum method where two, three or more contradicting objective functions are turned into a one normalized objective function.

$$\min \quad Z_{Multi} = W_C \,.Z_C + W_{CO2} \,.Z_{CO2} + W_{Pr} \,.Z_{Pr} \tag{3.94}$$

Where W_C, W_{CO2} and W_{Pr} are the weights adopted to combine the different single objectives into one function. Ideally the weight of each single objective function is to be assigned by the decision makers based on their collective knowledge. However, because different objective functions can have different magnitudes, the weights assigned by decision makers need to be normalized. Thus the weights are considered to be formed of fragments, DM weights and normalization factors.
Three different methods to define the values of the normalization weights have been commonly utilized in this method [69, 70]:

- The objective functions are normalized by each objectives magnitude at an initial point (x_o):

$$W_C = U_C \cdot \frac{1}{Z_C(x_o)} \,, W_{CO2} = U_{CO2} \cdot \frac{1}{Z_{CO2}(x_o)} \,, W_{Pr} = U_{Pr} \cdot \frac{1}{Z_{Pr}(x_o)} \tag{3.95}$$

Where U_C, U_{CO2} and U_{Pr} are weights assigned by the decision maker according to the importance of each objective.

- The objective functions are normalized by each objectives minimum value when optimized alone, known as Utopia value, see Figure 3.8:

$$W_C = U_C \cdot \frac{1}{Z_C^U} \,, W_{CO2} = U_{CO2} \cdot \frac{1}{Z_{CO2}^U} \,, W_{Pr} = U_{Pr} \cdot \frac{1}{Z_{Pr}^U} \tag{3.96}$$

- The objective functions are normalized by difference between each objectives magnitude when the other objective is minimized, also known as Nadir value demonstrated in Figure 3.8, and each objectives minimum value when optimized alone , i.e. Utopia value:

$$W_C = U_C \cdot \frac{1}{Z_C^N - Z_C^U} \,, W_{CO2} = U_{CO2} \cdot \frac{1}{Z_{CO2}^N - Z_{CO2}^U} \,, W_{Pr} = U_{Pr} \cdot \frac{1}{Z_{Pr}^N - Z_{Pr}^U} \tag{3.97}$$

According to Grodzevich and Romanko [69], the initial point, i.e. first scheme, may provide very poor representation of the function behavior at optimality and in addition in case that $f(x_o)$ is equal to zero, which is often, this scheme cannot be used. The use of optimal solutions, i.e. second schemes, to individual problems can lead to very distorted scaling since optimal values by themselves are not related to the geometry of the Pareto set. Based on this, the first two schemes have been found to be ineffective and non-practical. On the other hand, the third scheme provides the best normalization results as the objective function is being normalized by the true intervals of their variation over the Pareto optimal set. Therefore, the third normalization set was adopted in this work.

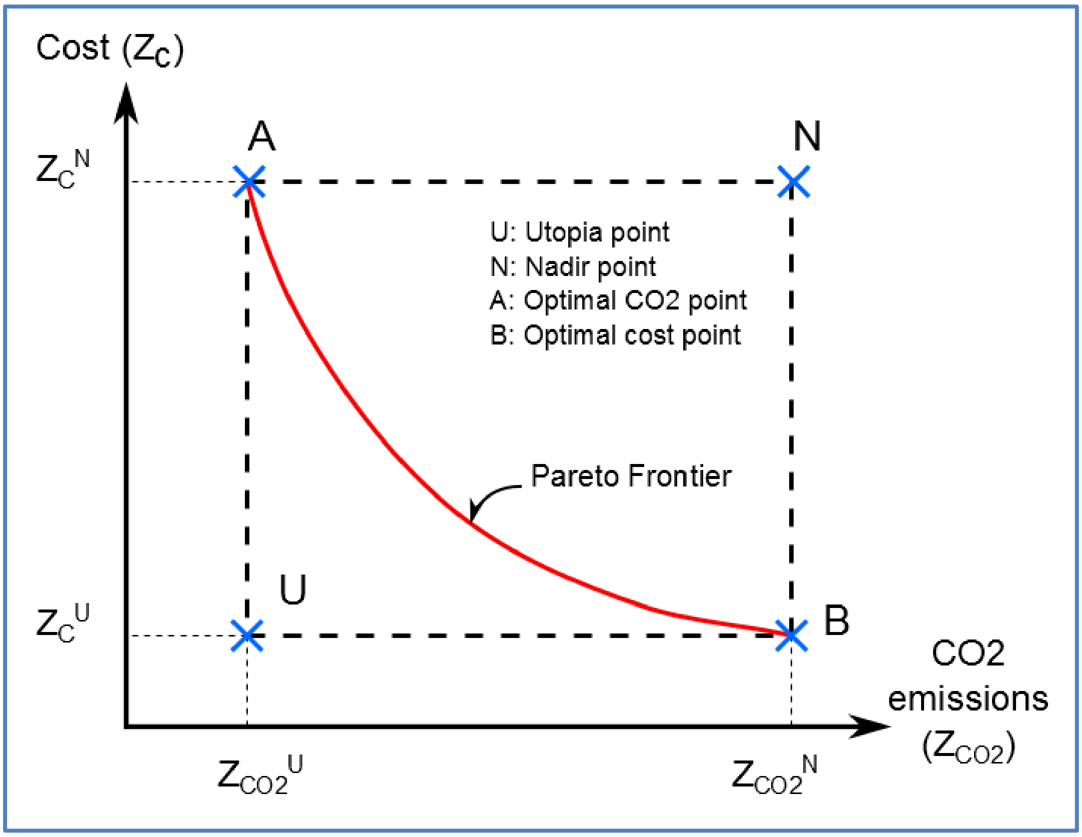


Figure 3.8: Utopia and Nadir points for a two objectives optimization case.

3.4 Optimization Environment

The optimization model has been implemented using GAMS (General Algebraic Modeling System). It is an optimization environment that utilizes several mathematical programming algorithms, i.e. solvers. Those algorithms are chosen and applied according to the type of the developed model, i.e. LP, NLP, MIP, or MINLP. In General, DC systems are complicated to model due to their high variety of possible combinations of technologies and different operational conditions [73]. The optimization model developed in this work is a mixed integer linear programing (MILP) model. The decision of choosing GAMS was due its flexibility to model energy systems and the availability of a high number of state of the art solvers.

Figure 3.9 shows the GAMS modeling interface, known as GAMS IDE (Integrated Development Environment), where all parameters are to be entered, variables to be defined and equations to be written down. Usually, the programmer or user can write the optimization model using GAMS without caring for which solving algorithm is going to be used to solve the problem. After implementing the model, setting all essential energy balances and constraints, adjusting the GAMS solving options, e.g. solving tolerance, to suitable values, and selecting the desirable solver algorithm to be used, the model can be solved mathematically and thus optimized. The solutions obtained, i.e., optimal cooling system for the proposed case, are then retrieved by GAMS as shown in Figure 3.10 where an optimized value is assigned to each continuous and binary variable in the model. Now the user can read the obtained design configuration and operational parameters directly from GAMS IDE results window.

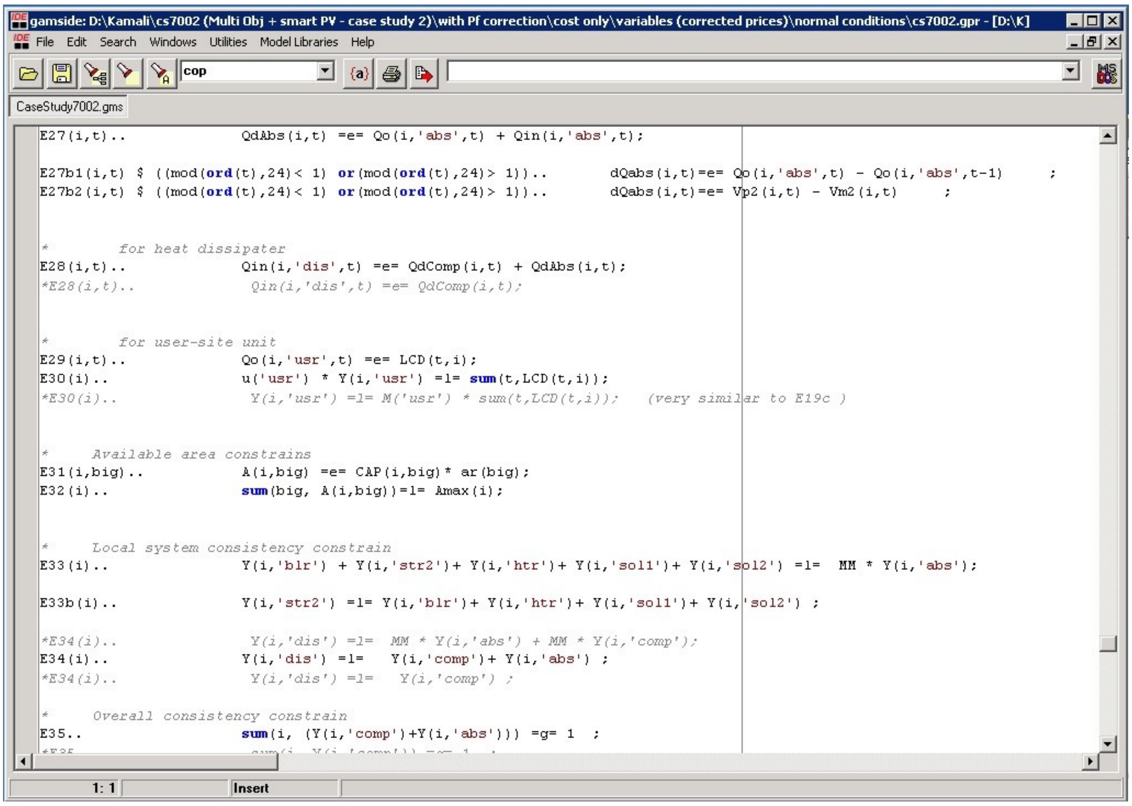


Figure 3.9: GAMS IDE (Integrated Development Environment) screenshot.

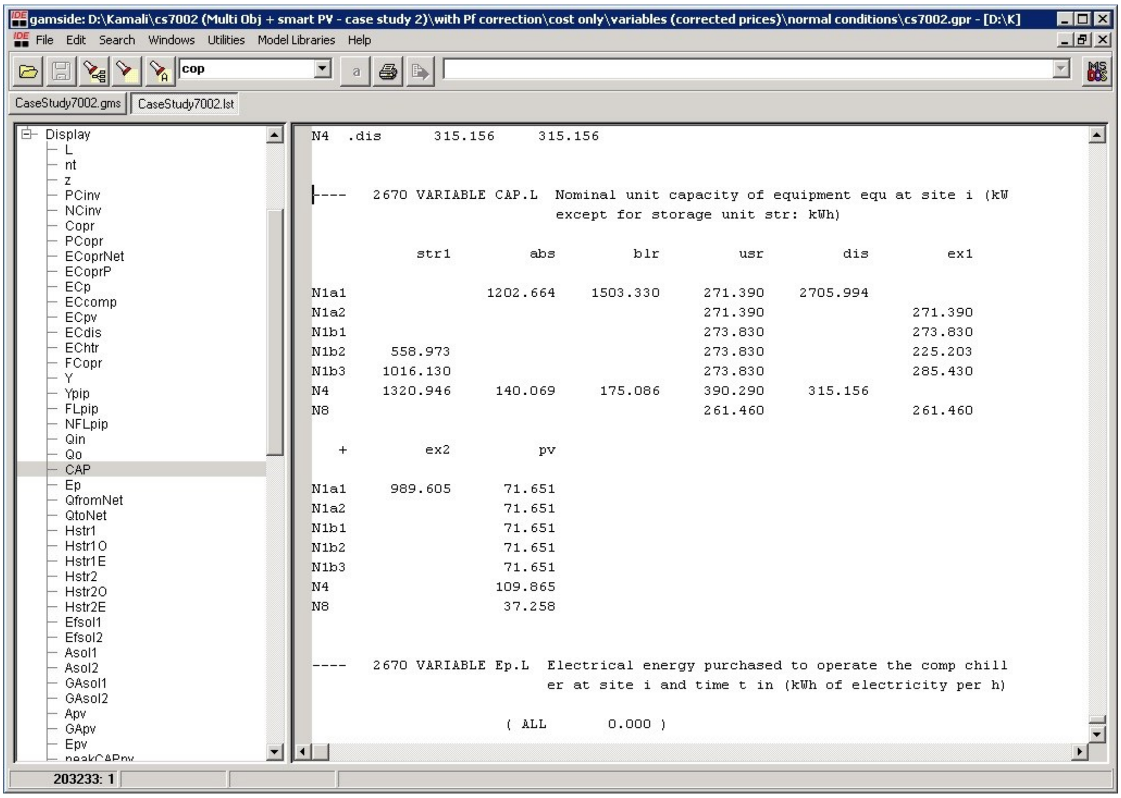


Figure 3.10: A screenshot of GAMS IDE results window after optimization.

3.5 Summary

Based on the ultimate aim of this work, that is to help decision makers at early design stages, and brief survey in the state of the art that was presented in the previous chapter, a multi objective optimization model was developed using mixed integer linear programming MILP and introduced as a useful instrument to support the decision making process.

Different strategies or methods of selecting time periods and representative days presented by several researchers were reviewed and discussed. Considering the characteristics of each strategy, type of building, and nature application the method of selecting a single representative day for each moth was adopted in this work especially that variable electricity and primary energy prices are in the consideration of this work. The adopted method does not require making any distinction between different types of days such as working and non-working days. Some variables can be more influenced by the profiles of selected days than the number of these days therefore a minimum number of representative days can be suggested. Because this work is concerned only with the cooling season, only 6 typical days are to be chosen representing the months of April to September. The number of selected representative days and their time steps can be easily adjusted in the optimization model depending on the complexity of the problem. The selection criteria and process of selecting these representative days are to be presented within each case study in the following chapters.

The developed multi objective optimization model to optimize the structural design and operational parameters of the cooling system has been presented in this chapter. The model is to optimize the size and location of each equipment in the system, the size and location of the each distribution pipeline, the energy flow rates in those pipelines and how the production and storage units should be hourly operated to cover the hourly cooling load of each building in the district. A superstructure comprising all equipment and technologies which are possible to be installed was developed. The model consists of different sub-models for the cooling system units and equipment as well as the mathematical algorithm of the optimization model that include the objective function and lots of constraints such as energy balances and operational constraints. Each unit in the cooling system is represented with a set of equations controlling its behavior and interaction with other units in the system. Multiple objective functions were implemented in the model, including annual total cost and annual CO_2 emissions, and then combined into one universal objective function using the weighted sum method. The aim of the multi objective optimization stage is to generate Pareto solution sets. Generating Pareto solutions is an objective task while selecting a specific Pareto solution is a subjective task that depends extremely on the decision maker preferences.

The optimization model was implemented using GAMS and solved using CPLEX 12 solver. In General, DC systems are complicated to model due to their high variety of possible combinations of technologies and different operational conditions. The optimization model developed in this work is a mixed integer linear programing (MILP) model. The decision of choosing GAMS was due its flexibility to model energy systems and the availability of a high number of state of the art solvers. Two examples of case studies are presented in the following chapters, i.e. Chapter 4 and 5.

Chapter Four

Case Study I

Chapter Four

Case Study I

4.1 Introduction

After an extensive validation process through researching and obtaining optimal systems for several small cases using the developed model, the research was carried on into another stage were different case studies are to be investigated. Two case studies, with different dominant occupation patterns, were chosen to be investigated within this work. The first case study, presented in this chapter, is dominated with residential buildings. It consists of seven buildings including five residential buildings. Several major assumptions were adopted in different combinations and various scenarios were investigated where cooling systems were optimized and analyzed taking into consideration changes in parameters and conditions such as equipment prices, electricity tariffs, cooling loads, available areas, distances between buildings, availability of resources, variability of efficiencies and COPs as well as some common and logical operation control conditions.

In this chapter a detail description of the first case study and the characteristics of the buildings are presented in Section 4.2 along with a brief overview to the optimization approach adopted in the work. Cost optimization investigations are introduced in section 4.3 where various scenarios were analyzed to study the sensitivity of the cost optimal solution to a group of design and operational parameters. Section 4.4 discusses the CO_2 emission optimization which was carried out as the second single objective optimization stage in this study. Multi objective optimization scenarios that combine both cost and CO_2 objectives with an approach to include decision makers in the optimization process are offered in section 4.5.

4.2 Overview of the case study

In the two recent decades, many new modern urban cities, mostly occupied by residential buildings, have been constructed around the world. A significant amount of these urban areas is located in the Middle East, a subtropical region that has a high cooling energy demand which requires considerable design and operation optimization efforts to obtain cost-effective systems and networks with environment-friendly solutions. The hot climate of this region supports the aims of this investigation; therefore, a part of a prospective planned residential district was chosen to be investigated using the developed optimization model. The following sections offer a detailed description of the chosen district, the cooling load profiles of the buildings and an explanation of the optimization approach.

4.2.1 Description of Selected District

A small area was chosen out of a prospective planned residential district in a hot climate region. Based on the similarity between the several residential in the original plan (Figure 4.1a), a group of residential building were selected to be investigated in the case study along with other non-residential buildings. The selected district is presented in Figure 4.1b & c. The subtracted area includes seven buildings. Two of them are public none-residential buildings, a school and a town council. The other five buildings are multi-residents apartments with almost identical cooling load profiles. The distances between the buildings in this case study are relatively small and the peak cooling loads are in a range of 220-340kW.

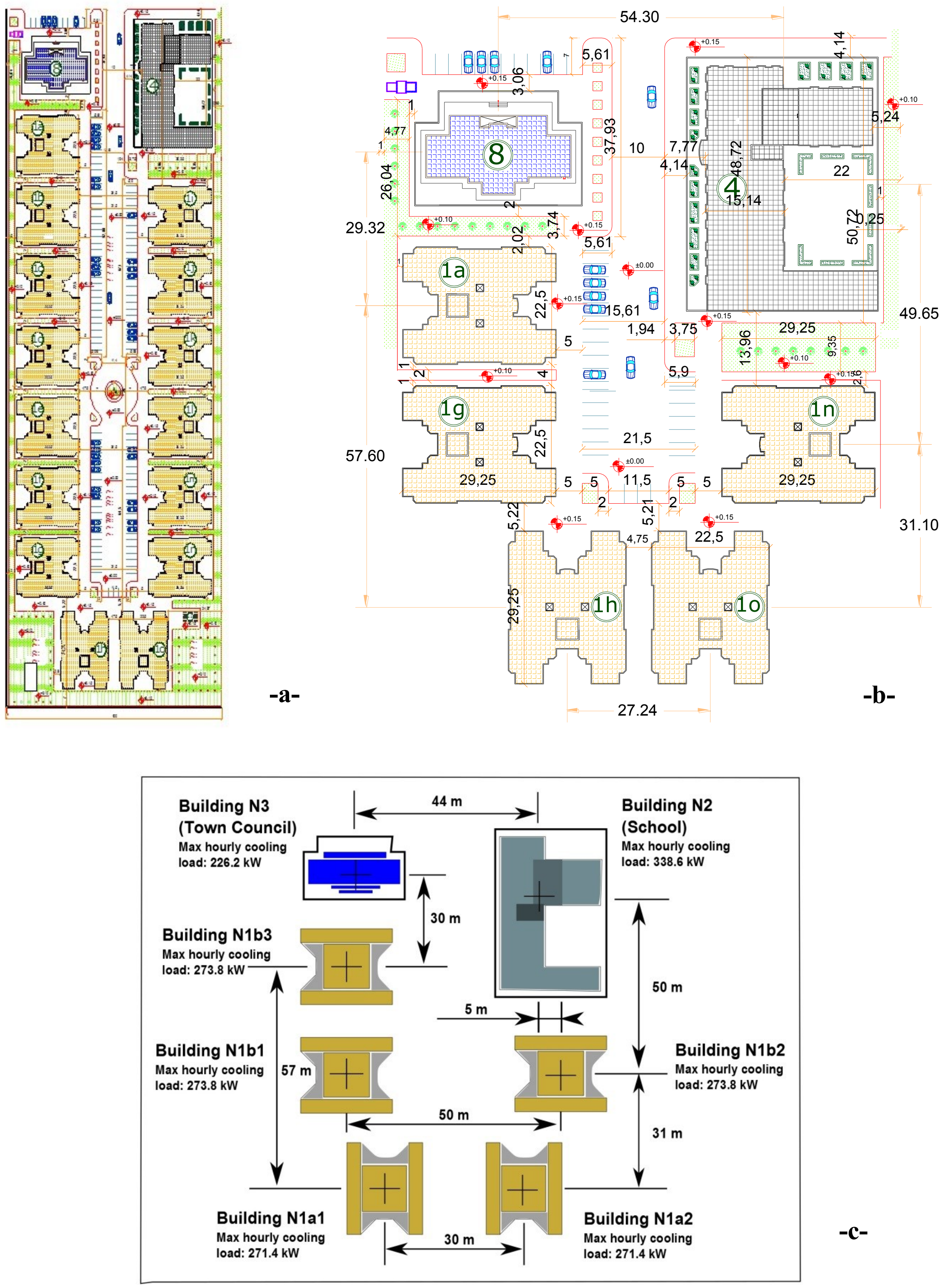


Figure 4.1: a) The prospective planned residential area; b) selected section to be investigated as case study 1; c) a schematic map for Case Study 1.

4.2.2 Buildings' occupation and cooling load profiles

In order to estimate the cooling load profiles for the buildings in case study 1, each of the buildings in Figure 4.1 was assumed to have an amount of available area which can be used to install cooling system equipment and auxiliaries. The occupation pattern for the residential buildings was assumed to be the same while the two none-residential buildings (N2 and N3) were quite different. The buildings' construction data, occupation profiles, lightening and other design assumptions are presented in Table 4.1. As described in Chapter 3, the buildings were simulated using TRNSYS to obtain the cooling load profiles for an entire year. Later on, six representative days, each representing one month during the summer season (April – September), were chosen.

Table 4.1: Construction, occupation and design data of the buildings in case study 1.

Building name/code	N1a1, N1a2, N1b1, N1b2 & N1b3	N2	N3
Building type	Residential Building	None-residential building	None-residential building
Floor Area	675 m^2	1,210 m^2	351 m^2
Building Height	9.5 m	7 m	6 m
Wall Orientation and Area [1]	S,N wall = 202 m^2 E,W wall = 270m^2	S,N wall = 350 m^2 E,W wall = 336 m^2	S,N wall = 136 m^2 E,W wall = 65m^2
Total glass area percentage of the outside surface area	22 %	23 %	30 %
Max. number of occupants	36	500	30
Occupancy schedule at week days	12 Per. (from 7 am to 2 pm)	500 Per. (from 8 am to 2 pm)	30 Per. (from 8 am to 2 pm)
Occupancy schedule at weekend days	36 Per. (for 24 hours)	0 Per. (for 24 hours)	0 Per. (for 24 hours)
Ventilation	0.5 A-ch/hr (for 24 hours)	0.5 A-ch/hr (from 8 am to 2 pm)	0.5 A-ch/hr (from 8 am to 2 pm)
Lightening	5 W/m^2	5 W/m^2	5 W/m^2
Infiltration	0.5 A-ch/hr	0.5 A-ch/hr	0.5 A-ch/hr
Computers, equipment & printers	60 (from 7 am to 12 am) 12 (from 12 am to 7 am)	60 devices (from 8 am to 2 pm)	30 devices (from 8 am to 2 pm)
Cooling set temperature	24 ^{o}C (for 24 hours)	24 ^{o}C (from 8 am to 2 pm)	24 ^{o}C (from 8 am to 2 pm)

[1] The orientation of N1b1, N1b2 and N1a3 buildings is rotated by 90 degrees.

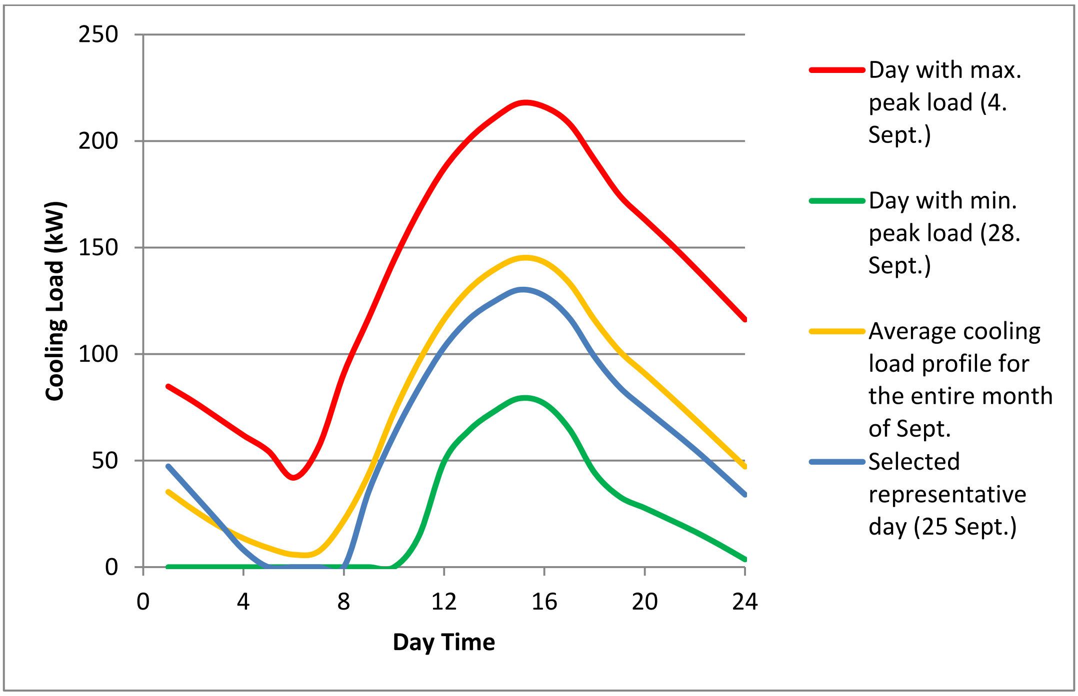


Figure 4.2: Selection of a representative day for September based on the minimum sum of square differences to the average cooling profile of the month.

The selection of a representative day for each month, except of July, was based of finding the best match of a daily cooling load profile within the month to the average cooling load profile of that month as shown in Figure 4.2. This was achieved by calculating the minimum sum of the hourly square difference between each day and the average cooling load profile of the month. Figure 4.3 shows the estimated cooling load profile for building (N1a1) for six representative days. It can be noticed that the peak cooling load occurs in July afternoon with a value of around 270 kW. Since building (N1a2) has the same architectural construction and occupation pattern, the same simulated load profile from building (N1a1) was used. The other three residential buildings (N1b1, N1b2 and N1b3) show a difference in their orientation which reflects very slightly on the cooling load profile and peak value as shown in Figure 4.4, demonstrating building (N1b1) as an example. The same profile was used for the other two buildings. The two buildings left in the case study are none-residential buildings (a school and a town council); therefore, their cooling demand is limited to the working hours of the day. Their peak cooling load is estimated to be around 340 kW for N2 (school) and 226 kW for N3 (town council) as shown in Figures 4.5 and 4.6, respectively.

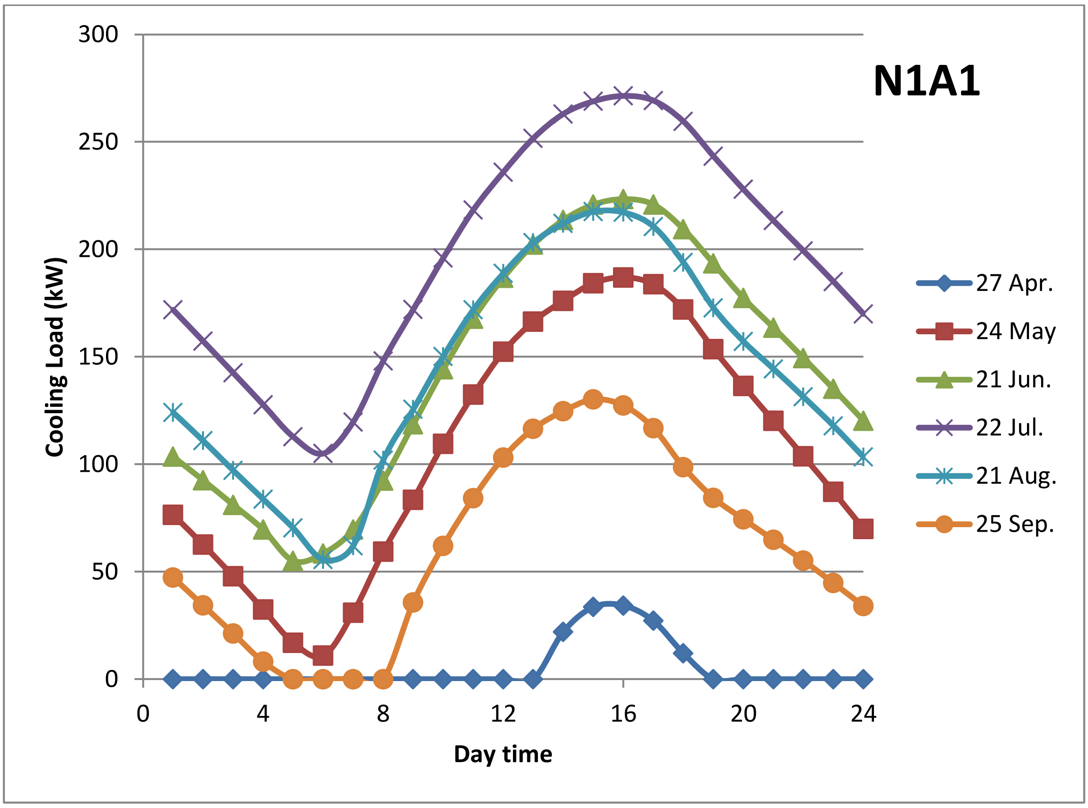


Figure 4.3: Cooling load profiles for 6 representative days for building (N1a1).

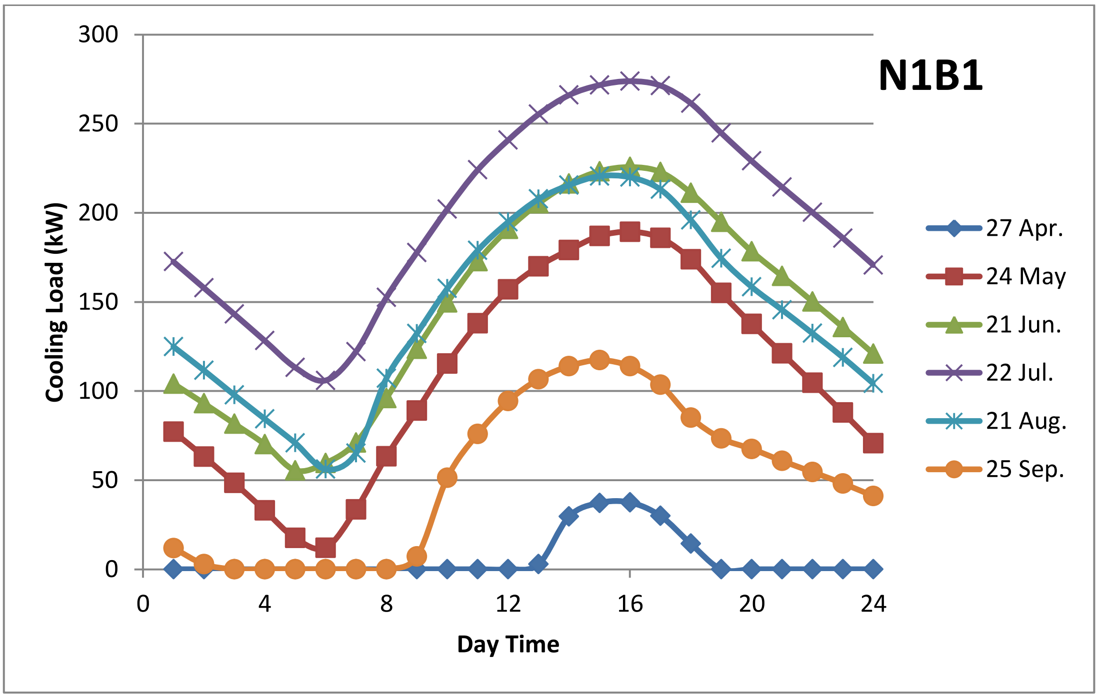


Figure 4.4: Cooling load profiles for 6 representative days for building (N1b1).

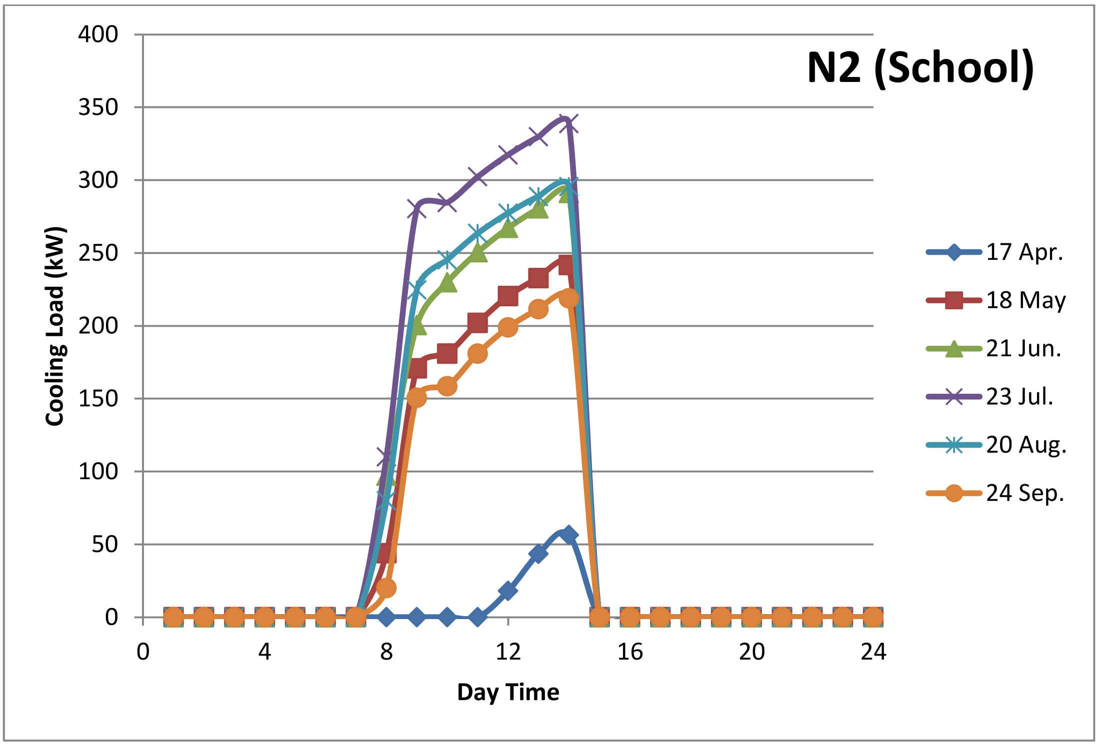


Figure 4.5: Cooling load profiles for 6 representative days for building (N2).

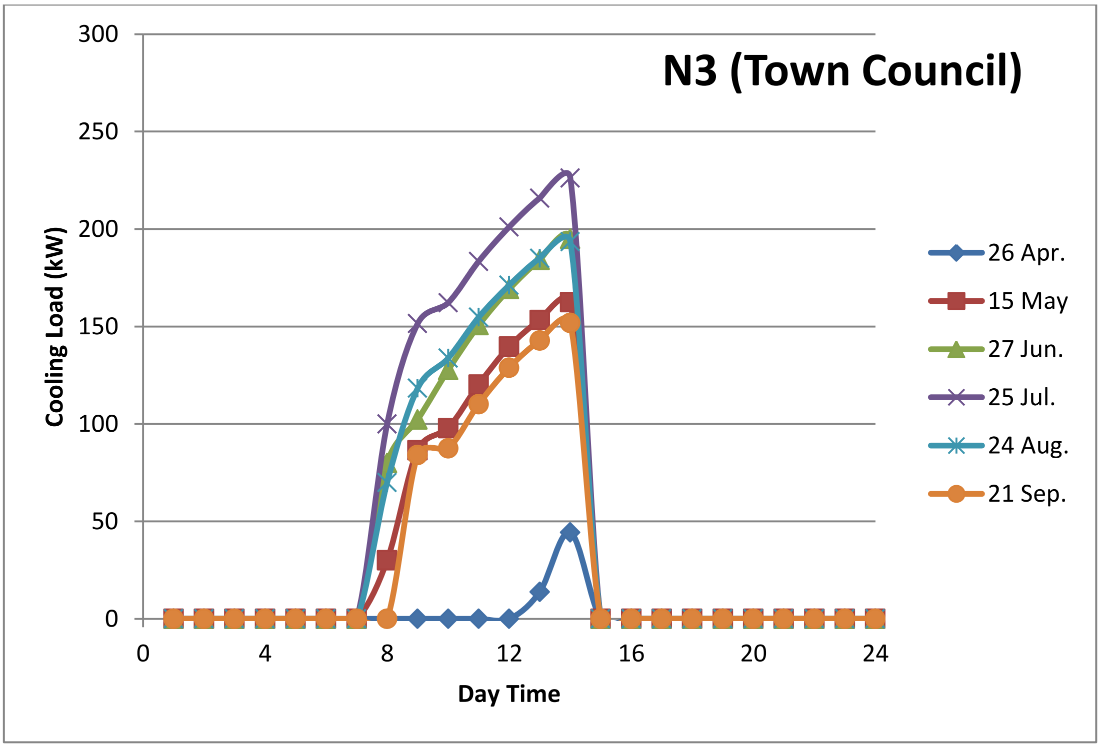


Figure 4.6: Cooling load profiles for 6 representative days for building (N3).

4.2.3 Optimization Methodology and Approach

As presented in chapter 3, a MILP optimization model was applied using GAMS language and solved using the commercial solver CPLEX12. The investigation has been carried out at three different stages of optimization.

- First stage: A single objective optimization for minimizing annual investment and operational costs was investigated and tested for different cases and conditions (scenarios).
- Second stage: Another single objective optimization approach was carried out for minimizing CO_2 emissions for a variety of design and operation scenarios.
- Third stage: Optimal solutions were approached and obtained by means of multi-objective optimization including both, overall cost and CO_2 emission objectives.

Moreover, two major investigation assumptions were adopted when investigating the above three stages. The first was whether to have centralized district cooling system (DCS) or a de-centralized DCS where a group of, or all, buildings can have their own separated individual cooling systems. The second major assumption was whether to adopt a constant COP for the compression chillers or a variable COP depending on the chiller size. These two assumptions were taken into consideration in this work in four combinations which were referred to as major investigation categories:

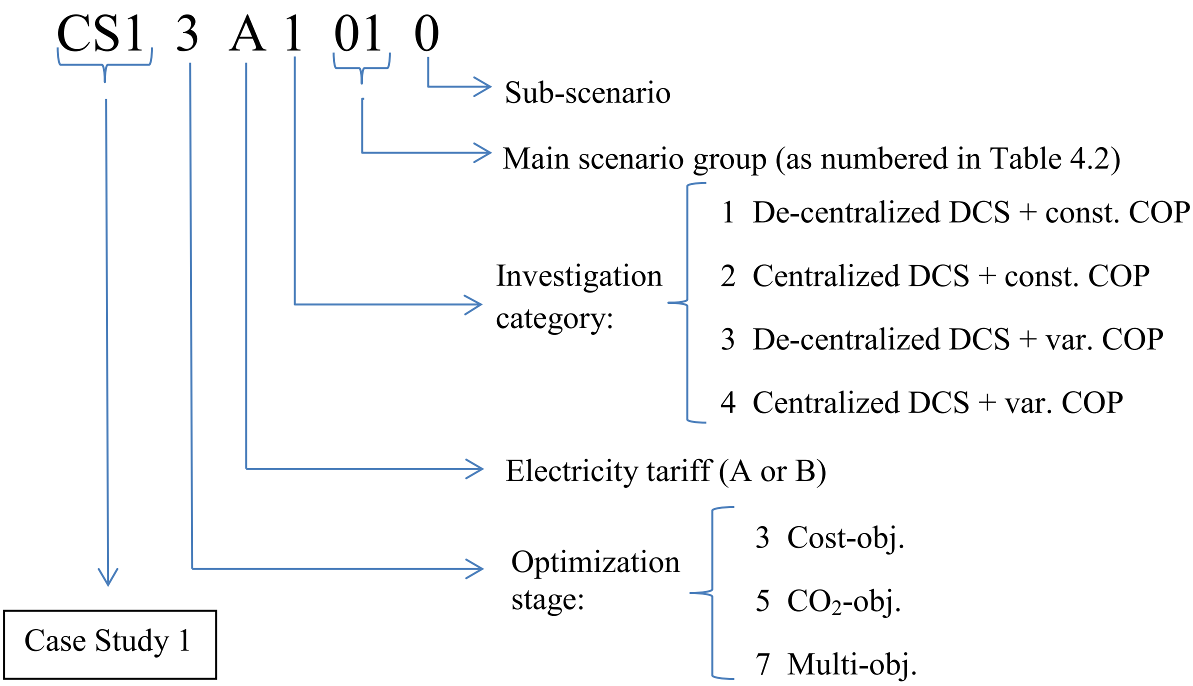
- Category 1: De-centralized DCS with constant COP.
- Category 2: Centralized DCS with constant COP.
- Category 3: De-centralized DCS with variable COP.
- Category 4: Centralized DCS with variable COP.

In the de-centralized DCS investigations the optimization model was given a free choice weather to install a full network connecting all buildings, a group of small networks or no network at all, i.e. leaving all buildings with individual systems. On the other hand, only one network, connecting all buildings, with one production site was allowed in the centralized DCS investigations. These major investigation categories were implemented in all three stages of optimization: Cost, CO_2 and Multi-objective optimizations. The study was carried out for several groups of scenarios; each of them being analyzed for the sensitivity of the optimal solution toward a certain design parameter or operation conditions. The analysis approach for the case study was designed in a way that starts with a reference scenario with minimum design and operational constraints. Later on, more realistic conditions were integrated in each new scenario toward the actual conditions of the case study. Table 4.2 shows the main scenario groups considered in each optimization stage. These main scenarios and their sub-scenarios will be explained in more details in the following sections.

Table 4.2: Main scenario groups investigated in each investigation category.

Optimization	Main Scenario Groups	Stage 1	Stage 2	Stage 3
Reference Scenario	1. A: Reference Scenarios (Tariff A)	X	X	X
Design Constraints	2. Available Area Constraints Scenarios	X		
	3. Chiller Location Constraints Scenarios	X		
	4. Storage Location Constraints Scenarios	X		
	5. Piping prices Scenarios	X		
	6. Investment Cost Optimization Scenarios	X		
Operational Constraints	1. B: Reference Scenarios (Tariff B)	X	X	X
	7. Waste Heat Availability Scenarios	X		
	8. Load Shifting Condition Scenarios	X		
	9. Outdoor Temperature Effect Scenarios	X		
Investigation categories	Category 1: De-centralized DCS with constant COP	X	X	
	Category 2: Centralized DCS with constant COP	X		
	Category 3: De-centralized DCS with variable COP	X	X	X
	Category 4: Centralized DCS with variable COP	X	X	X

The coding system adopted to label each of these scenarios is:



4.3 Cost Optimization Objective

The investment cost of a cooling system is a major aspect to be considered in any decision-making criteria. Additionally, many design companies take the life time operational cost of the proposed systems into consideration during their decision-making procedure. Therefore, the first investigation stage for the first case study was a single objective optimization for the annual cost of the cooling system which included both investment and operational costs. The objective cost function is explained in details in chapter 3 of this work. This objective was optimized for all the investigation categories and the scenarios stated in Table 4.2.

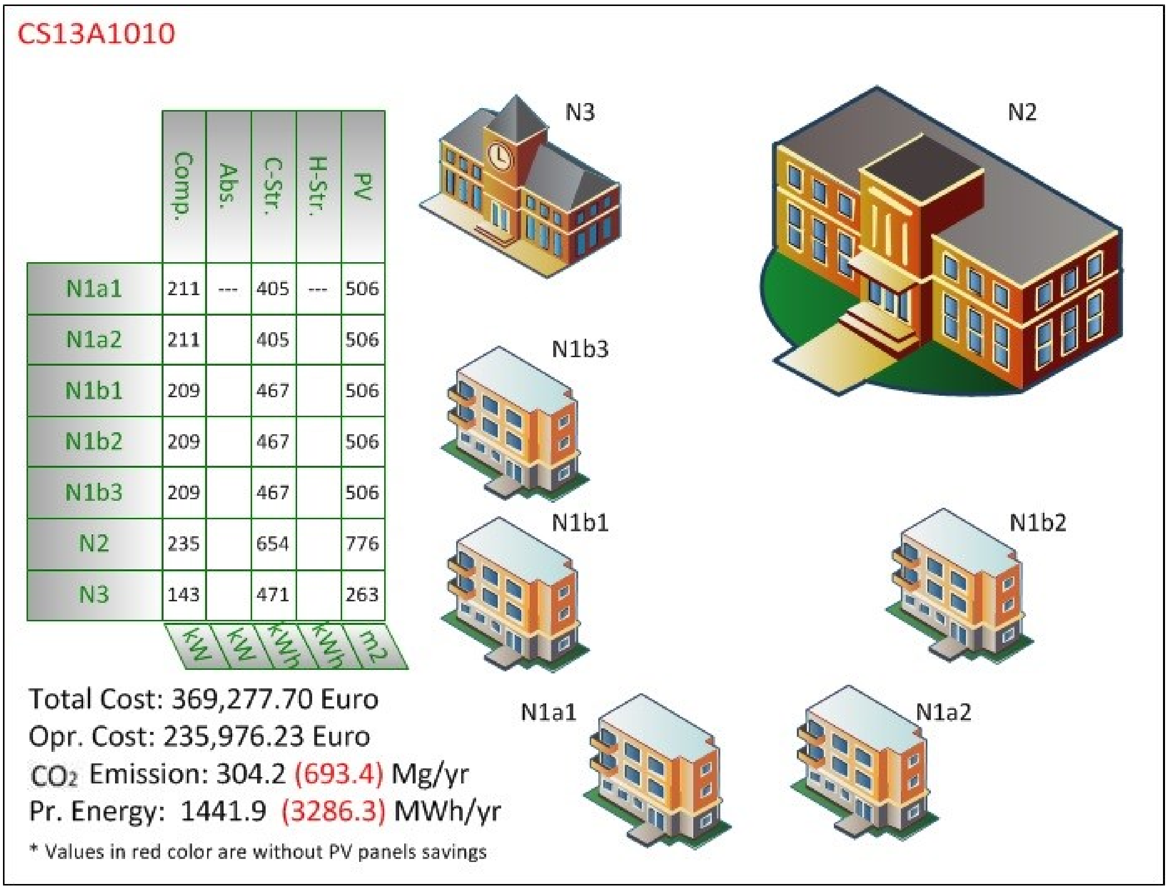
4.3.1 Investigation category 1: Reference Scenario

The analysis approach was initiated with a reference scenario with a group of assumptions:

- All buildings were assumed to have an entire floor or basement as free space to install the cooling system equipment.
- 30% of the roof area was preserved for installing heat dissipaters, e.g. cooling towers, while the rest was utilized by the optimization model.
- Chilled water entering the buildings at 6°C and leaving at 12°C.
- Fixed tariff for the electricity was implemented (Tariff A).
- Waste heat availability was not considered.
- No operation conditions such as load shifting were applied.
- Fixed COPs for the chillers regardless of partial load and outdoor temperature variation were considered at this stage of the research.
- Fixed COPs for the chillers regardless of the chiller size, which is to be obtained by the model, were assumed as well.

Figure 4.7 shows that the optimized solution for a reference scenario for case study 1 for electricity tariff A (constant prices) and a constant COP for the compression chillers of 3, would be a group of individual systems at each building. Compression chillers of reduced size were chosen to meet the cooling load with the assistance of cold storage tanks where peak cooling load periods were met with the energy stored in the cold storage tanks. The full capacities of the chillers were around 76-77% of the peak load for the residential buildings while 69% and 63% of the peak load for the school and city council, respectively. This is because non-residential buildings have several hours of no-load which allows installing smaller chillers, operating them during these hours and store the cooling energy to be used at peak load hours. Such strategy is very limited by the cooling load profile when applied for residential buildings. For the non-residential buildings, the lower the peak load is, the lower percentage of chiller capacity to the peak load can be achieved by installing smaller chiller and storage tank.

PV panels were installed on 70% of the roof area which was also assumed to be free to use. The energy produced by these panels is either to be used to operate the chillers, if the chillers were ON at the time of production, or to be sold to the national electricity grid. The selling price of the produced energy, 0.16 Euro/kWh, was lower than the purchase price of the electricity from the grid, 0.26 Euro/kWh, which makes local consumption, whenever possible, of the energy produced by the PV panels a much cost effective within this case study.



	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	211	---	405	---	506
N1a2	211		405		506
N1b1	209		467		506
N1b2	209		467		506
N1b3	209		467		506
N2	235		654		776
N3	143		471		263
	kW	kW	kWh	kWh	m2

Figure 4.7: Annual cost optimization reference scenario for case study 1 with electricity tariff A and constant COP for the compression chillers of 3.

Observing Figure 4.8 indicates that the cooling demands for each individual building were fully met by the separated systems suggested by the optimization model. The cold storages were assumed to have initial stored energy values which were optimized within the range of 25% to 75% of the full capacity of the storage tanks under the condition that these values should be re-obtained by the system at the end of the day. The optimized capacities of the storage tanks might have been overestimated as a result of another implemented restriction that limits the hourly output of a storage tank to, by maximum, 25% of its capacity. That is a fully charged storage tank will need 4 hours minimum to fully discharge is stored energy.

The reference scenario was re-optimized under the same conditions but with different values for the compression chiller COP. The investigated COP values were 4, 5, 6 and 7. The results showed that a de-centralized system, similar to the system in Figure 4.7, consisting of a group of separated individual cooling systems for each building was still chosen as optimal solution. This is due to the fact that the COPs were considered as constant values, regardless of their sizes, in each scenario. However, the capacities of the installed compression chillers and cold storage tanks were slightly varying, especially for the residential systems, from one scenario to another as shown in Figure 4.9. The obtained solutions when adopting higher COPs were heading towards a balance point between the installed capacities of chillers and storage tanks.

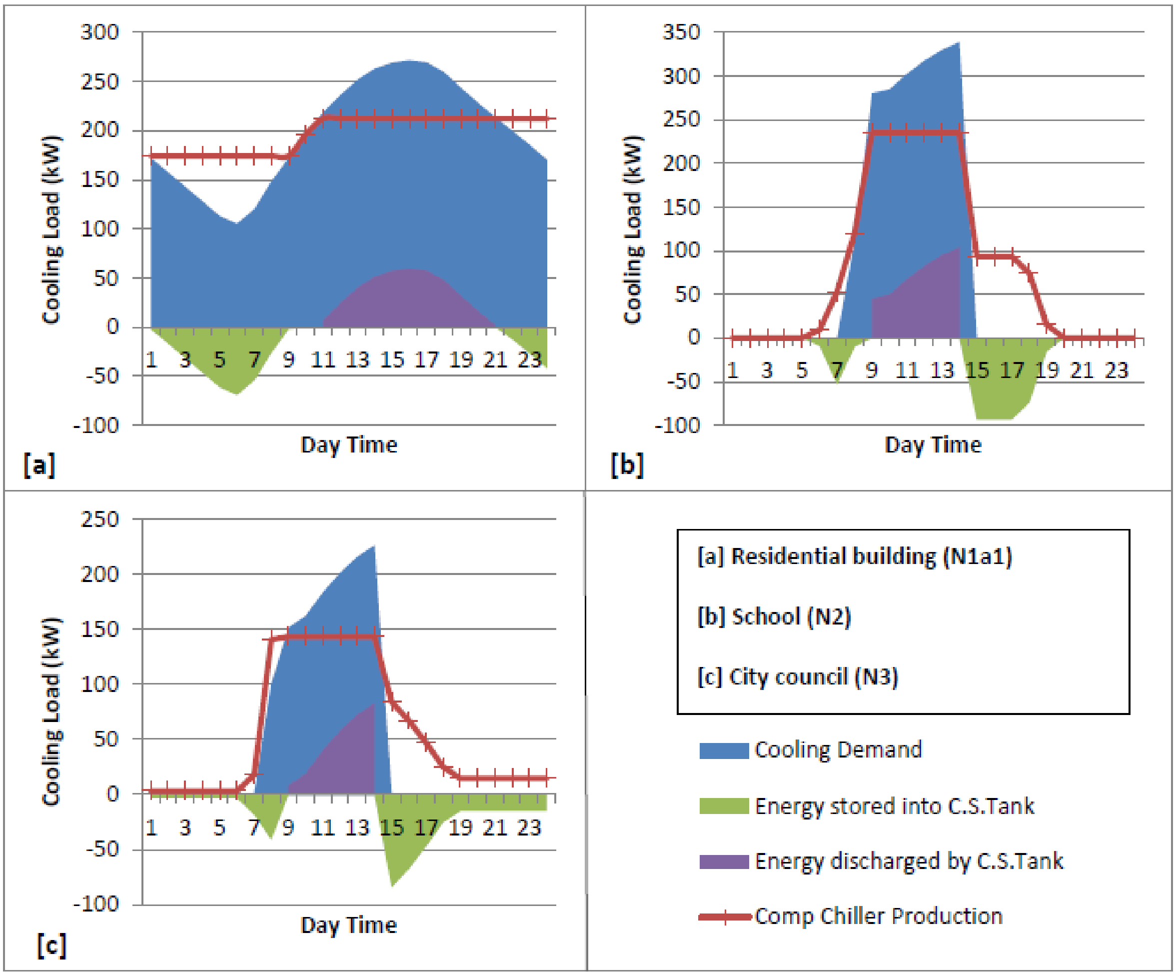


Figure 4.8: Cooling energy provided by individual systems in scenario CS13A1010 to meet cooling load profiles of three buildings (N1a1, N2 & N3) at a typical hot day in July.

Figure 4.10 show the annual total, investment, and operational costs and annual CO_2 emissions obtained for the investigated sub-scenarios with COP values of 3, 4, 5, 6 and 7. Adopting a compression chiller with COP=7 instead of 3 has resulted in 35% reduction in the total annual cost and 55% reduction in operational cost. However, no DC network pipelines were installed. This COP sensitivity investigation is to be carried out again when optimizing CO_2 emissions objective.

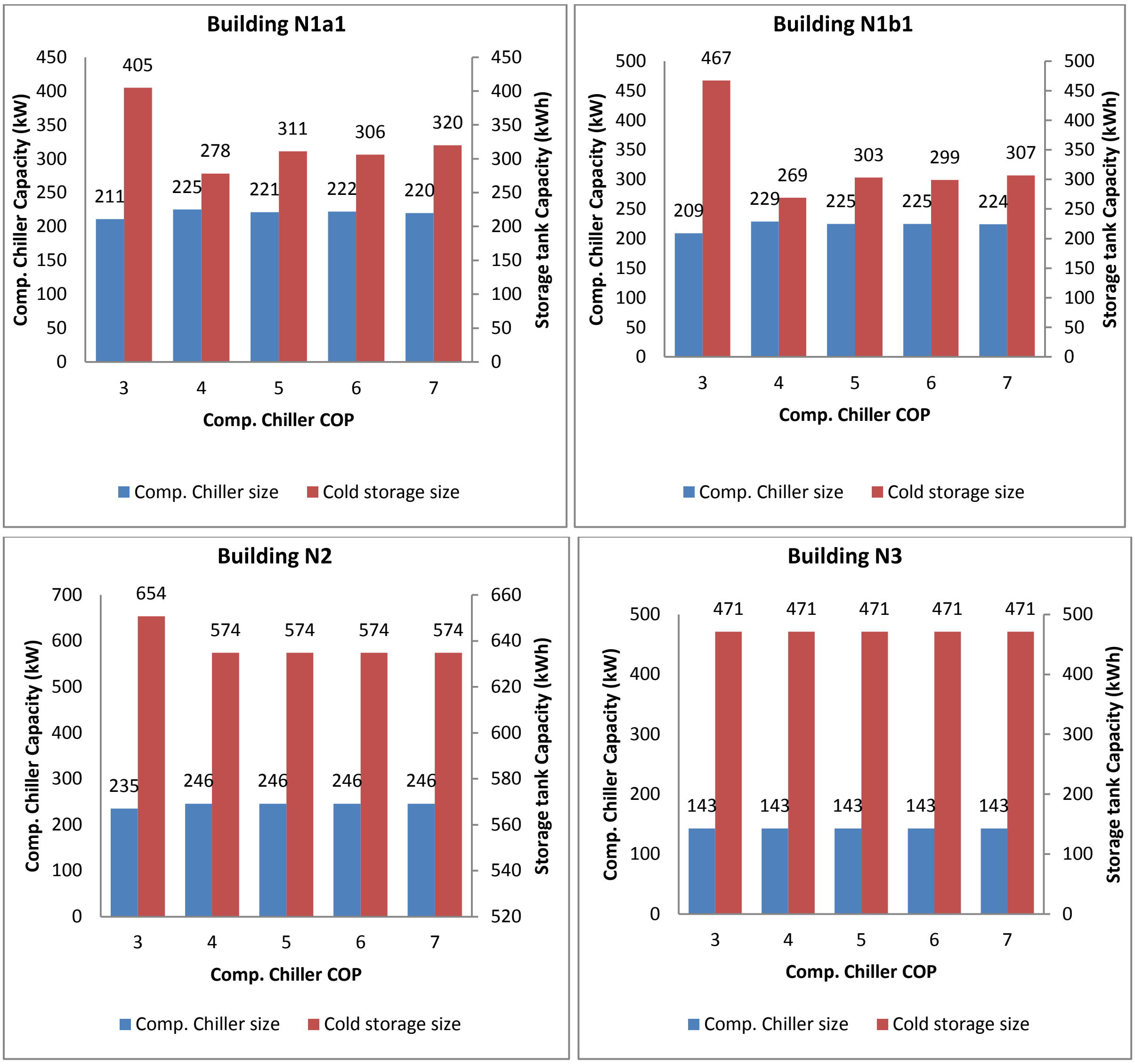


Figure 4.9: Capacities of compression chillers and storage tanks for reference scenarios optimized with different values for Chiller COPs with electricity tariff A.

As it is noticed the model suggested compression chillers instead of absorption chillers for all buildings. This can be described as a reasonable option since compression chillers have lower investment cost compared to absorption chillers and also considering that no waste heat resources were assumed to be available in this scenario. Although absorption chillers have higher investment costs and much lower COPs than compression chillers, they might still represent an optimal solution for certain cases depending on market prices for electricity and fuel as well as the availability of free or cheap heat resources. For example, if COPs for absorption and compression chillers were assumed to be 0.8 and 4, respectively. That means a compression chiller will require 0.25 kWh_{el} of electricity to produce one kWh of cooling for one hour (kWh_{cl}). While an absorption chiller will require 1.389 kWh_f of fuel energy to produce one kWh_{cl}, assuming 90% boiler efficiency. Electricity price was 0.26 €/kWh_{el} and fuel price was 0.067 €/kWh_f. The total cooling load for all the buildings in the case study was approximately 2750000 kWh for the entire 6 months period. By multiplying the total load by energy requirement for each chiller and by their input-energy prices, we get the total cost of the total required energy as shown in Table 4.3.

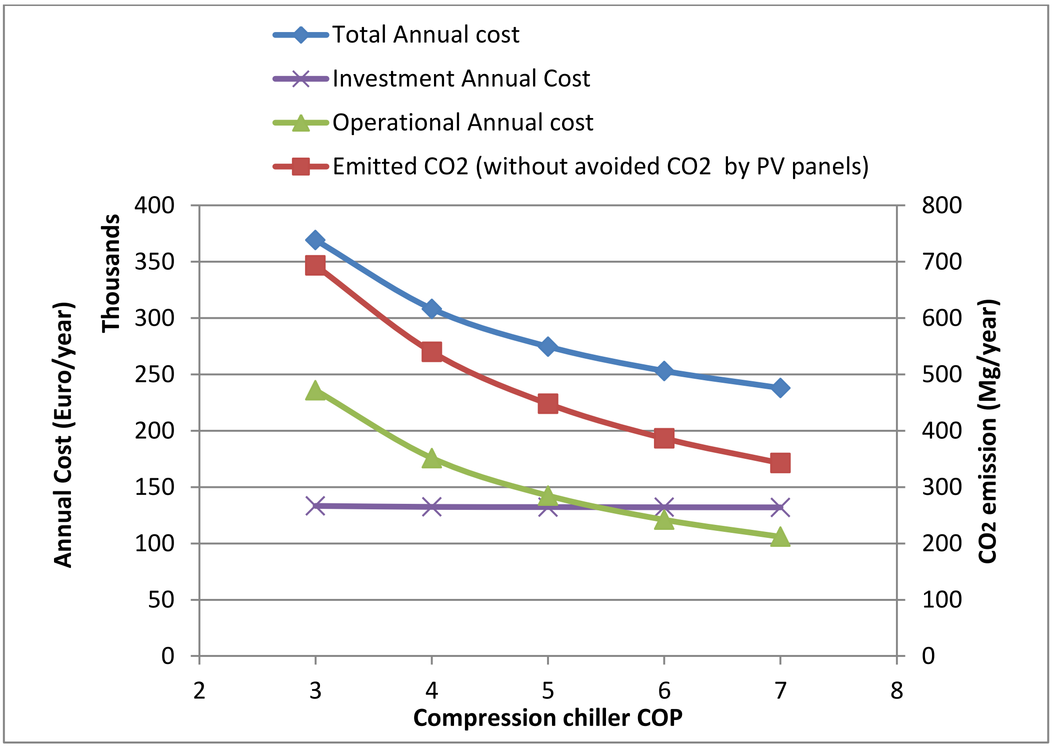


Figure 4.10: Total, investment and operational annual costs and CO_2 emission obtained for the COP sensitivity analysis with electricity tariff A under minimizing total annual cost as the objective of optimization.

Table 4.3: Operational costs compression for compression and absorption chillers.

Operational Costs	compression chillers	absorption chillers
Cost of one kWh of cooling	0.25*0.26 = 0.065 €/kWh$_{cl}$	1.389*0.067 = 0.093 €/kWh$_{cl}$
Operational energy cost	0.065*2750000 = 178750 € per year	0.093*2750000 = 255750 € per year

By repeating the same calculations under the same conditions and assumptions, values can be derived for which absorption chillers may be preferable to traditional compression chillers, based on operational costs, as presented in Figure 4.11 where the blue line represents the cooling energy in respect to the fuel cost while the red dashed lines demonstrate the cooling energy costs in respect to four different electricity prices. The blue dashed line represent the fuel price used in this work and its corresponding cooling energy cost. For Example, by observing Figure 4.11, when the local fuel cost, at a certain city, is (0.04 €/kWh$_f$), then the cost of the cooling energy produced by absorption chiller would be (0.055 €/kWh$_{cl}$). This exact cooling energy cost can be provided by compression chiller when the electricity cost is (0.22 €/kWh$_{el}$). If the electricity price in that city is higher than this value then it is recommended to select absorption chiller. However, if the electricity price in that city is lower than (0.22 €/kWh$_{el}$) then a compression chiller would be more reasonable.

This cost analysis, Figure 4.11 , represent only the consumption related operational cost per kWh of cooling for both chiller types without taking in consideration the difference in investment costs for each of them which are usually in favor of compression chillers as well. However, there are sufficient cases where absorption chillers might be a cost-effective solution such as when electricity prices are high and fuel can be provided at adequate prices. Absorption chillers are also recommended when sufficient amount of waste heat is available. Several sub-scenarios investigating the effect of waste heat availability are presented later on in this chapter.

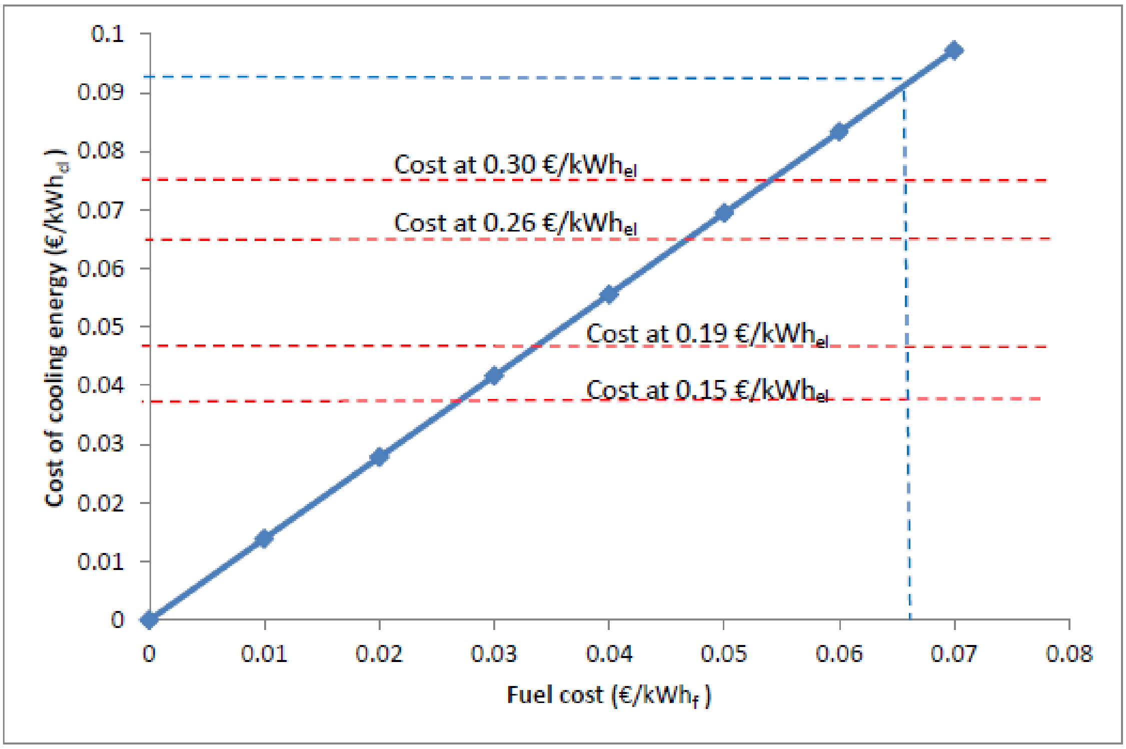


Figure 4.11: Estimated cost of cooling energy (€/kWhcl) in relation to fuel cost (blue line) along with four cooling energy costs in relation to different electricity costs (red dashed lines).

It was noticed that operational cost has a big impact on the optimal solution. Therefore, some sub-scenarios were investigated to optimize the investment cost solution regardless of the operational cost in the following sections.

4.3.2 Investigation category 2 (Centralized DCS with constant COP) reference scenarios

After obtaining an optimal solution for the reference scenario, several centralized district cooling sub-scenarios were carried out where a single central cooling energy production plant was installed to meet the overall cooling load of the entire district. The aim of these investigations is to compare centralized DC systems to the reference scenario. Two different restrictions were used to force the model to choose a central district cooling system:

- Available area restrictions
- Chiller location restrictions

In the first restriction, the amount of available area to install DC equipment were limited to each building one by one, at each sub-scenario, while other buildings were assumed to have no available areas. This kind of restriction forces the optimization model to install all system equipment in a one central station. The actual available area situation was that only the local school (N2) has enough available area to install cooling equipment, e.g. chillers. However, hot and cold storages were possible to install in all other buildings. Therefore, the second restriction method was introduced.

The second restriction method was to force the model to choose one central chiller at each building one by one, at each sub-scenario, while other equipment, e.g. cold storage tanks, were allowed to be installed at the other buildings. Thus, each of the buildings in the case study was assumed to be the central cooling energy production station at a certain sub-scenario.

The total annual costs of sub-scenarios of both restriction methods are presented in Table 4.4. In both restriction methods, building (N2) was proven to be the optimal location to install a central DCS although it is not the central location in the case study. This is due to its relatively high cooling load in compare to the other buildings as well as its relatively bigger roof area which allow installing more PV panels that can be integrated to the DC energy production plant.

Table 4.4: Total annual costs of the central district cooling systems scenarios.

Central Unit	Availability area restriction		Chiller location restriction	
	Code	Cost (Euro/year)	Code	Cost (Euro/year)
At building (N1a1)	CS13A1021	428,135.50	CS13A1031	427,493.60
At building (N1a2)	CS13A1022	428,800.00	CS13A1032	427,858.50
At building (N1b1)	CS13A1023	427,915.30	CS13A1033	427,487.90
At building (N1b2)	CS13A1024	429,524.30	CS13A1034	428,641.30
At building (N1b3)	CS13A1025	428,148.80	CS13A1035	427,836.40
At building (N2)	CS13A1026	426,435.80	CS13A1036	425,937.10
At building (N3)	CS13A1027	432,926.20	CS13A1037	432,743.70

Figure 4.12 demonstrates the optimized systems for the two optimal solutions, at building (N2), within the two restriction methods. For the purpose of validation, a separated centralized DC optimization where the model was free to select the location of the central chiller, CS13A2010, was performed by merely limiting the number of chillers to be installed to one. This sub-scenario resulted in the same system shown in Figure 4.12b which represents the optimal centralized district cooling system. It is noticed that the difference between the total annual costs for the two obtained solutions in Figure 4.12 is too small thus the advantage of second restriction was merely mathematical. From a practical point of view these annual costs are almost identical therefore a final decision is expected to be made based on other aspects.

Since that building N3 (city council) occurred to be the most expensive option when chosen as the central production plant, a cost comparison with optimal scenario, when N2 is the central production plant, is presented in Table 4.5. Unlike the expectations, it is noticed that investment cost has less impact since the difference between the investment costs of the two scenarios, for both restriction methods, is small in comparison to the operational costs difference. The pipeline network cost had higher costs, both investment and operational, in the optimal solution, CS13A1026; when N2 is the central production plant, than the scenario CS13A1027, when N3 is the central plant. However, it was the electricity purchase costs that had the biggest impact. This particular aspect is very much dependent on the PV panels' energy consumption profile. Where the optimization was modeled in a way that, energy produced by PV panels is either to be locally consumed, i.e. used to operate the chillers if the chillers were ON at the time of production, or to be sold to the national electricity grid. However, only the energy produced at the same building where the chiller is installed can be used for local consumption. Energy produced at other buildings had to be sold to the grid. And since that the electricity selling price to the grid (0.16 €/kWh) is lower than the purchase price of electricity from the grid (0.24 €/kWh), any further selling of PV panels' energy to the grid will result in income loses. The PV electricity income for scenarios CS13A1027 and CS13A1037, in Table 4.5, is higher than that of scenarios CS13A1026 and CS13A1036. This indicates that more electricity was sold to the grid, at the low price, and thus more income lose for those systems, i.e. CS13A1027 and CS13A1037, than if that energy was locally consumed. Where the best case scenario should be when as much as possible of PV panel electricity is locally consumed and thus the lowest income achieved from selling PV panels' energy to the grid. The electricity production and local consumption of PV panels form both scenarios, when N2 or N3 are production sites, is presented in Figure 4.13. Results of optimizations without installing PV will be presented later on in this chapter.

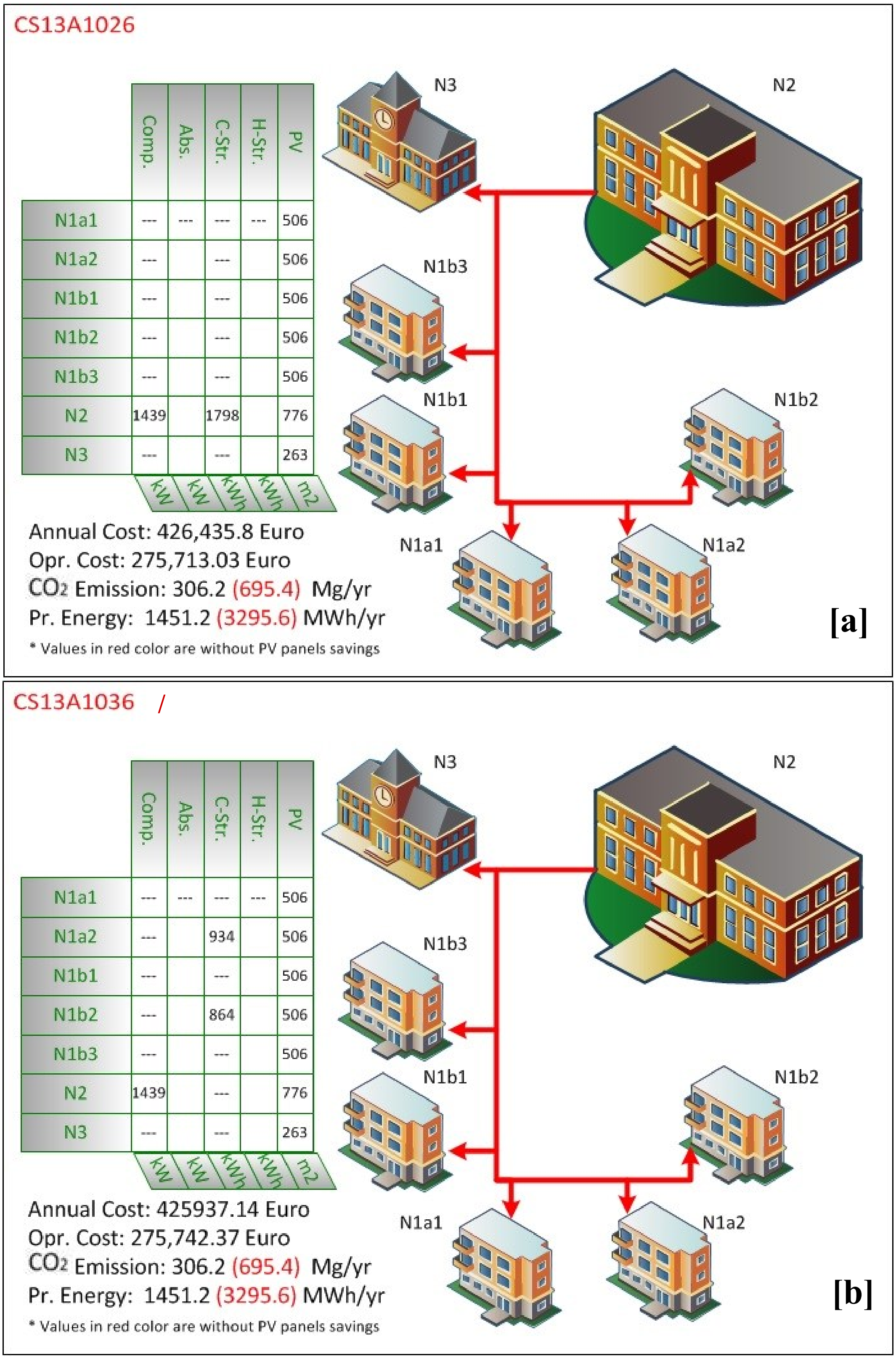


Figure 4.12: Cost optimization under: a) Available area restriction, and b) Chiller location restriction, to (N2) for electricity tariff A.

Table 4.5: Details of costs for the scenarios of Centralized DC at buildings N2 and N3 and for both restriction methods with electricity tariff A.

Type of cost [1]	Availability area restriction		
	Central Pl. at N2 CS13A1026	Central Pl. at N3 CS13A1027	Difference
Total annual costs	426,435.80	432,926.20	-6,490.40
1. Total plant investment cost	118,386.01	118,537.78	-151.77
2. Total Network investment cost	32,336.77	31,071.40	1,265.37
3. Total operational cost	275,713.03	283,317.10	-7,604.07
3.1. Plant site operational cost	100,761.61	100,846.01	-84.40
3.2. Electrical network (pumping) cost	806.13	552.857	253.27
3.3. Electrical plant site operational cost	174,145.27	181,918.23	-7,772.96
3.3.1. Comp. chiller electricity cost	209,379.60	229,589.28	-20,209.68
3.3.2. PV panels electricity income [2]	78,681.69	91,118.42	-12,436.73
3.3.3. Heat dissipater electricity cost	43,447.36	43,447.36	0.00
Type of cost [1]	**Chiller location restriction**		
	Central Pl. at N2 CS13A1036	Central Pl. at N3 CS13A1037	Difference
Total annual costs	425,937.10	432,743.70	-6,806.60
1. Total plant investment cost	118,525.99	118,623.14	-97.15
2. Total Network investment cost	31,668.78	30,731.67	937.11
3. Total operational cost	275,742.37	283,388.91	-7,646.54
3.1. Plant site operational cost	100,790.95	100,871.81	-80.86
3.2. Electrical network (pumping) cost	806.13	552.85	253.28
3.3. Electrical plant site operational cost	174,145.27	181,964.24	-7,818.97
3.3.1. Comp. chiller electricity cost	209,379.60	229,708.92	-20,329.32
3.3.2. PV panels electricity income [2]	78,681.69	91,192.04	-12,510.35
3.3.3. Heat dissipater electricity cost	43,447.36	43,447.36	0.00

[1] All costs are in Euro.
[2] The PV electricity income is to be subtracted when calculating the electrical plant site operational cost.

Total costs for chiller location restrictions were lower than the area restriction conditions due to the possibility to install other equipment at different locations in the district. For the restricted available area, a compression chiller with a capacity of (1,439.2 kW), 74.6% of the total peak load, was always installed at the central production location along with cold storage with a capacity of (1,798.4 kWh) as shown in Figure 4.12a. Storage tank was always installed at the central production location due to the area restrictions. This resulted in relatively bigger cold storage and network pipeline sizes leading to higher network investment costs than that of the chiller location restriction sub-scenario. See Table 4.5.

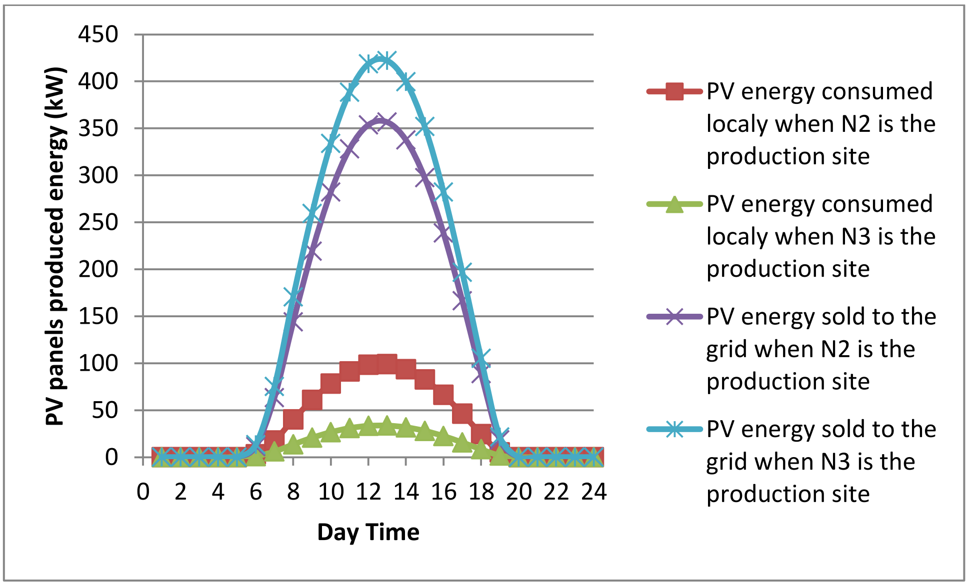


Figure 4.13: PV panels electricity production and local consumption of both scenarios, when N2 or N3 are production sites.

On the other hand, for the chiller location restrictions, as shown in Table 4.6, a compression chiller with an approximate capacity of (1290kW), around 67% of the total peak load, was installed when the production location was restricted to be at any of the residential buildings along with two cold storages with approximate capacities of (1050 kWh) and (1800kWh). However, when the production location was restricted to be at any of the two none-residential buildings (N2 or N3), a relatively bigger compression chiller (1439.2 kW)), 74.6% of the total peak load, was installed with two smaller cold storages (approx. 935 kWh and 860 kWh) as shown in Figure 4.12b. In most of these sub-scenarios the locations of the storage tanks were not at the production plant but rather at the far end of the DC network.

Table 4.6 shows that the location of the storage tanks, within the chiller location restrictions sub-scenarios, is effected by the location of the compression chiller itself. Two storage tanks were installed in all sub-scenarios. When compression chiller is installed at one of the none-residential buildings, N2 or N3, storage tanks were installed at the two buildings on the other end of the network, i.e. building N1a2 and N1b2. This enables the system to have smaller sizes for the network pipelines which are used to transport a more steady flow of cooling energy to charge the cold storages during off-peak load hours. On the other hand, when compression chiller is installed at one of the residential buildings, building N2 was a permanent choice to install one of the storage tanks. The other storage tank location was changing, between N1b2 and N1b3, depending on how far the chiller is installed. Thus, three buildings were found as recommended locations for installing storage tanks:

- Building N2, especially if this building was not the chiller site itself, due to its high peak cooling load in comparison to the other buildings.
- Building N1b2, because it represents the building on the other end of the network.
- Building N1b3, where it has a central location and it represent the connection point between residential and none-residential buildings.

Table 4.6: Location and capacity of chillers and storage tanks in the chiller location restriction sub-scenarios with electricity tariff A.

Scenario Code	Central Chiller			Cold Storage Tanks	
	Location	Capacity (kW)	Percentage of capacity to the total peak load*	Location	Capacity (kWh)
CS13A1031	N1a1	1296.31	67.2 %	N1b2 N2	1015.64 1807.33
CS13A1032	N1a2	1289.01	66.8 %	N1b3 N2	1064.04 1858.35
CS13A1033	N1b1	1290.02	66.9 %	N1b2 N2	1064.04 1803.35
CS13A1034	N1b2	1289.01	66.8 %	N1b3 N2	1064.04 1898.29
CS13A1035	N1b3	1290.15	66.9 %	N1b2 N2	1064.04 1778.05
CS13A1036	N2	1439.25	74.6 %	N1a2 N1b2	934.14 864.31
CS13A1037	N3	1439.25	74.6 %	N1a2 N1b2	938.97 859.48

* The total peak load of all buildings is 1929 kW.

The operational production profiles of the two optimal solutions of Figures 4.12a and 4.12b to meet the overall hourly cooling load of the whole system are presented in Figures 4.14 and 4.15. As it is shown in the energy production curve of the compression chiller, the production was not on a fixed steady rate. This is due to the high difference between the peak load and the lowest point in the load profile which means that the system will need cold storage tanks with high capacities or multi-storages at each building.

An additional optimization was carried out with a condition of installing 7 storage tanks, i.e. one storage at each building, to observe the chiller production performance and system total cost in comparison to the obtained optimal systems within both area and chiller location restrictions. Where CS13A1026 represent the option of installing one central storage tank at the same location of the chiller, CS13A1036 represent installing and optimized number of storages for a centralized network and CS13A1047 represent a centralized system with a storage tank at each building. The total and operational costs are presented in
Table 4.7. Investigations have shown that the first and third cases, i.e. CS13A1026 and CS13A1047, do not represent optimal cost systems however the difference in their total annual costs to that of the system with optimized number of storages, i.e. CS13A1036, is less than 0.5%. And the operation profiles of the chillers, shown in Figure 4.16, do not indicate a significant advantage of either scenario. However it is expected that greater impacted would be observed when different electricity tariff, with lower prices at night, is adopted. Thus, for constant electricity tariff, installing one central storage tank or an optimized number of storages is recommended unless installing a storage tank at each building would provide some kind of flexibility in controlling the system. Figure 4.17 shows the investment and operational cost of the three DC systems in comparison to the De-Centralized optimal scenario. The three centralized DC systems have around 15% percentage increase in the annual total cost in compare to De-centralized system. This shows that designing a DC system under constant COP and electricity tariff does not favor installing DC networks.

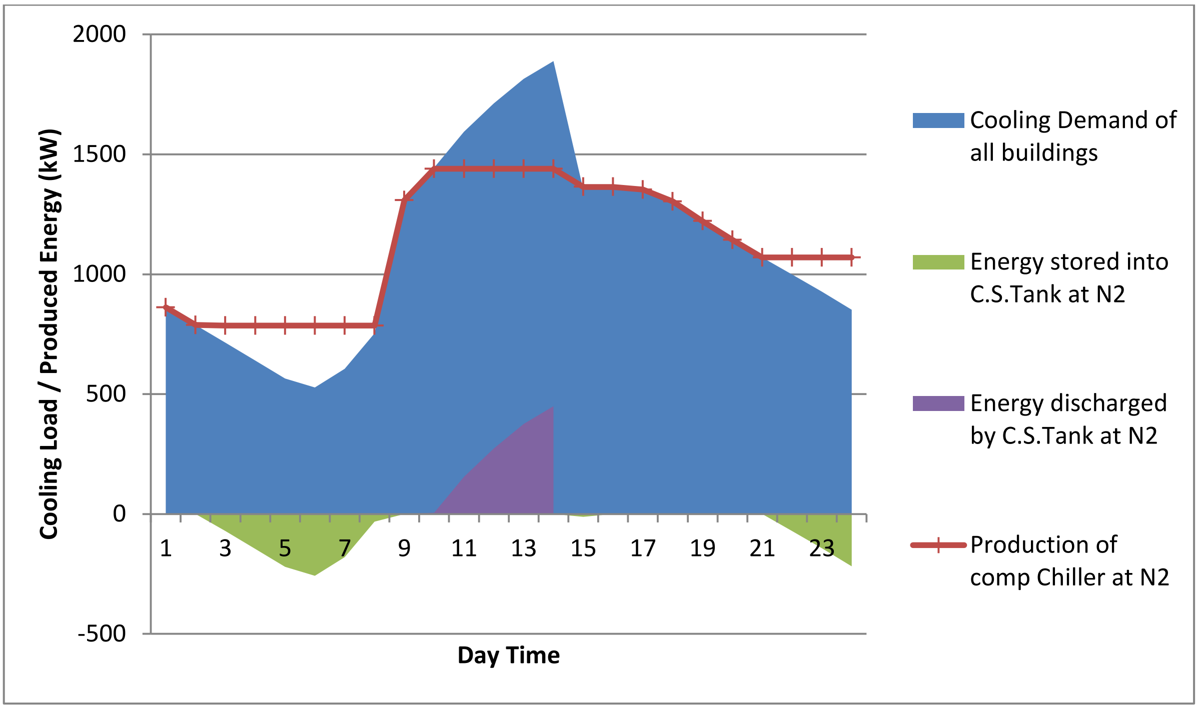


Figure 4.14: Cooling energy provided by the centralized DC system at building (N2) in scenario (CS13A1026: Figure 4.12a) to meet overall cooling load of all buildings at a typical summer day in July.

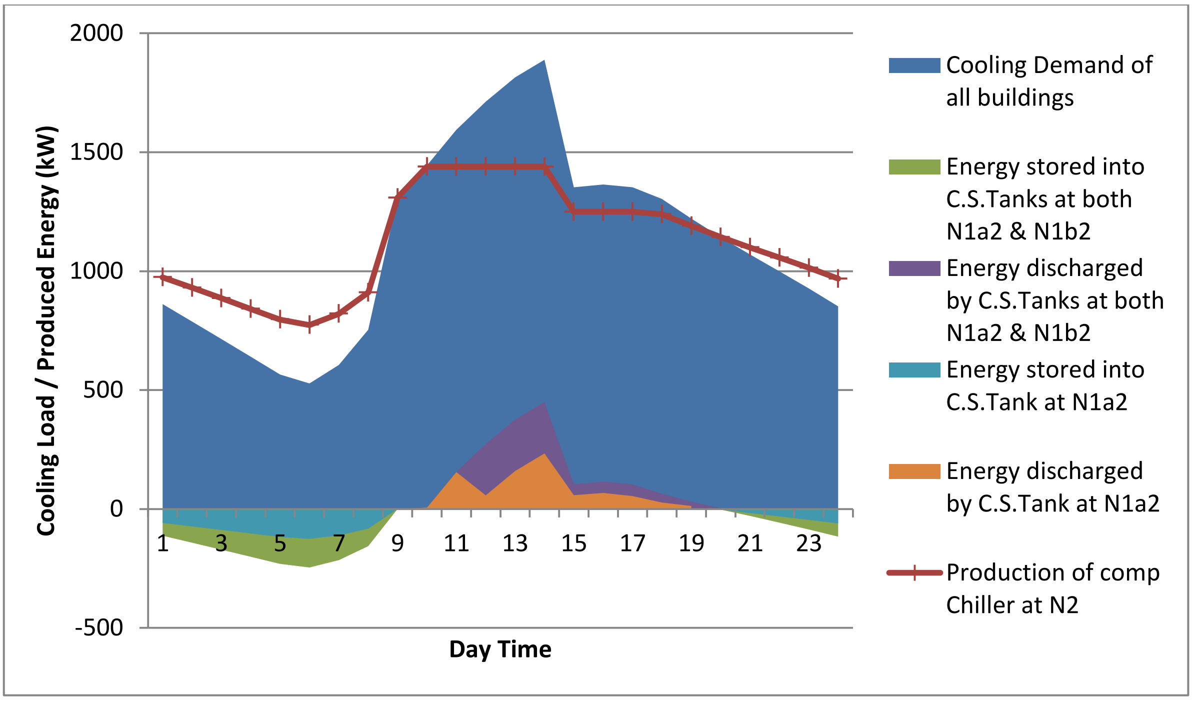


Figure 4.15: Cooling energy provided by the centralized DC system at building (N2) in scenario (CS13A1036: Figure 4.12b) to meet overall cooling load of all buildings at a typical summer day in July.

Table 4.7: Total and operation costs for three centralized DC systems with different number of storage tanks for electricity tariff A.

Scenario	Description	Annual operational cost (Euro)	Total annual cost (Euro)	Percentage of difference in total cost
CS13A1026	One central storage tank	275,713.03	426,435.80	0.12 %
CS13A1036	Optimized number of storage tanks	275,742.37	425,937.10	---
CS13A1047	One storage tank at each building	275,778.67	427,838.40	0.45 %

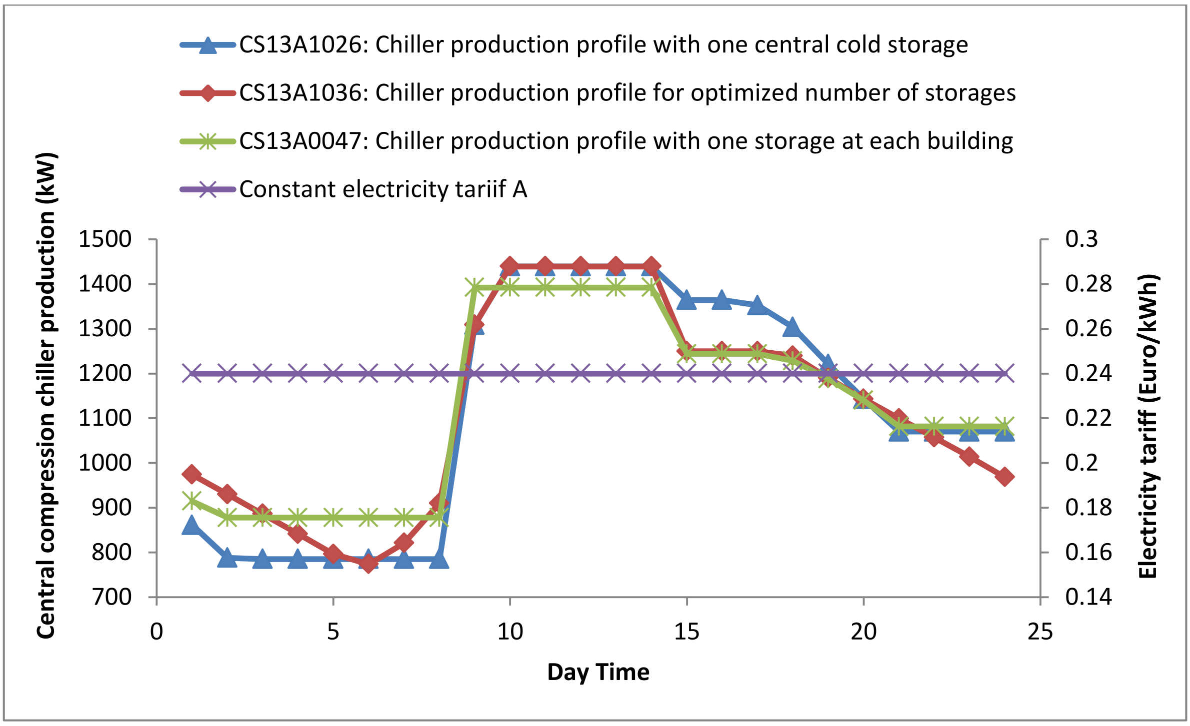


Figure 4.16: Chillers energy production profiles of three centralized DCSs with: a) Central storage, b) Optimized no. of storages, and c) One-storage at each building, for electricity tariff A.

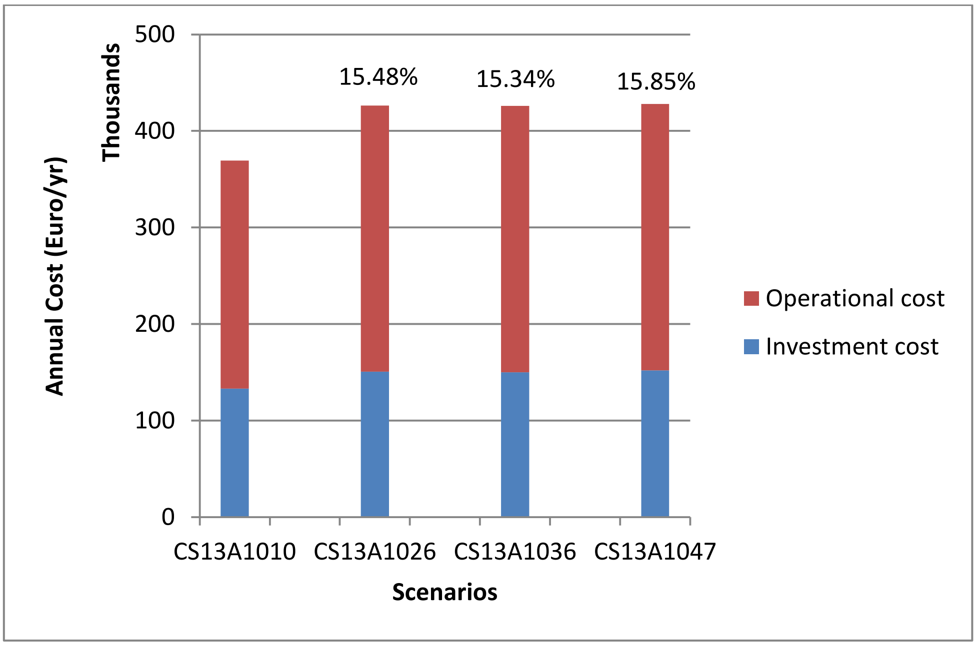


Figure 4.17: Annual investment, operational costs and percentage of increase in total cost of three centralized DCSs with: a) Central storage, b) Optimized no. of storages, and c) One-storage at each building, in comparison to the De-centralized optimal solution CS13A1010 with electricity tariff A.

4.3.3 Piping Prices Scenarios

Since the reference optimization scenario (CS13A1010) suggested a group of separated cooling systems at each building as a cost optimal solution, a sensitivity analysis towards piping investment costs was carried out to obtain common conclusions that support decision-makers when considering district cooling systems. During this analysis, the investment cost function of network pipelines, as presented in chapter 3, was used. While gradually decreasing the price by 20, 35, 50, 65 and 80%, holding all other variables constant, the effects of these price changes on the optimal solution were observed.

It was noticed that network pipeline investment costs did not have a big impact on the obtained optimal solution even when they were reduced by up to 50%. The impact of reducing the piping investment cost was starting to be effective when reducing the piping prices by around 65% with electricity tariff A. Only then an additional pipeline was added between the school building (N2) and the residential building (N1b2) as a replacement for the cold storage and a smaller chiller in that building, in comparison to the reference scenario (Figure 4.7). The same network and system was selected by the model when reducing the pipeline prices by 80%, as demonstrated in Figure 4.18. This pipeline complements the local chiller at (N1b2) in covering the peak load hours by energy provided from (N2). However, the reduction in the total annual cost for this case (CS13A1055) was 0.37% which is very low considering the high decrease of piping prices. However, considering that the investment cost of DC pipeline network of the centralized DC systems, see Table 4.5, is too small in compare to the overall annual cost of the system, it seems to be reasonable that such high reduction in pipeline prices would not have great impact on the system design. Table 4.8 presents the total annual costs and cost reduction percentages due to various reductions in network piping prices, given in percentages.

Table 4.8: Total annual costs of piping pricing sub-scenarios for total cost optimizations under electricity tariff A.

Reduction Percentage in Piping investment costs	Optimizing total annual costs		
	Code	Total Cost (Euro/year)	Reduction Percentage
Standard prices	CS13A1010	369,277.70	---
20 % reduction	CS13A1051	369,277.70	0 %
35 % reduction	CS13A1052	369,277.70	0 %
50 % reduction	CS13A1053	369,277.70	0 %
65 % reduction	CS13A1054	368,966.41	0.08 %
80 % reduction	CS13A1055	367,883.31	0.37 %

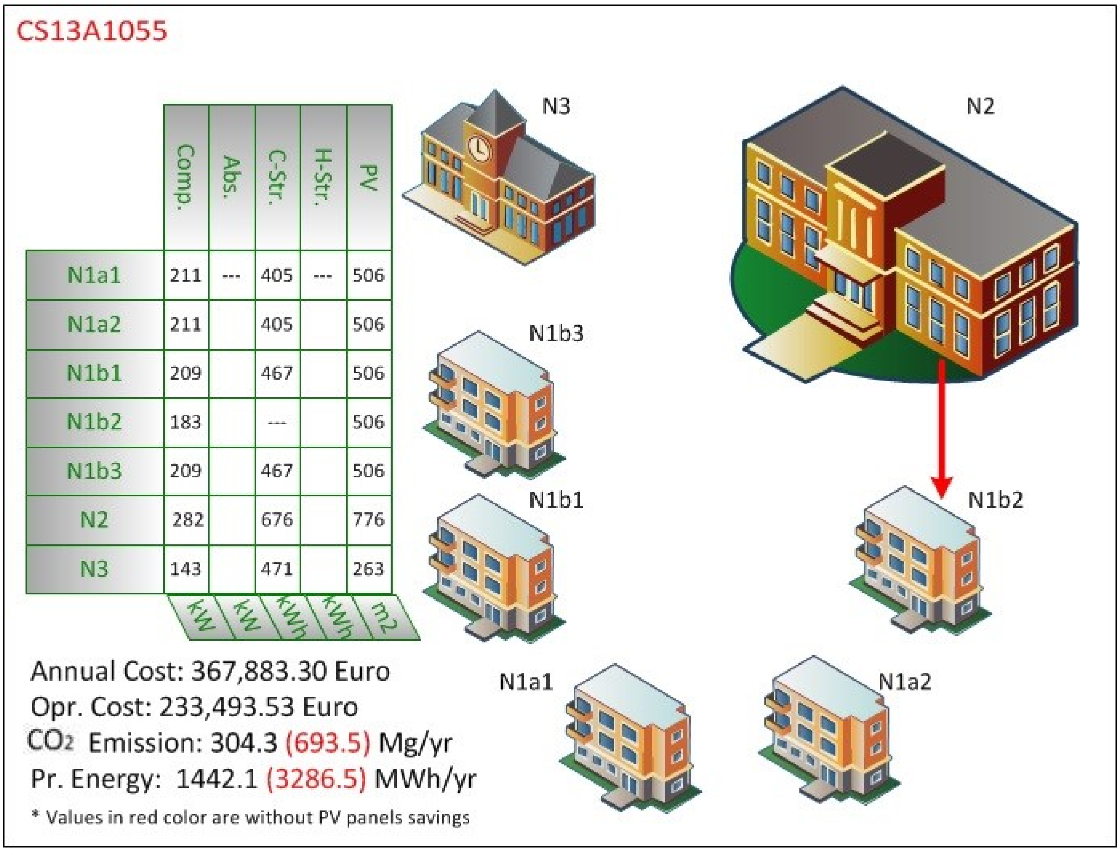


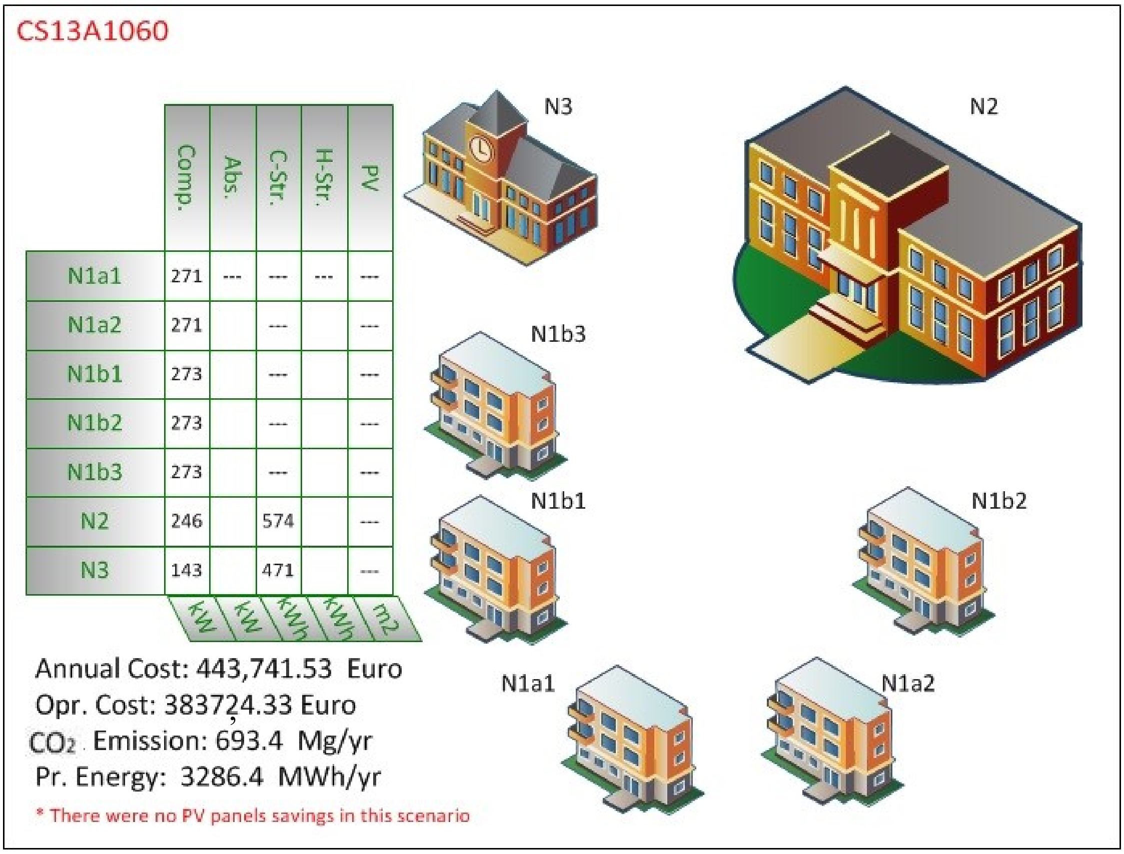
Figure 4.18: Cost optimization with 80% reduction in DC network pipeline prices with electricity tariff A.

This investigation have shown reducing the pipeline prices has little impact on the system design especially that the investment cost of a full centralized DC system is too small in comparison to the total annual cost of the system. These results indicate that optimizing the total annual cost of a cooling system under the conditions of constant COP for the chillers, regardless of their capacities, and constant electricity tariff would result in separated individual systems for each building excluding the option of installing a centralized DC system even when the pipeline prices are significantly low.

4.3.4 Investment cost optimization Scenarios

Another attempt was carried out in order to validate the so far obtained conclusion, that separated individual systems are preferable within investigation categories 1 and 2 with electricity tariff A. The same conditions and assumptions used in reference scenario CS13A1010 were optimized once again by the developed model but by adopting only the investment cost as the objective function.

Figure 4.19 shows the system obtained when optimizing investment cost only. Operational cost was not considered in the optimization objectives and therefor energy incomes from PV panels were ineffective and thus no PV panels were installed in the obtained system. Cold storage tanks were installed merely at the none-residential buildings, while the residential buildings were equipped with compression chillers only. However, there was no network implemented in the obtained system.



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1a1	271	---	---	---	---
N1a2	271		---		---
N1b1	273		---		---
N1b2	273		---		---
N1b3	273		---		---
N2	246		574		---
N3	143		471		---

Figure 4.19: Investment cost optimization of the reference scenario with electricity tariff A.

Although the optimization has achieved a 54% reduction, in compare to CS13A1010, in the investment cost, it has resulted in a high increase in the operational cost since it is not included in the minimization objective. As a result, the total annual cost of the obtained system was 20% higher than that of the reference system, when optimizing total cost, as presented in Figure 4.20.

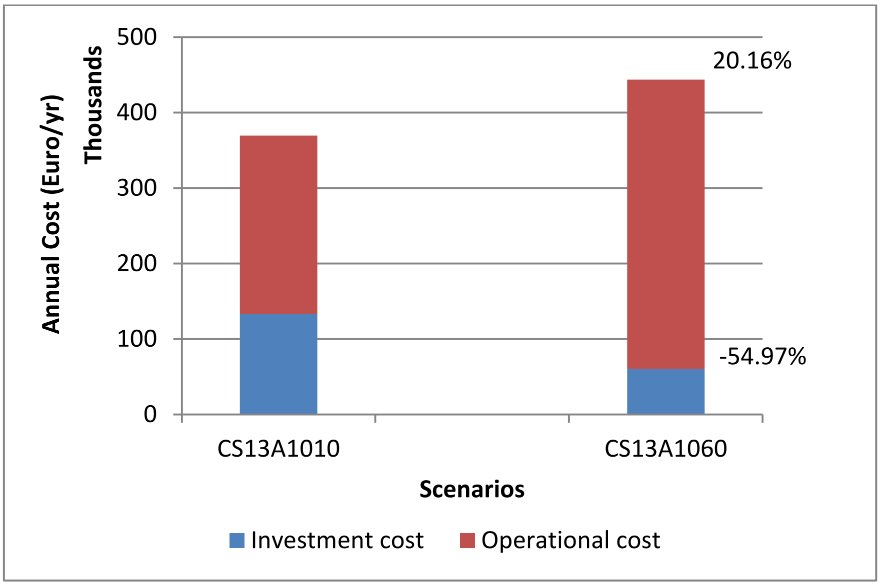


Figure 4.20: Annual investment, operational costs and percentage of increase in investment and total cost of the reference systems when optimizing; a) total cost, i.e. CS13A1010; b) Investment cost only, i.e. CS13A1060, with electricity tariff A.

Similar investigations, with minimizing investment cost only, were carried out with pipeline prices reductions at percentages of 20, 35, 50, 65 and 80%. Table 4.9 presents the investment costs, total annual costs and reduction percentages in the investment cost due to various reduction percentages in network piping prices within investment cost optimization scenarios. A reduction by up to 35% of piping costs did not have any impact on the optimized system under standard prices (CS13A1060). However, a network connecting building (N1b3) as a production location to buildings (N3) and (N1b1) has been selected by the model when pipeline prices were reduced by 50%, as shown in Figure 4.21. The reduction percentage in the investment cost was 0.26% in comparison to the standard prices scenario (CS13A1060). This percentage was dramatically increased with further reductions in pipeline prices by 65 and 80 %. However, such high price reductions are unlikely to occur in the market. Low investment cost for network pipeline would encourage installing bigger grids however this would also result in operational cost to circulate the chilled water. Because it was not considered in the objective function, operational cost was slightly fluctuating and thus the total cost. The reduction in the total cost for the last scenario, CS13A0065, is due to lower investment rather operational cost. And yet it is still not competitive to the total annual cost of the reference scenario, CS13A1010.

Table 4.9: Total annual costs of piping pricing scenarios for investment cost optimizations.

Reduction Percentage in Piping investment costs		**Optimizing investment costs only**			
	Code	Investment cost (Euro/year)	Operational cost (Euro/year)	Total Cost (Euro/year)	Reduction in Inv. cost
Standard prices (Figure 4.19)	CS13A1060	60,017.20	383,724.33	443,741.53	---
20 % reduction	CS13A1061	60,017.20	383,723.54	443,740.77	0 %
35 % reduction	CS13A1062	60,017.20	383,724.33	443,741.53	0 %
50 % reduction	CS13A1063	59,860.92	384,386.62	444,247.54	0.26 %
65 % reduction	CS13A1064	57,627.64	386,439.45	444,067.09	3.98%
80 % reduction	CS13A1065	53,182.34	386,430.60	439,612.94	11.39%

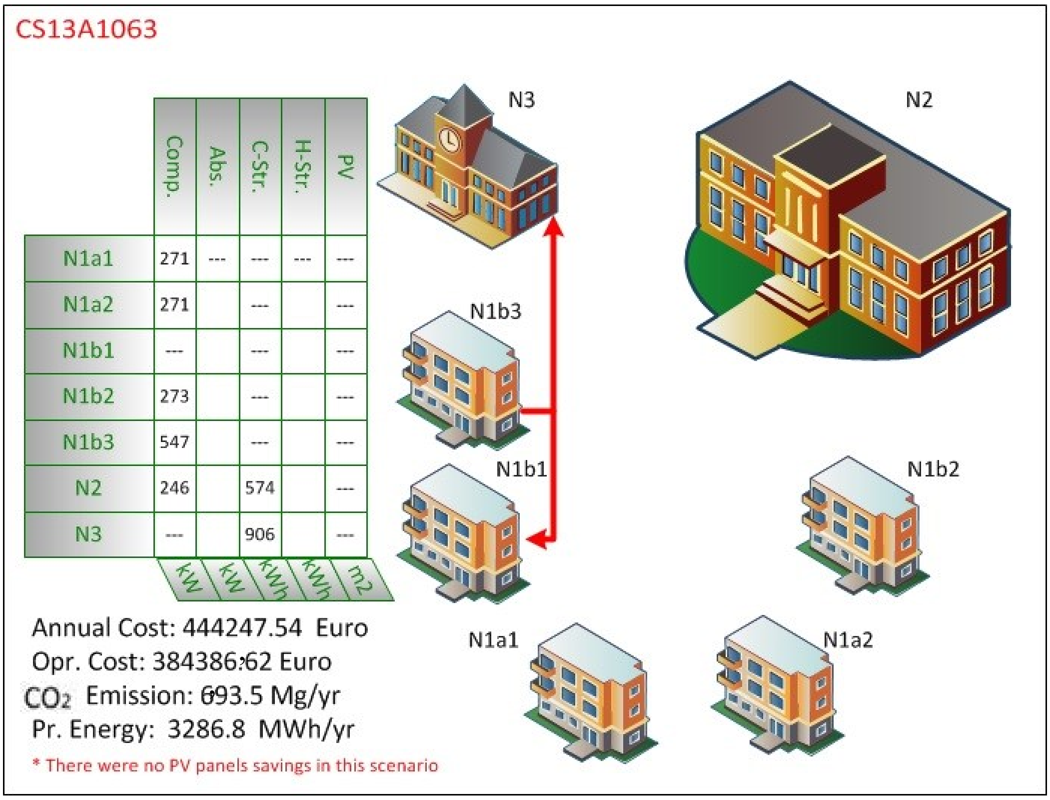


Figure 4.21: Investment cost optimization with 50% reduction in pipeline prices.

This investigation was carried to validate the previous conclusion obtained in section 4.3.3 that is DC pipeline investment cost has little impact on system design. Based on the investigations carried out so far, it is recommended to implement more focus on the operation cost when designing a cooling system within the assumption of constant COP for the compression chillers regardless of their capacities.

4.3.5 Operation Constraints Scenarios for investigation categories 1 and 2

For all the previous optimized scenarios, there were no restrictions for the operational pattern obtained by the model except for that the storage tank cannot charge or discharge more than 25% of its total capacity per one hour. Realistically, various operational restrictions should be included to present a more reliable operational pattern. Therefore, four different operational restrictions will be applied into the optimization model to analyze their impact on the optimal solutions in this section. These operational restrictions include:

- Variation in electricity prices during day and night periods (Tariff B).
- Availability of waste heat energy.
- Load shifting strategy.
- Variation in the values of COPs between day and night due to a change in ambient temperature.

The first restriction will be investigated for both Centralized and De-centralized DC systems to analyze impact of having variable electricity tariff on the design outcomes of both investigation categories. The other three operational restrictions will be applied on both Electricity tariffs A and B within the De-centralized investigation category to observe which one would have a positive impact towards implementing DC networks.

4.3.5.1 Day and Night Electricity Prices Scenarios (Tariff B)

4.3.5.1.1. Investigation category 1 (De-Centralized DCS with constant COP) scenarios

Until this point, all implemented scenarios assumed electricity tariff A representing a constant tariff over the whole day. A variable electricity tariff that changes between day and night hours was also considered. This variable electricity price system is known throughout the following chapters as tariff B. The electricity prices for both tariffs are presented in Table 4.10. All previous investigated scenarios under electricity tariff A will be re-investigated and compared to the equivalent scenarios under tariff B.

Table 4.10: Electricity prices in (€/kWhel) according to the two tariffs A and B [66].

Time period	Tariff A	Tariff B
Day time (6:00 – 21:00)	0.26	0.26
Night time (22:00-5:00)	0.26	0.19

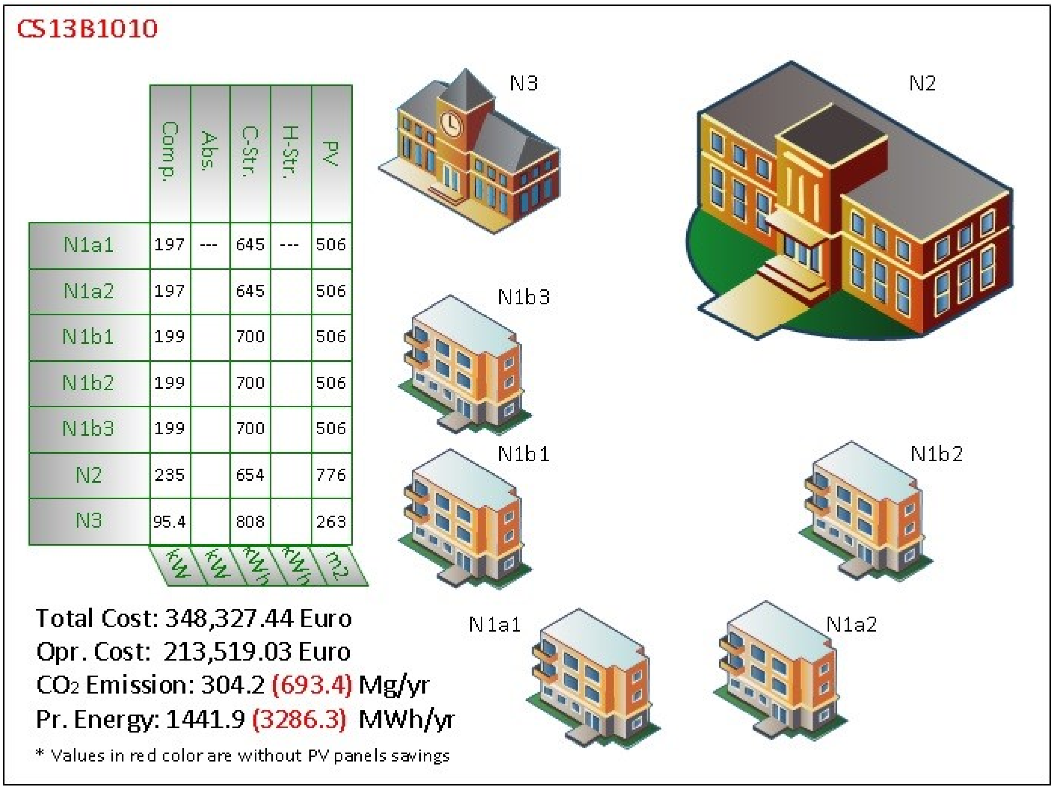


Figure 4.22: Total annual cost optimization for de-centralized reference scenario - electricity tariff B.

The first impact to be recognized on the optimized design of the De-centralized DC system for the reference scenario with electricity tariff B (CS13B1010: Figure 4.22), in comparison to reference scenario with electricity tariff A (CS13A1010: Figure 4.7), is the change in the sizes of chillers and storage tanks for all buildings except N2, as presented in Figure 4.23. For the residential buildings, chiller capacities were reduced by 5-6 % while bigger cold storage tanks were installed with an increase in capacity around 33 – 37%. This change in design option is due to the lower electricity prices at night hours which allow a special operation pattern to be adopted. This operational pattern can be clearly observed in building (N1a1) as presented in Figure 4.24a. Where, the chiller is operated at full capacity during night hours as well as at load hours during the day in order to charge the storage tank. This stored energy is to be utilized later, at peak load hours.

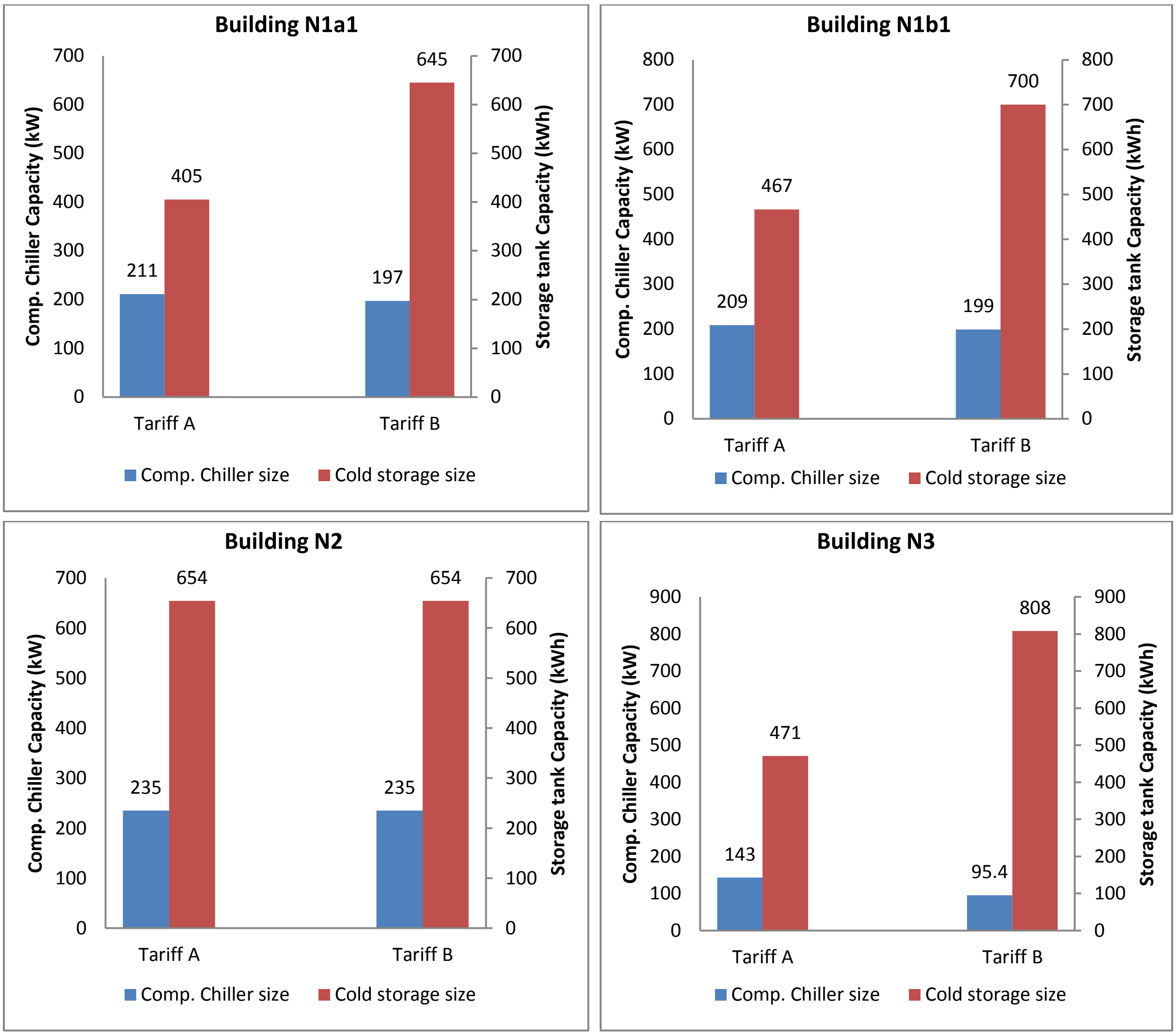


Figure 4.23: Capacities of compression chillers and storage tanks for reference scenarios optimized with electricity tariffs A (CS13A1010) and B (CS13B1010).

The operation strategy suggested for building (N1a1) was not adopted for the school (building N2), see Figure 4.24b, neither were the capacities of the chiller or storage tank in this building changed in comparison to the refrence scenario with tariff A (CS13A1010) as presented in Figure 4.23. This is due to the relatively high cooling peak load meaning that a high capacity storage tank would be required to meet the peak load, in case the chiller was wished to operate on low full capacity for 24 hours, which would result in a higher investment cost. In other words, the savings in operational costs resulting from adopting the same operation strategy as in the residential builings would be lower than the required additional investment cost.

A similar operation strategy of the one adopted for (N1a1) was also adopted for the city council (building N3) as shown in Figure 4.24c. Where, the chillers are operated at almost full capacity at some night hours when electricity prices are low, with the surplus energy being stored up in the tanks. Later, at high tariff periods, the amount of energy produced drops down in order to decrease the system's operational costs. At load hours, Chillers are restarted again to meet the cooling load. When the load hours reach their peak and cannot be met with the chillers anymore, stored energy from storage tanks is discharged to meet the peak load. Another possible solution could be to only produce energy at night when electricity prices are low and meet the cooling load entirely from the storage tanks. However, this approach would require a larger storage tank which in turn might be a more expensive option depending on the On/Off peak load ratio. The optimization model offers here a good consultation service in the form of mathematical comparison between the above mentioned design and operation trade-offs.

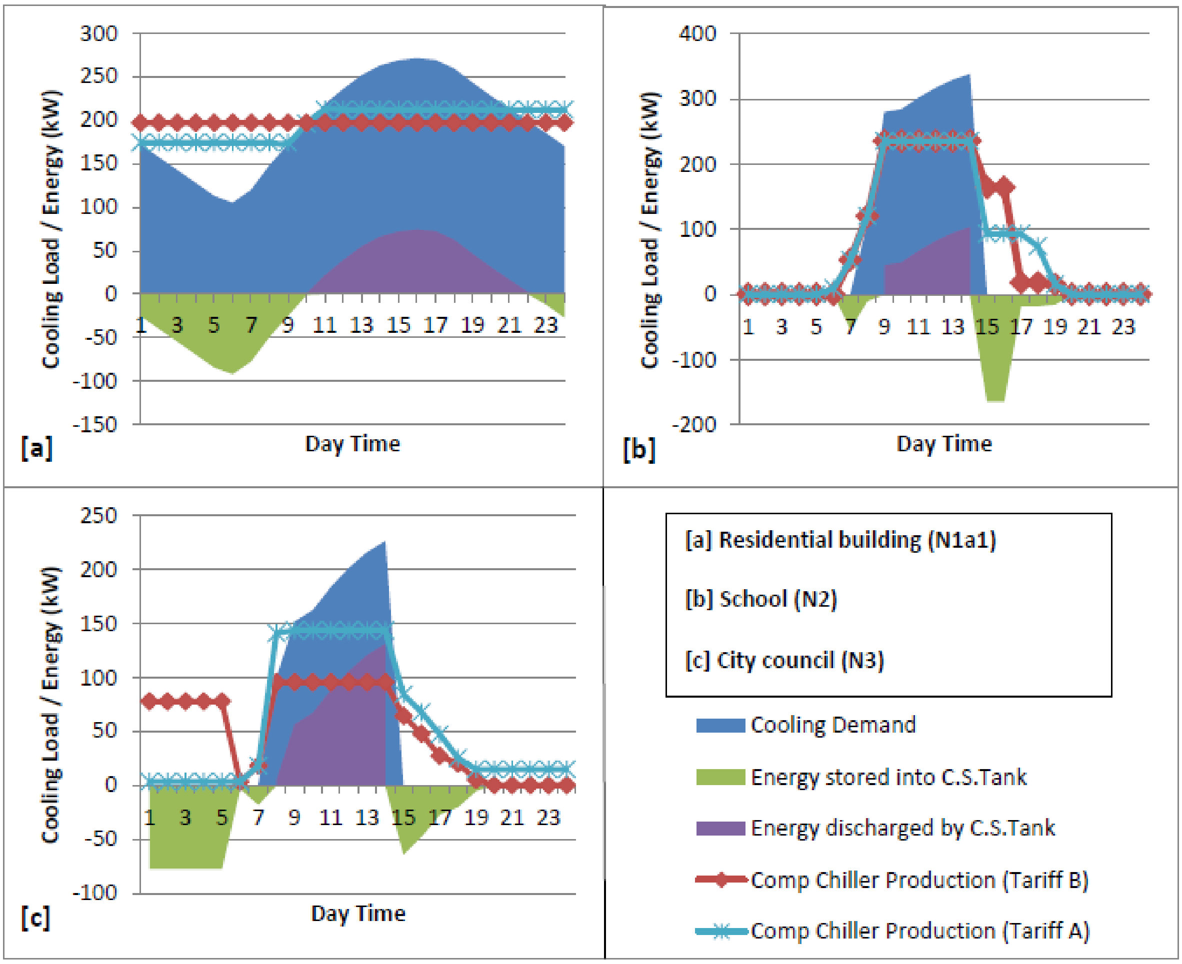


Figure 4.24: Cooling energy provided by individual systems in scenario CS13B1010 to meet cooling load profiles of three buildings (N1a1, N2 & N3).

As with electricity tariff A, a COP sensitivity analyses were carried out to observe the impact of various compression chiller COP values on the obtained solution. Once again, because the COPs were considered as constant values regardless of their sizes in each scenario, which eliminate the advantage of installing a high capacity chiller with a network, a group of separated individual cooling systems were installed in each building as can be seen in Figure 4.25. This type of No-network de-centralized system solution was chosen by the optimization model for each of the investigated COP values, from 3 to 7. However, the change in capacities of the installed compression chillers and cold storage tanks was taking a certain pattern with the increase of compression chiller COP at each sub-scenario.

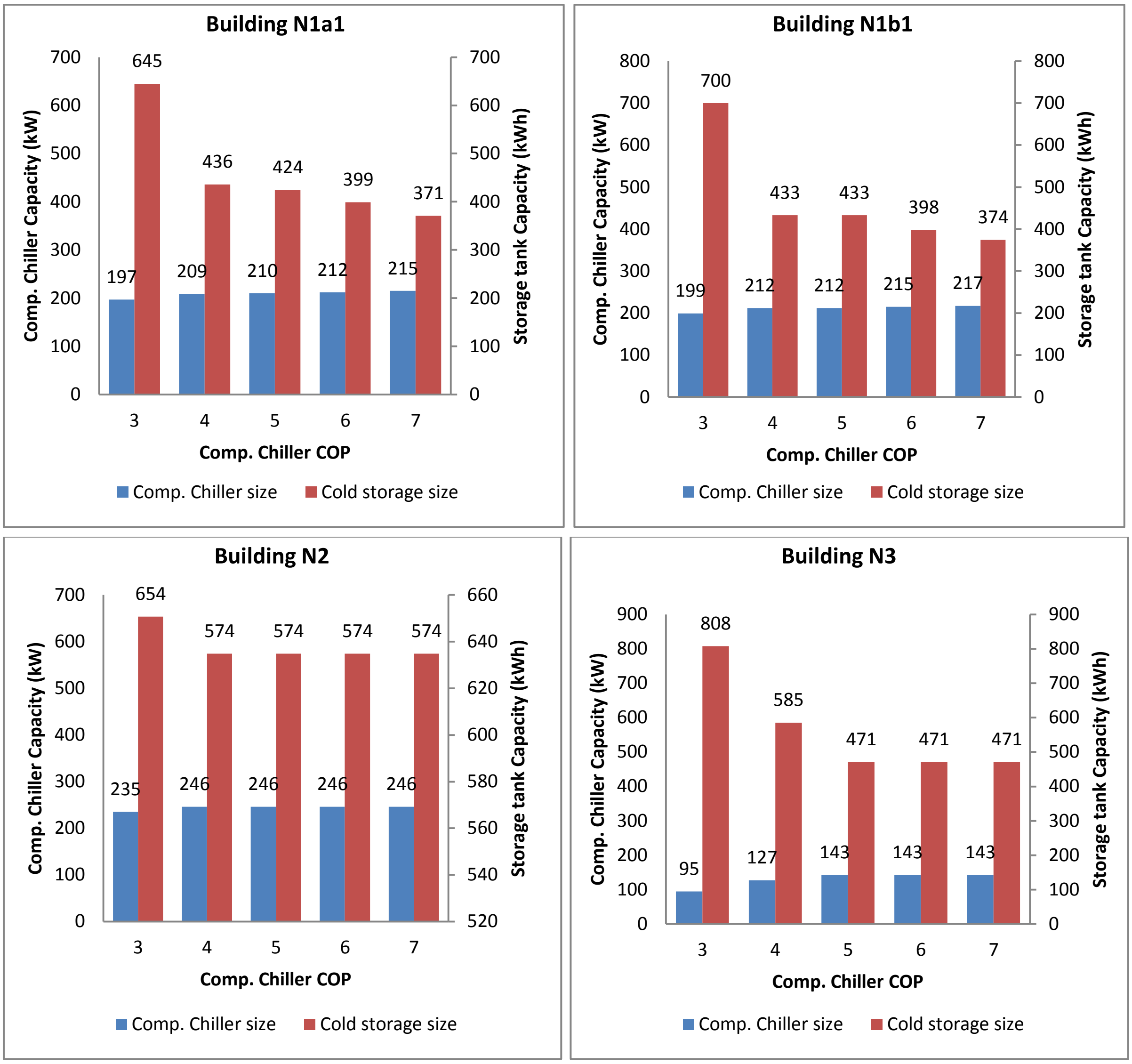


Figure 4.25: Capacities of compression chillers and storage tanks for reference scenarios optimized with different values for Chiller COPs with electricity tariff B.

For the residential buildings, adopting a higher value for the compression chiller COP resulted in choosing a smaller storage tank and slightly bigger chiller, as shown in Figure 4.25. Basically, a one-step higher COP allows the system to make advantage by producing more cooling energy from the same amount of consumed energy and thus meeting the cooling load of the building with less electrical energy consumption. The savings achieved in operational cost are used to install bigger chiller, which means smaller storage tanks are needed, however a balance has to be made between decrease in chiller operational cost and storage tank investment cost from one side and the increase in the chiller investment cost from the other side. Thus optimization model finds a balance point where any further increase in chiller capacity would not be useful because the additional investment cost will be higher than the gain in the operational cost. This search for the balance point occurs every time the COP changes. A similar pattern occurs for the none-residential buildings but only for the first one or two COP values. Later on, compression chiller and storage tank capacities stay on the same level regardless of further increase in the COP. Where the savings in operational cost resulted from adopting higher COPs are not sufficient yet to make the system cross the achieved balance point into another one. Figure 4.26 show the annual, investment, and operational costs and annual CO_2 emissions obtained for the investigated sub-scenarios. The obtained annual values are very close to those obtained with electricity tariff A, i.e. Figure 4.10, with very slight differences in operational costs.

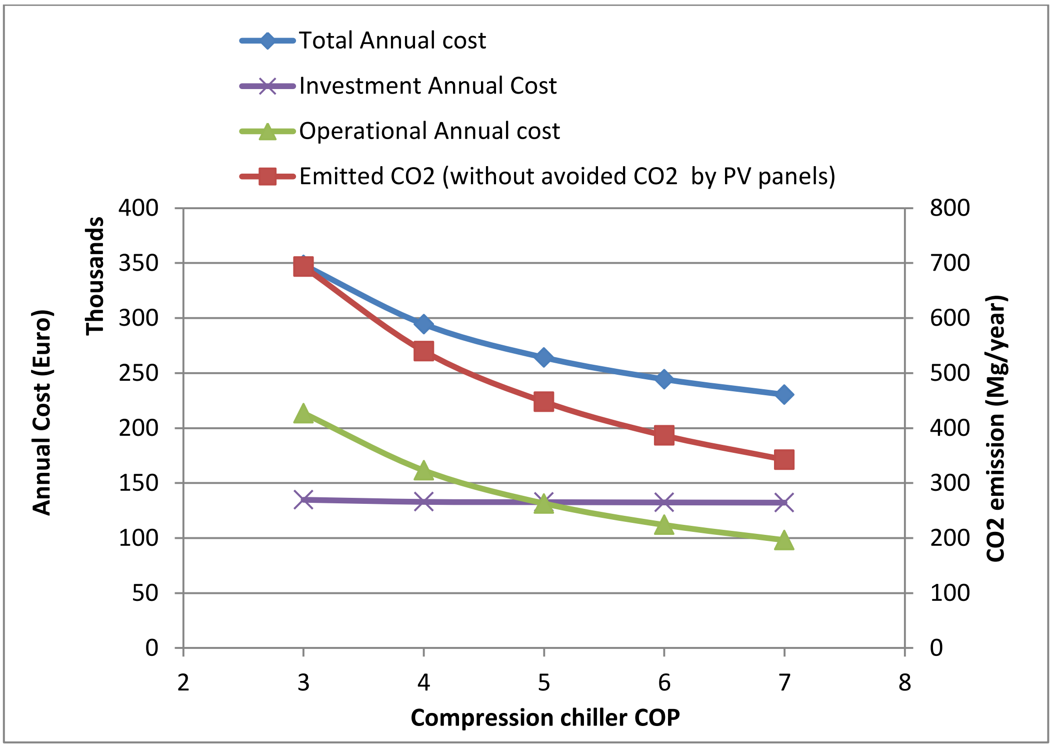


Figure 4.26: Annual total, investment, and operational cost and CO_2 emission obtained for the COP sensitivity analyses with electricity tariff B under minimizing total annual cost as the objective of optimization.

4.3.5.1.2. Investigation category 2 (Centralized DCS with constant COP) scenarios

Since the investigation for the reference scenario under tariff B has come out as such, i.e. a group of separated cooling systems for each building, centralized district cooling scenarios were carried out again under the new tariff. The same two restriction methods used previously, i.e. on area availability and chiller location, were used. Total annual costs of these sub-scenarios are presented in Table 4.11. Similar to what investigations with electricity tariff A have shown in Figure 4.12, the possibility to install other equipment at different locations in the district, especially cold storage tanks, resulted in lower total costs for the chiller location restrictions with electricity tariff B as well.

It was noticed once again that building N2 represents the best location for a central production station in the case of a centralized district cooling system due to having the highest cooling peak load among all other buildings which opens the possibility of installing pipelines with minimized sizes within the DC network. In addition, building N2 has required the lowest chiller capacity and lowest total storage tank capacities compared to the other six buildings when serving as the central production location. The optimized systems for the two optimal solutions at building (N2) under the two restriction methods are presented in Figure 4.27. A separated centralized DC optimization where the model is free to select the location of the central chiller within electricity tariff B, CS13B2010, was performed as well and resulted in the same system shown in Figure 4.27b which represents the optimal centralized district cooling system.

Table 4.11: Total annual costs of Centralized DC systems sub-scenarios under electricity tariff B.

Central Unit	**Availability area restriction**		**Chiller location restriction**	
	Code	Cost (Euro/year)	Code	Cost (Euro/year)
At building (N1a1)	CS13B1021	399,664.53	CS13B1031	399,238.57
At building (N1a2)	CS13B1022	400,326.96	CS13B1032	399,571.19
At building (N1b1)	CS13B1023	399,441.99	CS13B1033	399,218.55
At building (N1b2)	CS13B1024	401,044.47	CS13B1034	400,410.86
At building (N1b3)	CS13B1025	399,670.10	CS13B1035	399,503.51
At building (N2)	CS13B1026	398,018.21	CS13B1036	397,507.07
At building (N3)	CS13B1027	404,215.23	CS13B1037	404,020.22

A detailed cost comparison between optimal sub-scenario, when N2 is the central production plant, and the sub-scenario with highest total annual cost, which is when N3 is the central production plant, is presented in Table 4.12. Unlike the situation electricity tariff A, where operational cost difference seemed to have higher impact, both investment and operational cost seemed to share a balanced impact within investigation with electricity tariff B especially at the chiller location restriction sub-scenarios. The investment costs within electricity tariff B were higher than those within electricity tariff A. This is due to installing higher capacities for the storage tanks to benefit from the lower electricity prices at night within tariff B. Choosing building N2 as a central production plant achieved a evident advantage over building N3 in plant site investment cost yet obtained higher pipeline network investment cost. Generally, it was the electricity purchase costs that made the scenario with building N2 as a central production plant the optimal solution due to a bigger amount of locally consumed PV panels' electricity as explained previously in section 4.3.2.

While the cold storages were always installed at the central production location for the first set of sub-scenarios due to the area restrictions, two or three storage tanks were installed at different locations in the second set of sub-scenarios. This enables the system to have smaller sizes for the network pipelines which are used to transport a more steady flow of cooling energy to charge the cold storages during off-peak load hours. One of these storage tanks has a relatively high capacity and located at central production plant. Such central storage was not evident at the investigations within electricity tariff A. This storage main aim is to benefit from electricity price different by operating the central chiller at night hours and store the cold water for peak load hours. The operational production strategies of the two optimal solutions of Figure 4.27 to meet the overall hourly cooling load of the whole system are presented in Figures 4.28 and 4.29. See Figures 4.14 and 4.15 for electricity tariff A. Other smaller storage tanks, additional to the central storage, were added depending on the location of compression chiller and type of the building where the chiller is installed, as shown in Table 4.13. It was observed that when the compression chiller is installed at most of the residential buildings, two additional storage tanks were installed at the two buildings:

- Building N2, due to its high peak cooling load in comparison to the other buildings.
- Building N1b3, except for when the chiller location is next to it, where N1b3 has a central location and it represent the connection point between residential and none-residential buildings.

However, these were not the chosen locations when the chiller is installed at one of the none-residential buildings.

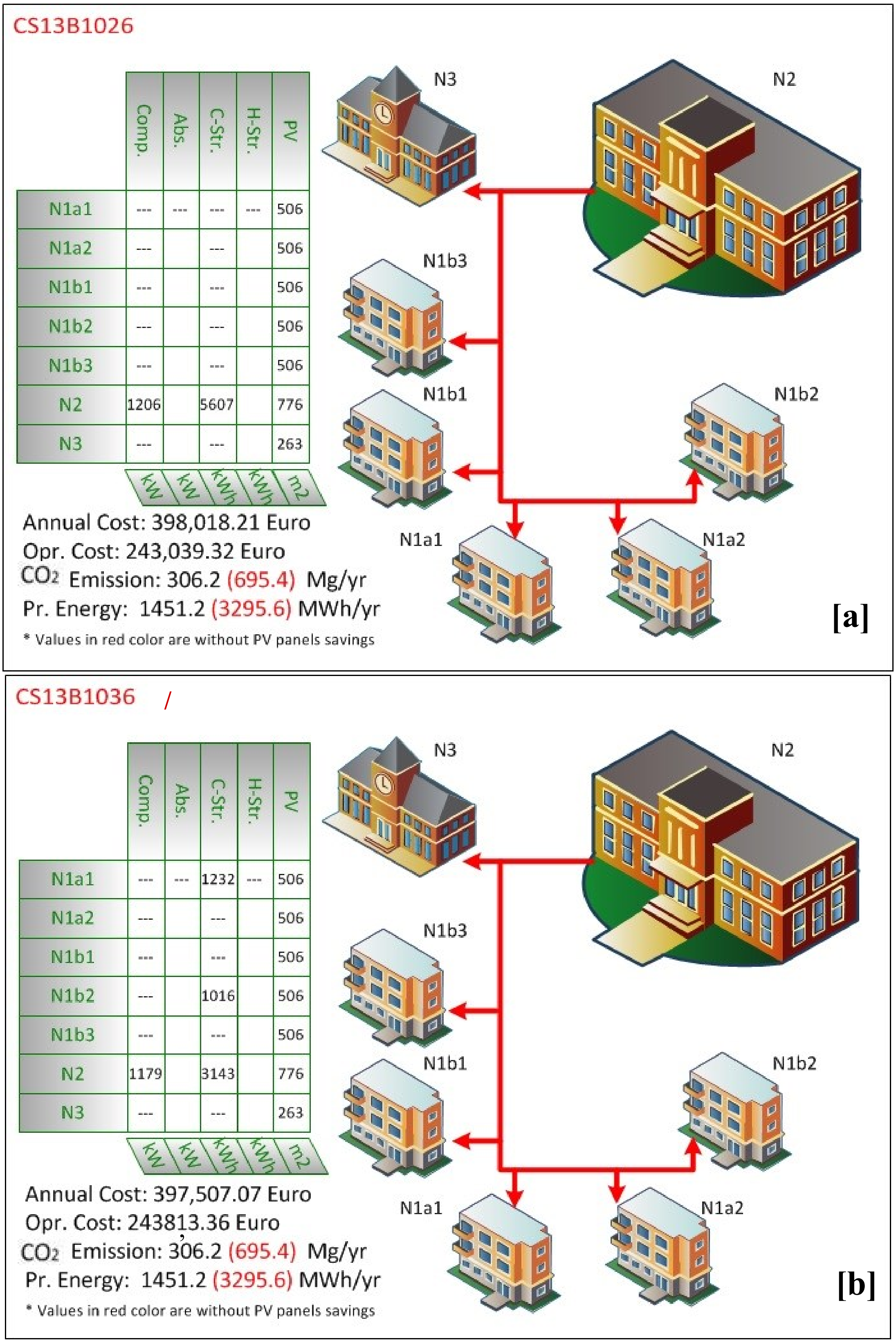


Figure 4.27: Cost optimization under: a) Available area restriction, and b) Chiller location restriction, to (N2) for electricity tariff B.

Table 4.12: Details of costs for the scenarios of Centralized DC at buildings N2 and N3 and for both restriction methods with electricity tariff B.

Type of cost [1]	**Availability area restriction**		
	Central Pl. at N2 CS13B1026	Central Pl. at N3 CS13B1027	Difference
Total annual costs	398,018.21	404,215.23	-6,197.02
1. Total plant investment cost	122,642.11	125,257.08	-2,614.96
2. Total Network investment cost	32,336.77	31,071.41	1,265.37
3. Total operational cost	243,039.33	247,886.75	-4,847.43
3.1. Plant site operational cost	102,415.18	102,769.04	-353.86
3.2. Electrical network (pumping) cost	760.154	522.181	237.97
3.3. Electrical plant site operational cost	139,863.99	144,595.53	-4,731.54
3.3.1. Comp. chiller electricity cost	180,327.67	197,959.88	-17,632.21
3.3.2. PV panels electricity income [2]	78,681.69	91,118.42	-12,436.73
3.3.3. Heat dissipater electricity cost	38,218.02	37,754.07	463.95
Type of cost [1]	**Chiller location restriction**		
	Central Pl. at N2 CS13B1036	Central Pl. at N3 CS13B1037	Difference
Total annual costs	397,507.08	404,020.22	-6,513.14
1. Total plant investment cost	122,364.09	125,992.12	-3,628.03
2. Total Network investment cost	31,329.61	30,586.04	743.58
3. Total operational cost	243,813.37	247,442.06	-3,628.69
3.1. Plant site operational cost	102,398.62	102,846.57	-447.96
3.2. Electrical network (pumping) cost	728.381	509.266	219.12
3.3. Electrical plant site operational cost	140,686.37	144,086.22	-3,399.85
3.3.1. Comp. chiller electricity cost	181,024.60	197,528.26	-16,503.66
3.3.2. PV panels electricity income [2]	78,681.69	91,118.42	-12,436.73
3.3.3. Heat dissipater electricity cost	38,343.46	37,676.38	667.08

[1] All costs are in Euro.
[2] The PV electricity income is to be subtracted when calculating the electrical plant site operational cost.

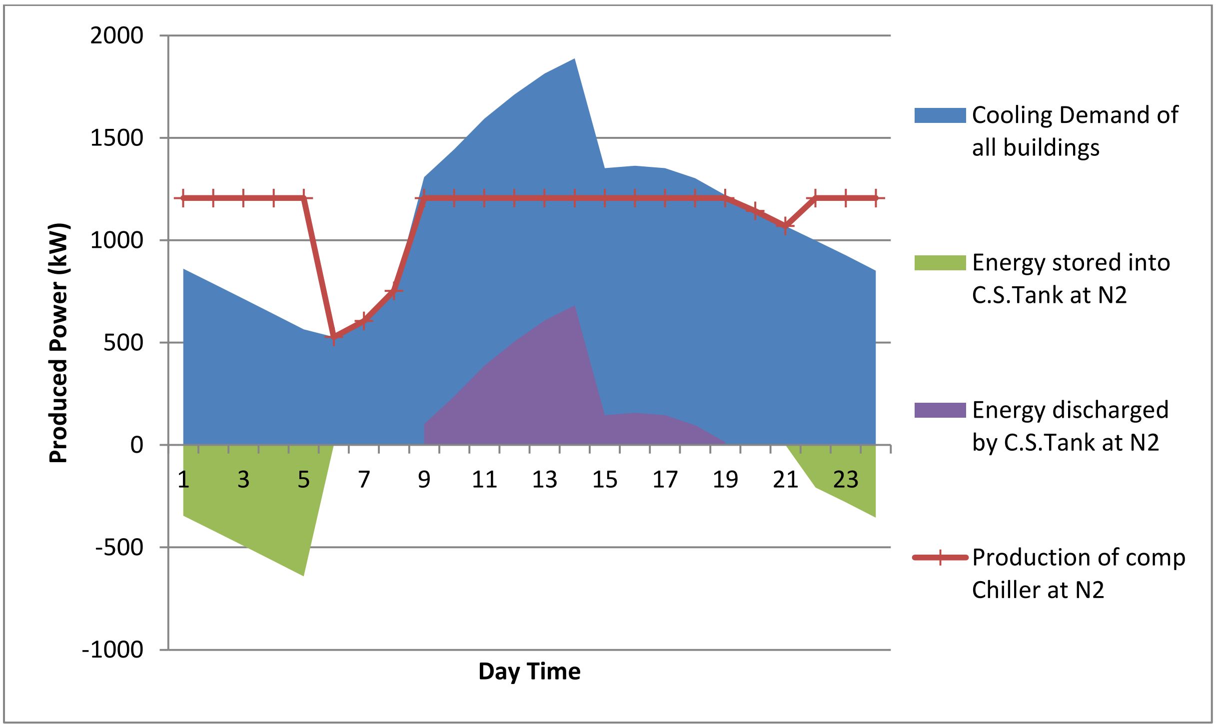


Figure 4.28: Cooling energy provided by the centralized DC system at building (N2) in scenario (CS13B1026: Figure 4.27a) to meet overall cooling load of all buildings at a typical summer day in July.

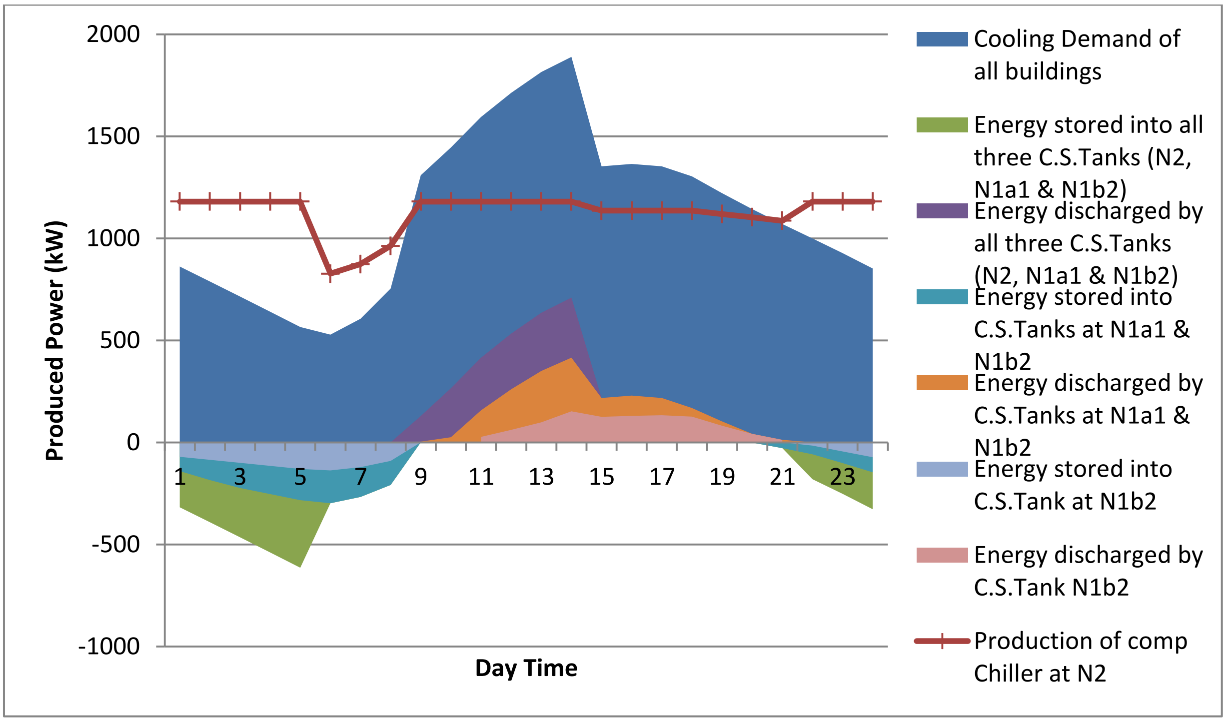


Figure 4.29: Cooling energy provided by the centralized DC system at building (N2) in scenario (CS13B1036: Figure 4.27b) to meet overall cooling load of all buildings at a typical summer day in July.

Table 4.13: Location and capacity of chillers and storage tanks in the chiller location restriction sub-scenarios with electricity tariff B.

Scenario Code	**Central Chiller**			**Cold Storage Tanks**	
	Location	Capacity (kW)	Percentage of capacity to the total peak load*	Location	Capacity (kWh)
CS13B1031	N1a1	1245.21	64.5 %	N1a1 N1b3 N2	3694.31 1077.78 1283.59
CS13B1032	N1a2	1251.97	64.9 %	N1a2 N1b3 N2	3694.31 1131.89 1283.59
CS13B1033	N1b1	1224.94	63.5 %	N1b1 N2	4724.72 1131.49
CS13B1034	N1b2	1254.99	65.1 %	N1b2 N1b3 N2	3668.77 1131.89 1334.66
CS13B1035	N1b3	1232.29	63.9 %	N1b2 N1b3 N2	1028.92 3770.36 1131.49
CS13B1036	N2	1179.70	61.2 %	N1a1 N1b2 N2	1232.60 1016.13 3143.87
CS13B1037	N3	1310.50	67.9 %	N1a2 N3	1232.60 5205.95

* The total peak load of all buildings is 1929 kW.

Central production chillers were operated at their full capacity during the night hours due to lower electricity prices and then dropped to a lower rate during day hours when electricity prices goes up. In order to obtain a more steady energy production pattern for the central chillers, an additional sub-scenario was carried out where seven storage tanks were installed, i.e. one at each building. Table 4.14 presents the total and operational annual costs for the three different energy storing strategies:

- Central storage at the central production plant location (CS13A1026)
- Optimized storage pattern, i.e. optimized number and capacities of storages (CS13A1036)
- One-storage at each building (CS13B1047).

Table 4.14: Total and operation costs for three centralized DC systems with different number of storage tanks.

Scenario	Description	Annual operational cost (Euro)	Total annual cost (Euro)	Percentage of difference in total cost
CS13B1026	One central storage tank	243039.32	398,018.21	0.13 %
CS13B1036	Optimized number of storage tanks	243813.36	397,507.07	---
CS13B1047	One storage tank at each building	243690.39	398,467.61	0.24 %

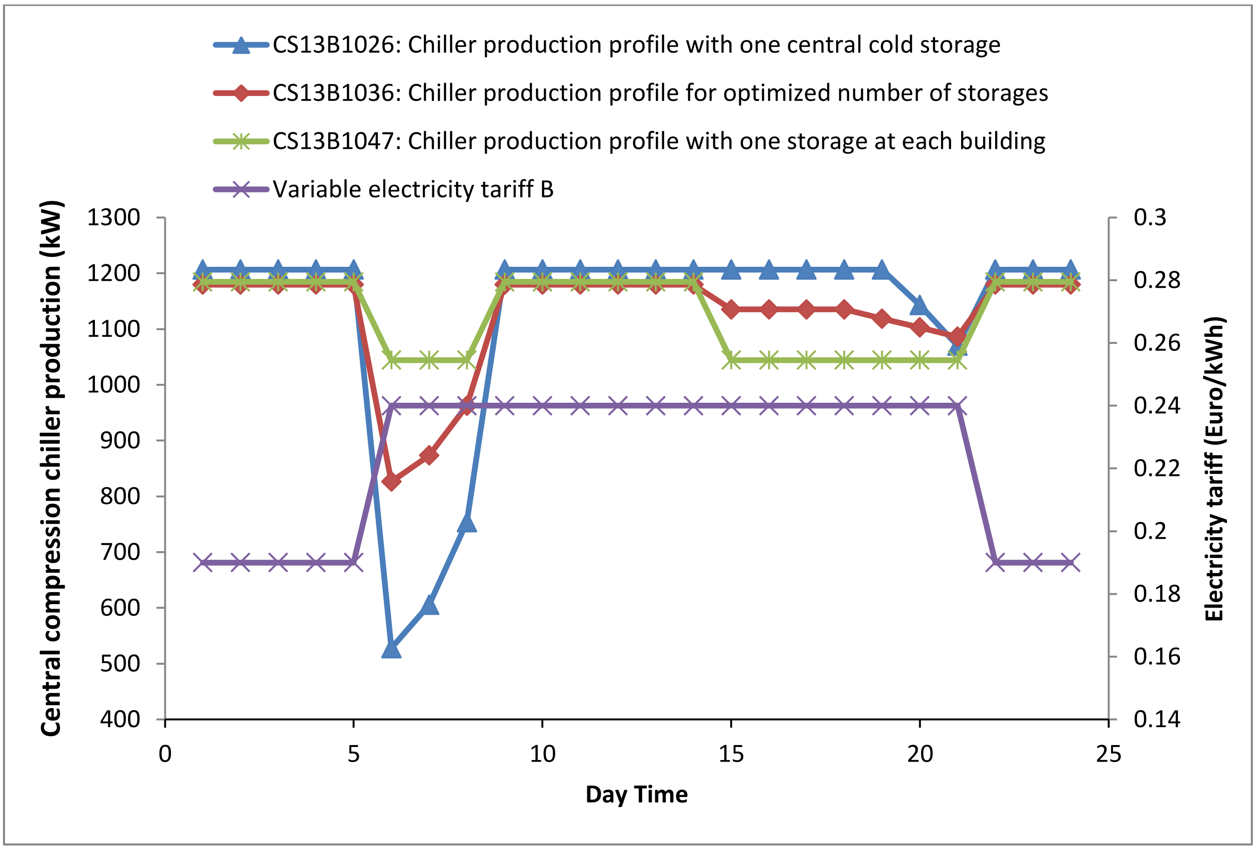


Figure 4.30: Chiller energy production profiles of three centralized DCSs with: a) Central storage, b) Optimized no. of storages, and c) One-storage at each building, for electricity tariff B.

Although, sub-scenario CS13B1036 had the lowest total annual cost, the increase in the total cost of the Centralized DC system is around 0.13% when adopting the central storage and 0.24% when implementing one-storage at each building theme as shown in Table 4.14. None of the three strategies did have significant advantage over the other two in terms of total annual cost where they all benefited from the low electricity prices at night even though they had different energy storing strategies. However, Figure 4.30 shows that the third sub-scenario, CS13B1047, provides a more steady cooling energy production profile. Thus it is recommended to invest in a multi-storage system with one storage tank at each building when designing a centralized DC system within variable electricity tariff. However, this investigation was carried out under the assumption of constant COP for the compression chillers. Hence, the concluded recommendation is limited to this assumption. A variable COP investigation is to be carried out later on in this chapter. Moreover, comparing the three centralized DC sub-scenarios to the De-centralized reference sub-scenario, CS13B1010, shows an evident increase in the total annual cost exceeding 14%, as shown in Figure 4.31, which indicates that designing DC system with constant COP for the compression chillers does not favor centralized DC system even when variable electricity tariffs are adopted.

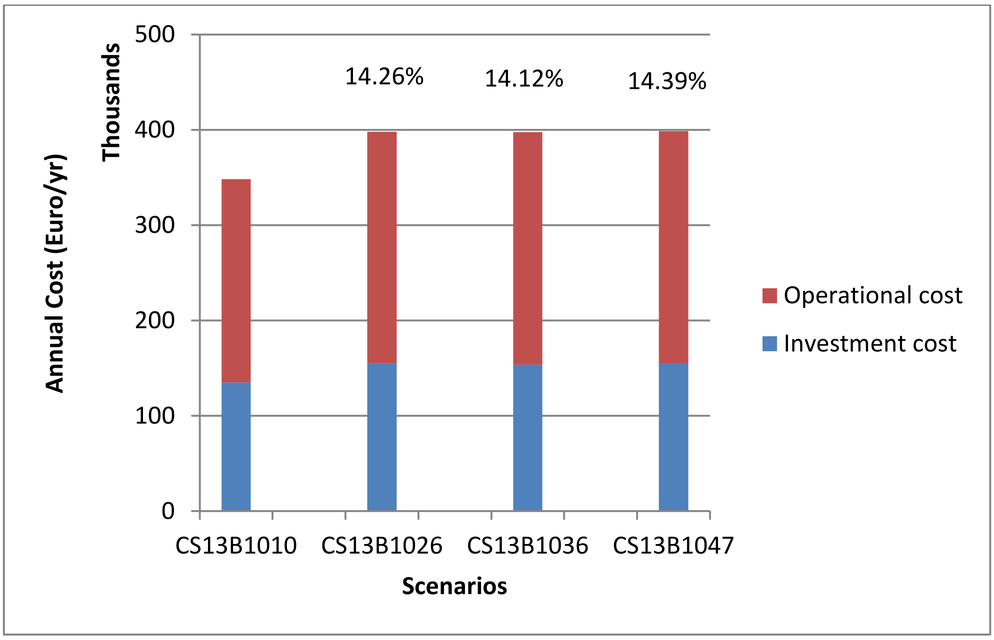


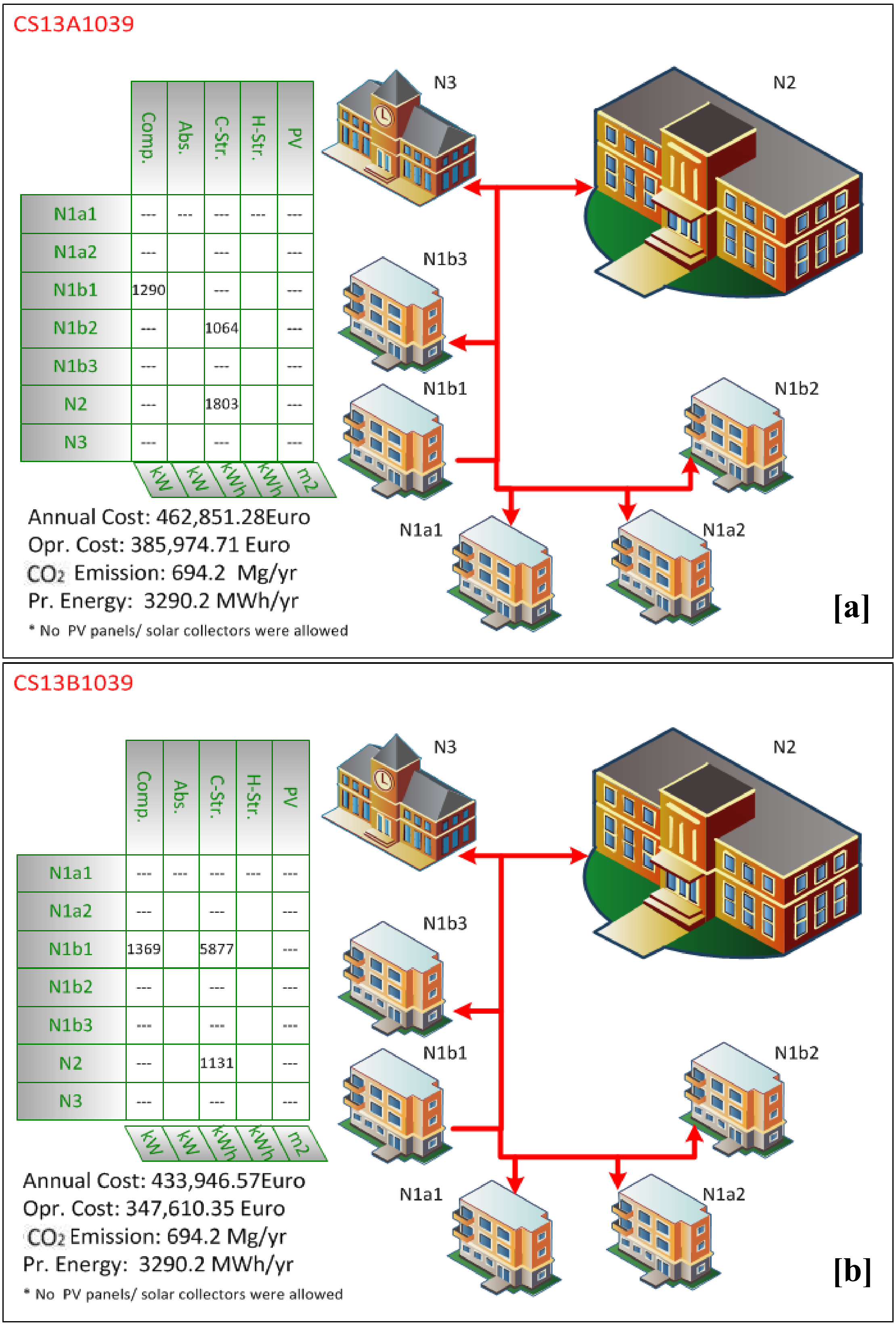
Figure 4.31: Annual investment, operational costs and percentage of increase in total cost of three centralized DCSs with: a) Central storage, b) Optimized no. of storages, and c) One-storage at each building, in comparison to the De-centralized optimal solution CS13B1010 with electricity tariff B.

4.3.5.1.3. Optimizing without considering solar energy

Investigation category 2, i.e. Centralized DC system with constant COP, for both electricity tariffs A and B have showed that it is the installed PV panels that gives building N2 the advantage to serve as central production plant through a relatively high amount of locally consumed PV panels' electricity which lowers the electricity purchase costs from the grid. Therefore, two other sub-scenarios were carried out for each of the electricity tariffs in order to validate this conclusion. In these sub-scenarios no PV panels or solar collectors were allowed to be installed. The adopted coding for these two sub-scenarios were CS13A1039 and CS13B1039 for electricity tariffs A and B, respectively. To ensure adopting of a central DC network the optimization model was free to select the location of the chiller, however only one chiller was allowed to be installed. Such restriction method was previously performed, with PV panels, and the results were the exact same obtained systems of CS13A1036 and CS13B1036.

The first major impact of excluding PV panels and solar collectors was the change of the central production plant where N2 is no longer serving as optimal solution for this task. Instead, building N1b1, which has a central location in the district, is serving as the central production plant, as shown in Figure 4.32. The storage adopted pattern was similar to the observed pattern so far where two storage tanks were installed at the ends of the network within electricity tariff A. While, in electricity tariff B, one was installed at the production plant and another one at building N2 due to its relatively high peak cooling load.

Cost comparison of the optimized sub-scenarios, presented at Table 4.15 and Figure 4.33, indicates that the systems obtained without utilizing solar energy, i.e. CS13A1039 and CS13B1039, have less investment cost than that of the systems when installing PV panels, i.e. CS13A1036 and CS13B1036. However, these later systems had a big advantage in operational cost especially electricity cost. Therefore, the total annual costs of the systems with PV panels where less and thus a better solution to adopt.



[a] CS13A1039

	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	---	---	---	---	---
N1a2	---		---		---
N1b1	1290		---		---
N1b2	---		1064		---
N1b3	---		---		---
N2	---		1803		---
N3	---		---		---
	kW	kW	kWh	kWh	m2

[b] CS13B1039

	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	---	---	---	---	---
N1a2	---		---		---
N1b1	1369		5877		---
N1b2	---		---		---
N1b3	---		---		---
N2	---		1131		---
N3	---		---		---
	kW	kW	kWh	kWh	m2

Figure 4.32: Cost optimization sub-scenarios without utilizing solar energy, i.e. PV or solar collectors within a) Electricity tariff A, and b) Electricity tariff B.

Table 4.15: Costs comparison for optimized Centralized DC sub-scenarios obtained with and without utilizing PV panels for both electricity tariffs A and B.

Type of cost [1]	Tariff A		
	CS13A1036	CS13A1039	Difference
Total annual costs	425,937.10	462,851.28	-36,914.18
4. Total plant investment cost	118,525.99	47,268.04	71,257.95
5. Total Network investment cost	31,668.78	29,608.53	2,060.25
6. Total operational cost	275,742.37	385,974.72	-110,232.35
6.1. Plant site operational cost	100,790.95	100,817.28	-26.33
6.2. Electrical network (pumping) cost	806.13	335.827	470.30
6.3. Electrical plant site operational cost	174,145.27	284,821.61	-110,676.34
6.3.1. Comp. chiller electricity cost	209,379.60	241,374.25	-31,994.65
6.3.2. PV panels electricity income [2]	78,681.69	0.00	78,681.69
6.3.3. Heat dissipater electricity cost	43,447.36	43,447.37	0.00
Type of cost [1]	**Tariff B**		
	CS13B1036	CS13B1039	Difference
Total annual costs	397,507.08	433,946.57	-36,439.50
4. Total plant investment cost	122,364.09	56,489.20	65,874.90
5. Total Network investment cost	31,329.61	29,847.01	1,482.60
6. Total operational cost	243,813.37	347,610.36	-103,796.99
6.1. Plant site operational cost	102,398.62	102,738.58	-339.96
6.2. Electrical network (pumping) cost	728.381	310.954	417.43
6.3. Electrical plant site operational cost	140,686.37	244,560.83	-103,874.46
6.3.1. Comp. chiller electricity cost	181,024.60	207,254.94	-26,230.34
6.3.2. PV panels electricity income [2]	78,681.69	0.00	78,681.69
6.3.3. Heat dissipater electricity cost	38,343.46	37,305.89	1,037.58

[1] All costs are in Euro.
[2] The PV electricity income is to be subtracted when calculating the electrical plant site operational cost.

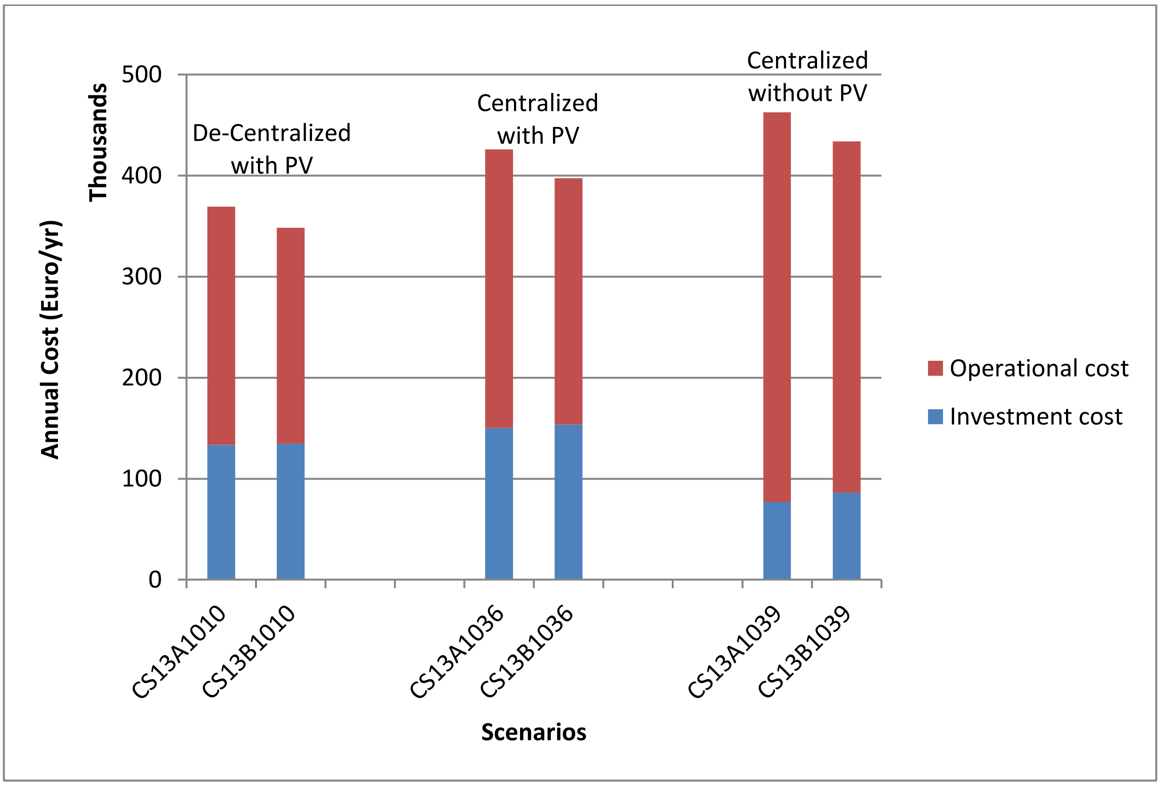


Figure 4.33: Annual investment and operational costs of sub-scenarios with and without PV panels with electricity tariffs A and B.

4.3.5.1.4. Piping Prices Scenarios within electricity Tariff B

Since that reference scenario for investigation category1, i.e. De-Centralized DCS with constant COP, has resulted in a group of separated individual systems for each building with no DC network being installed within electricity tariff B as well, a sensitivity analysis for piping investment costs, similar to that with electricity tariff A, was carried out with tariff B to validate and generalize the common conclusions drawn from the investigation as a further supporting mechanism for decision-makers. The investment costs of the network pipelines were reduced by percentages of 20, 35, 50, 65, and 80 % of their standard prices.

As in investigating tariff A scenarios, limited impact of the pipelines investment cost on the obtained optimal solution, was observed within tariff B sub-scenarios as well. A partial network, connecting four buildings, was installed by the optimization model when reducing the pipeline prices by 80%, as demonstrated in Figure 4.34. This network is supplied by energy provided from the main chiller at the school (N2) to meet the cooling loads at the city council (N3) and production building (N2) itself and to complement the local chillers at (N1b1 and N1b3) in meeting the cooling load at peak load hours. A 0.44% reduction in the total annual cost was the outcome of 80% reduction in pipelines investment cost. Such a low impact of a large price reduction is understandable considering the relatively low DC network investment cost in this case study. Table 4.12 shows that the investment cost for the DC network of the centralized system represent only 7% – 8% of the total annual cost of the entire system. Table 4.16 presents the total annual costs and cost reduction percentages due to various reductions in network piping cost. Based on these results it is concluded that pipeline investment costs should have very low impact on the decision making process at least under the assumption of constant COP for the compression chillers.

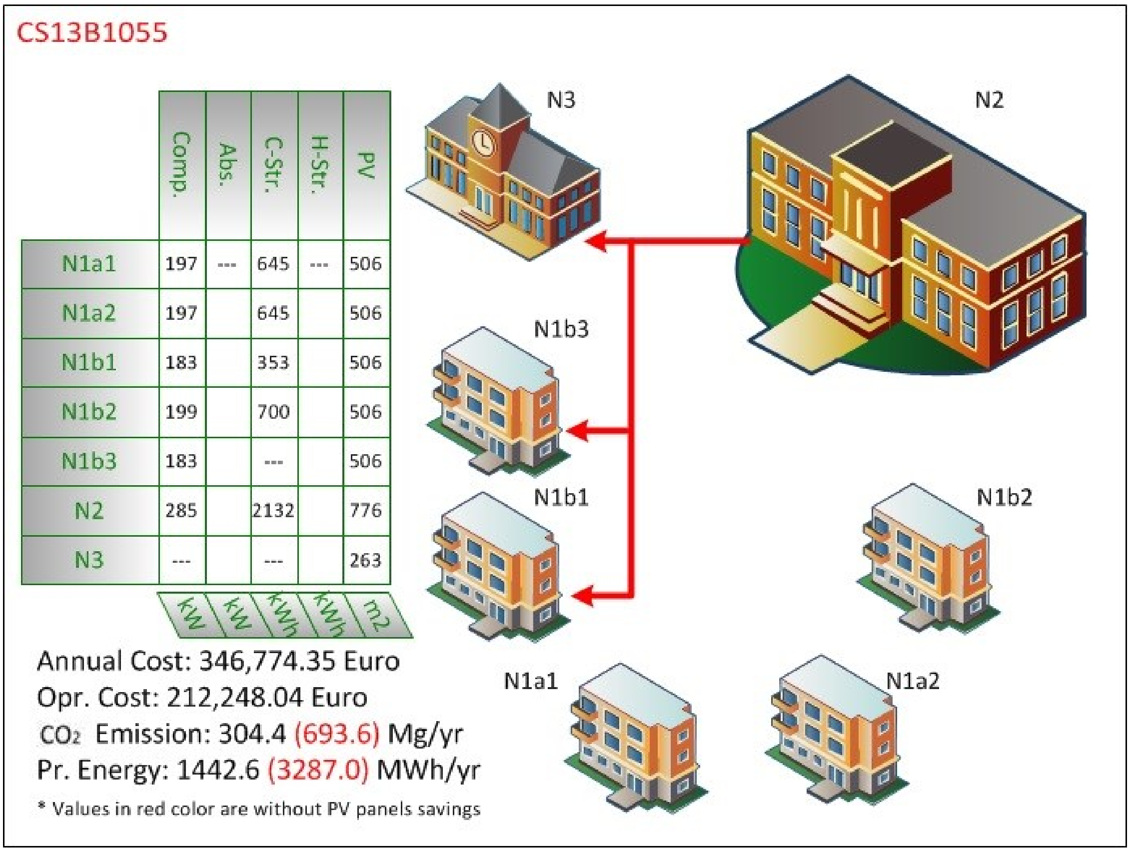


Figure 4.34: Total annual cost optimization with 80% reduction in network pipeline prices for electricity tariff B.

Table 4.16: Total annual costs of piping pricing sub-scenarios for total cost optimizations with electricity tariff B.

Reduction Percentage in Piping costs	Optimizing total annual costs		
	Code	Total Cost (Euro/year)	Reduction Percentage
Standard prices	CS13B1010	348,327.44	---
20 % reduction	CS13B1051	348,327.44	0 %
35 % reduction	CS13B1052	348,327.44	0 %
50 % reduction	CS13B1053	348,327.44	0 %
65 % reduction	CS13B1054	347,460.20	0.25 %
80 % reduction	CS13B1055	346,774.35	0.44 %

4.3.5.1.5. Investment cost optimization within electricity tariff B

Investigating a reference scenario to minimize the investment cost only under tariff B (CS13B1060) have led to the same de-centralized system obtained previously under electricity tariff A, i.e. CS13A1060, shown in Figure 4.19, since changing the electricity tariff has no impact on the new objective function, i.e. investment cost. This further validates the conclusion that operation cost has a higher impact on the optimization process and, consequently, the resulting cooling system designs. However, it is noticed that optimizing the investment cost alone causes an increase of around 20% in the total cost. Figure 4.35 shows that annual costs, when optimizing investment cost only, are higher than when optimizing total costs. This is because the model does suggest the smallest possible size of equipment in order to reduce investments costs regardless of the number of hours the chillers and other equepment have to operate which results in a higher operational cost for the system. Therefore, making decisions based on optimizing investment cost only should be avoided.

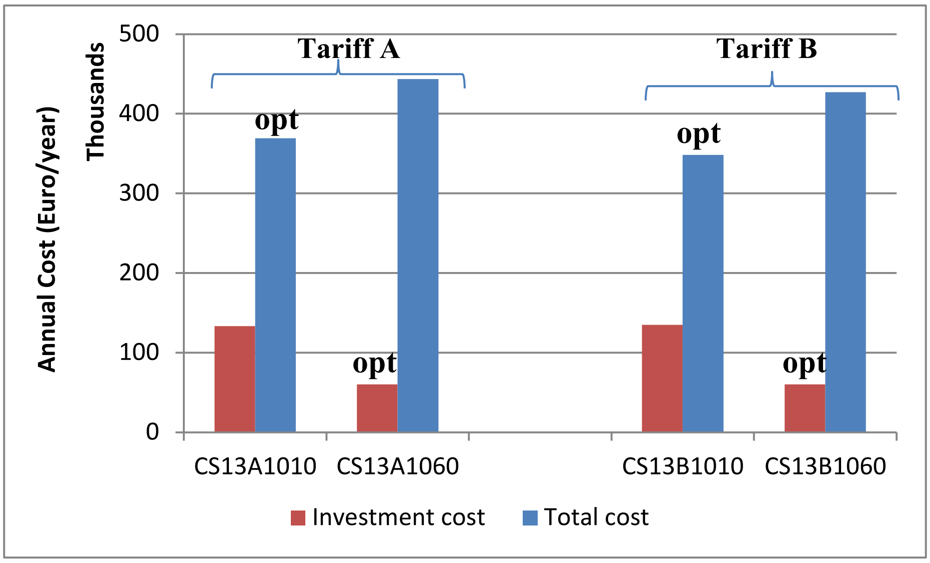


Figure 4.35: Annual investment and total costs of four reference scenarios for both electricity tariffs A & B and with optimizing total, CS13A1010 and CS13B1010, and investment, CS13A1060 and CS13B1060, costs.

4.3.5.2 Waste Heat Availability Scenarios

In order to investigate the competitiveness of absorption chillers to compression chillers and the impact of available free of charge heat, from different resources, on the decision making within the DCS design process under constant COP assumption, new investigations were carried out with new additional assumptions:

- The main adopted assumption within these sub-scenarios was that a certain percentage of the driving energy, e.g. waste heat, solar, or geothermal energy, of the absorption chiller is available at the location of the cooling energy production plant for free.
- This free of charge energy is to be named as 'waste heat' within this work.
- The availability of waste heat to drive the absorption chillers was investigated in five sub-scenarios where 20, 35, 50, 65 and 80% of the total driving energy of the absorption chillers, if chosen by the model, is to be provided from waste heat. The rest of the driving heat is to be provided by conventional boilers and electrical heaters.

The total annual costs of these scenarios and the reduction percentages in the total cost due to utilizing waste heat are shown in Table 4.17. The separated compression chillers system for each building was still representing the optimal solution for the first three scenarios, i.e. even when up to 50% of the absorption chillers input energy was provided through waste heat. This is due to the high investment and operational costs of the absorption chillers and their boilers compared to compression chillers. However, when 65% of the absorption chillers input energy was assumed to be provided through local waste heat, a district cooling system connecting all the residential buildings was suggested with an absorption chiller powered by a boiler in central production plant at building (N1a1), as shown in Figure 4.36, where (N1a1) represent the geographical central building among the residential buildings. The two remaining buildings, i.e. none-residential buildings, were provided with individual compression chillers combined with a storage tank for each building due to limited cooling load hours and thus run time.

Table 4.17: Total annual costs of waste heat availability scenarios with electricity tariffs A and B.

Waste heat availability percentage to driving energy of absorption chillers	Electricity Tariff A			Electricity Tariff B		
	Code	Total Cost (Euro/year)	Reduction Percentage	Code	Total Cost (Euro/year)	Reduction Percentage
No waste heat	CS13A0010	369,277.70	---	CS13B0010	348,327.44	---
20% of input energy	CS13A0071	369,277.70	0 %	CS13B0071	348,327.44	0 %
35% of input energy	CS13A0072	369,277.70	0 %	CS13B0072	348,327.44	0 %
50% of input energy	CS13A0073	369,277.70	0 %	CS13B0073	348,327.44	0 %
65% of input energy	CS13A0074	344,643.13	6.7 %	CS13B0074	339,676.20	2.5 %
80% of input energy	CS13A0075	309,245.09	16.3 %	CS13B0075	304,582.11	12.6 %

In the case of 80% availability of waste heat, two slightly different DC systems were suggested for each tariff. See Figure 4.37. The none-residential building with lower peak load, i.e. city council (N3), was connected directly to the district network with the central production unit at (N1a1) for both electricity tariffs. The annual investment and operational costs of the 65% and 80% electricity tariffs are presented in Figure 4.38. On the other hand, the school (N2) which has a higher peak load was provided with an individual compression chiller for electricity tariff A and a smaller individual absorption chiller for electricity tariff B. This is due to the difference in the electricity energy consumed by the cooling tower, maintenance costs and the investment cost between the two cases. Cooling towers consume electrical energy in order to dissipate heat. The cost of dissipating this energy is related to the electricity prices. Operating the chillers at night, i.e. during low electricity prices period, would result in lower heat dissipating costs since cooling towers have to operate in parallel to the chillers.

As shown in Figure 4.39, cooling energy produced via absorption chillers have lower total operational cost, i.e. including cooling tower operational costs, than those when produced via compression chillers for both 65 % and 80 % waste heat availability scenarios. However, compression chillers have lower investment costs than absorption chillers. When adding the investment and maintenance costs of the compression chiller to the total operational cost, the total annual cost will be less than that of the absorption chiller for the 65% waste heat availability scenario for both electricity tariffs. On the other hand, for the 80% waste heat availability scenario, absorption chillers have even a lower operational costs for the produced cooling energy while the operational cost of the compression chiller is still the same because they are not affected by the available free waste energy. When adding the investment and maintenance costs of the absorption chiller to the total operational cost, absorption chillers emerge as optimal solution for tariff B only. Figure 4.40 demonstrate the difference in the costs for building (N2) between compression and absorption chillers for the two scenarios.

We conclude from this, that the question of how much waste heat should be available to switch the decision from investing in compression chiller into absorption chillers is dependent on many factors including not only the market prices of these chillers and prices of electricity and fuel available but also the cooling load profile, peak load and fluctuation, which makes the decision making process a complicated one. Therefore, the use of mathematical models, similar to the one developed in this work, emerge as a highly recommended method in taking on such complicated tasks in decision making.

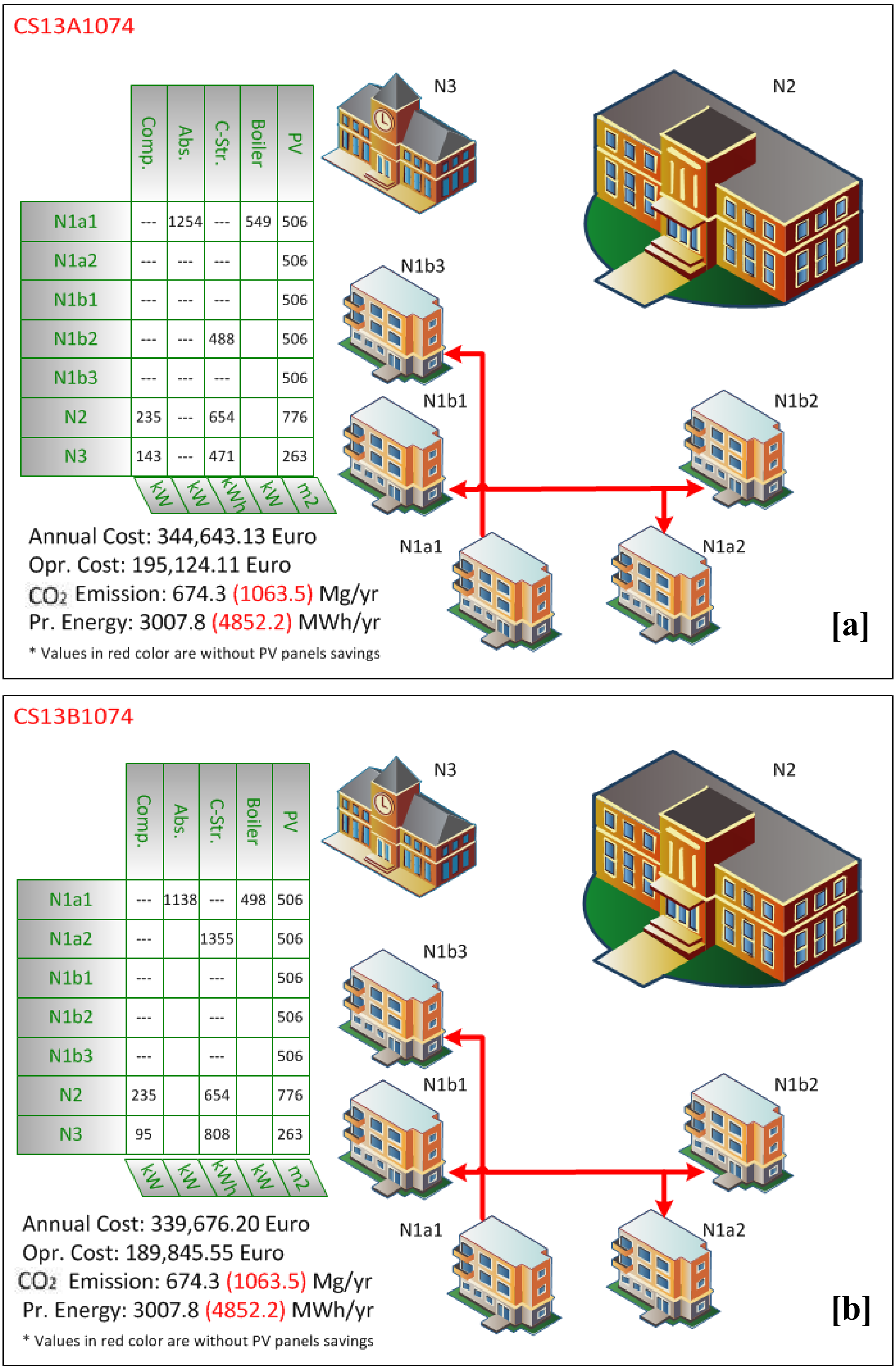


Figure 4.36: Cost optimization with 65% waste heat availability for: a) electricity tariff A, and b) electricity tariff B.

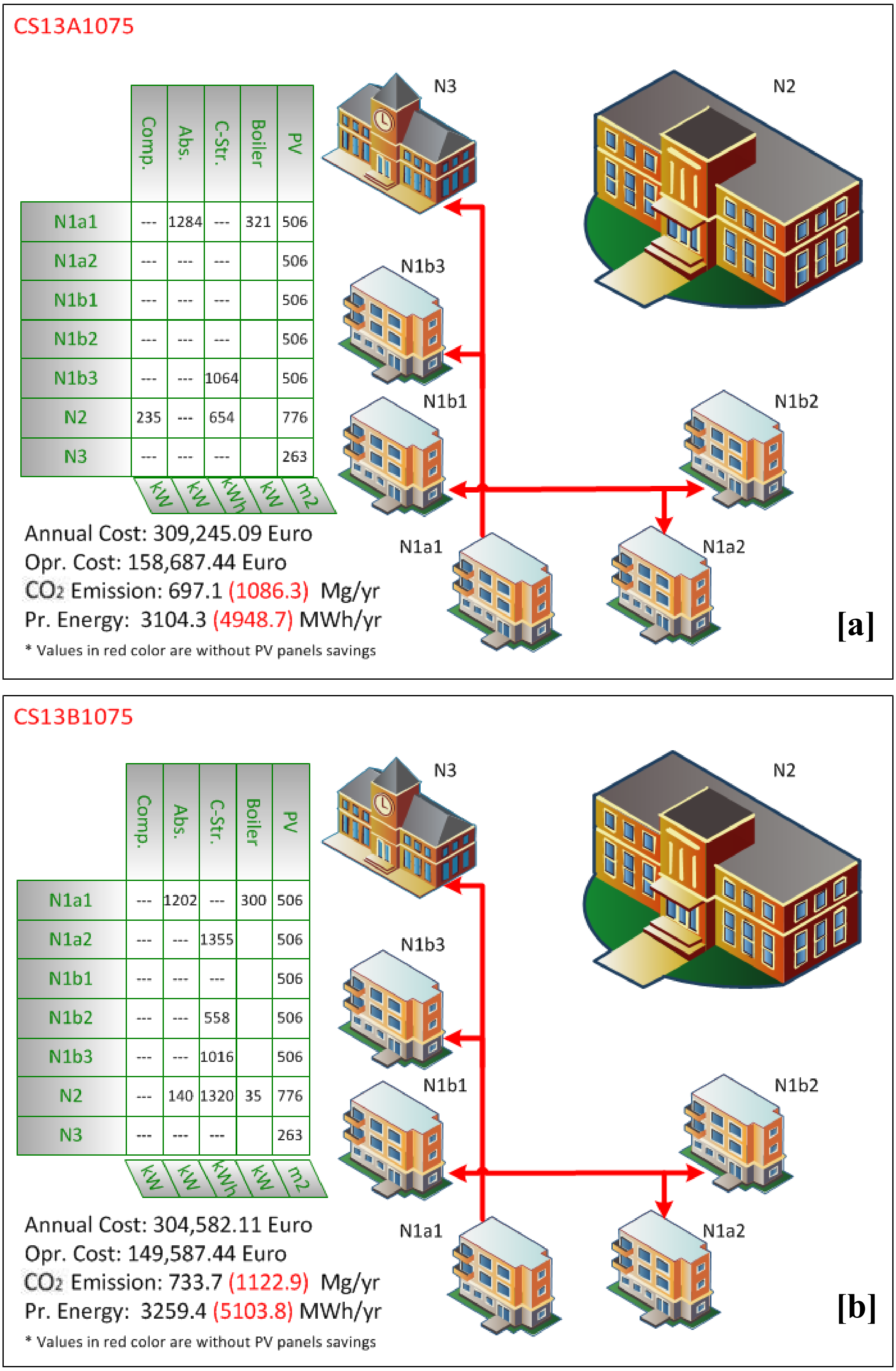


Figure 4.37: Cost optimization with 80% waste heat availability for: a) electricity tariff A, and b) electricity tariff B.

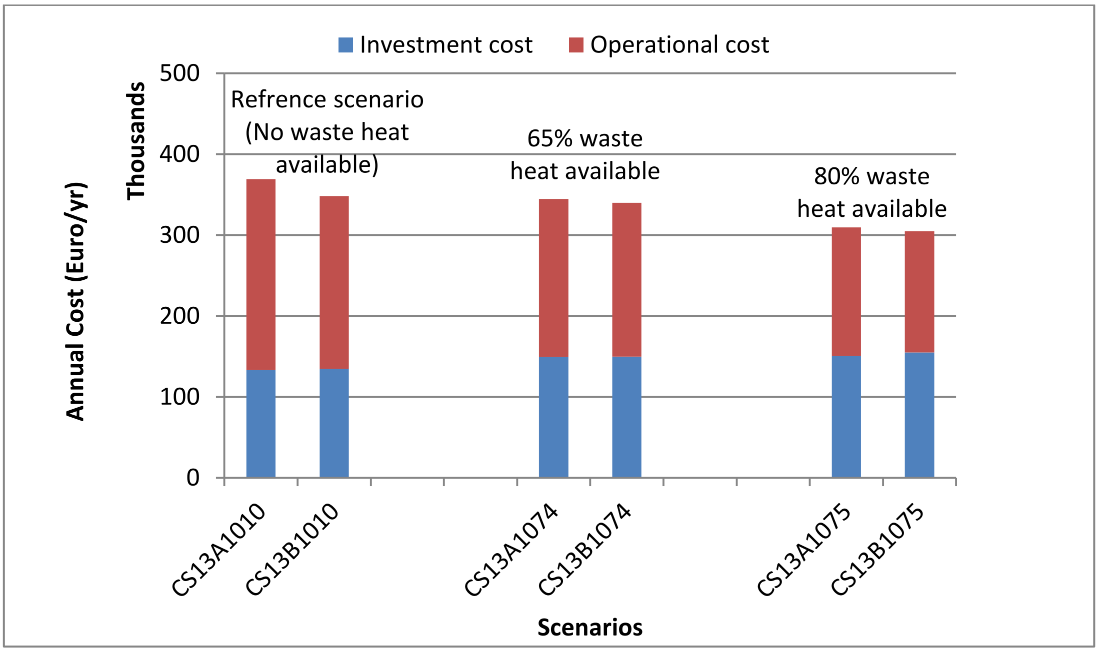


Figure 4.38: Annual investment and operational costs of sub-scenarios with 0, 65 and 80% availability of waste heat within electricity tariffs A and B.

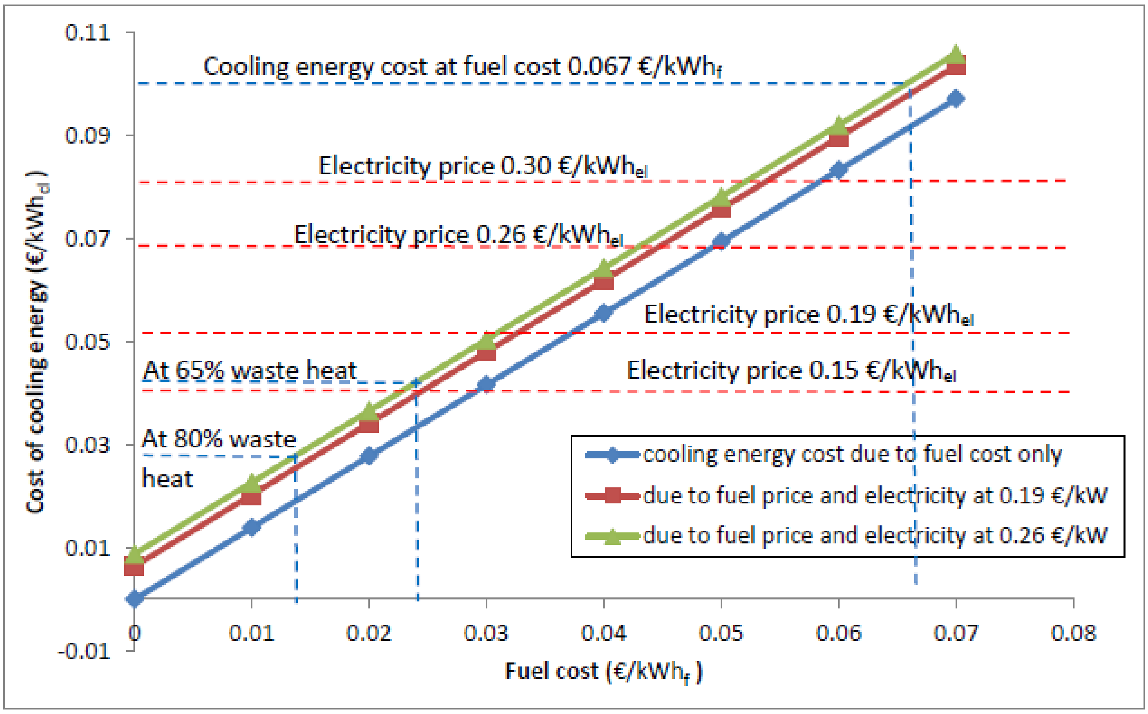


Figure 4.39: Estimated operational cost of cooling energy (€/kWhcl) in relation to fuel cost and electricity tariffs A & B, along with four cooling energy costs (red dashed lines) in relation to different electricity costs.

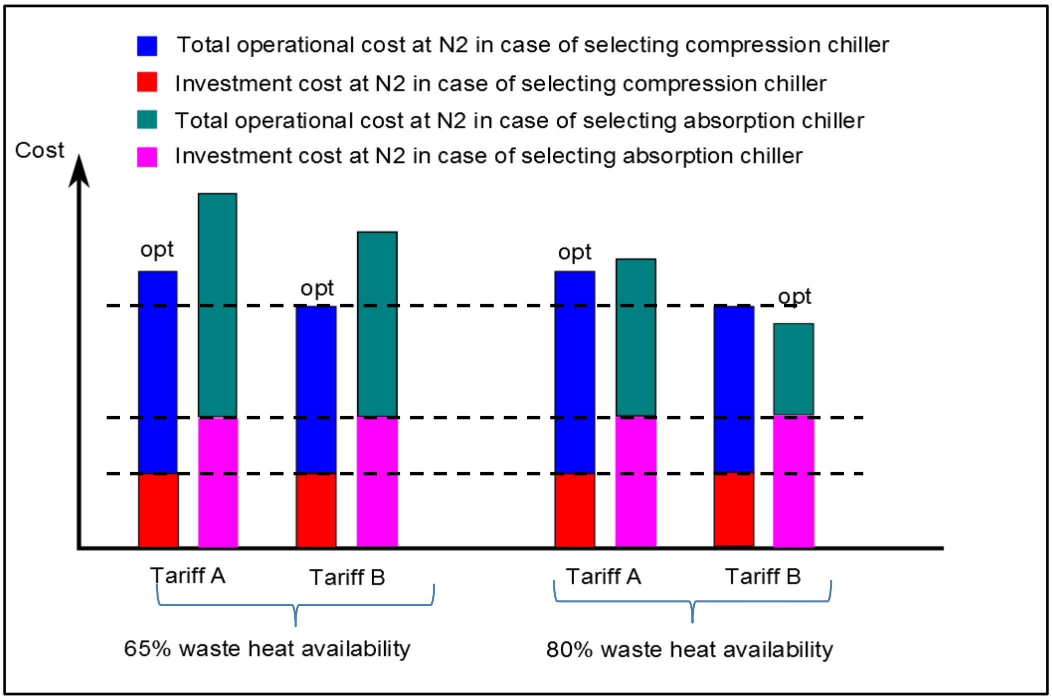


Figure 4.40: A graph demonstrating the difference in total costs for building (N2) between compression and absorption chillers for waste heat availability scenarios.

4.3.5.3 Load Shifting Scenarios

Another operation pattern condition that was investigated is load shifting. Hot climate areas have high peak cooling load amplitude which is mostly simultaneous to the peak electricity or energy demand. Therefore, a load shifting strategy is a common demand for decision makers. This operation strategy was investigated to observe its effects on both operation pattern and overall annual cost in comparison to the reference scenarios.

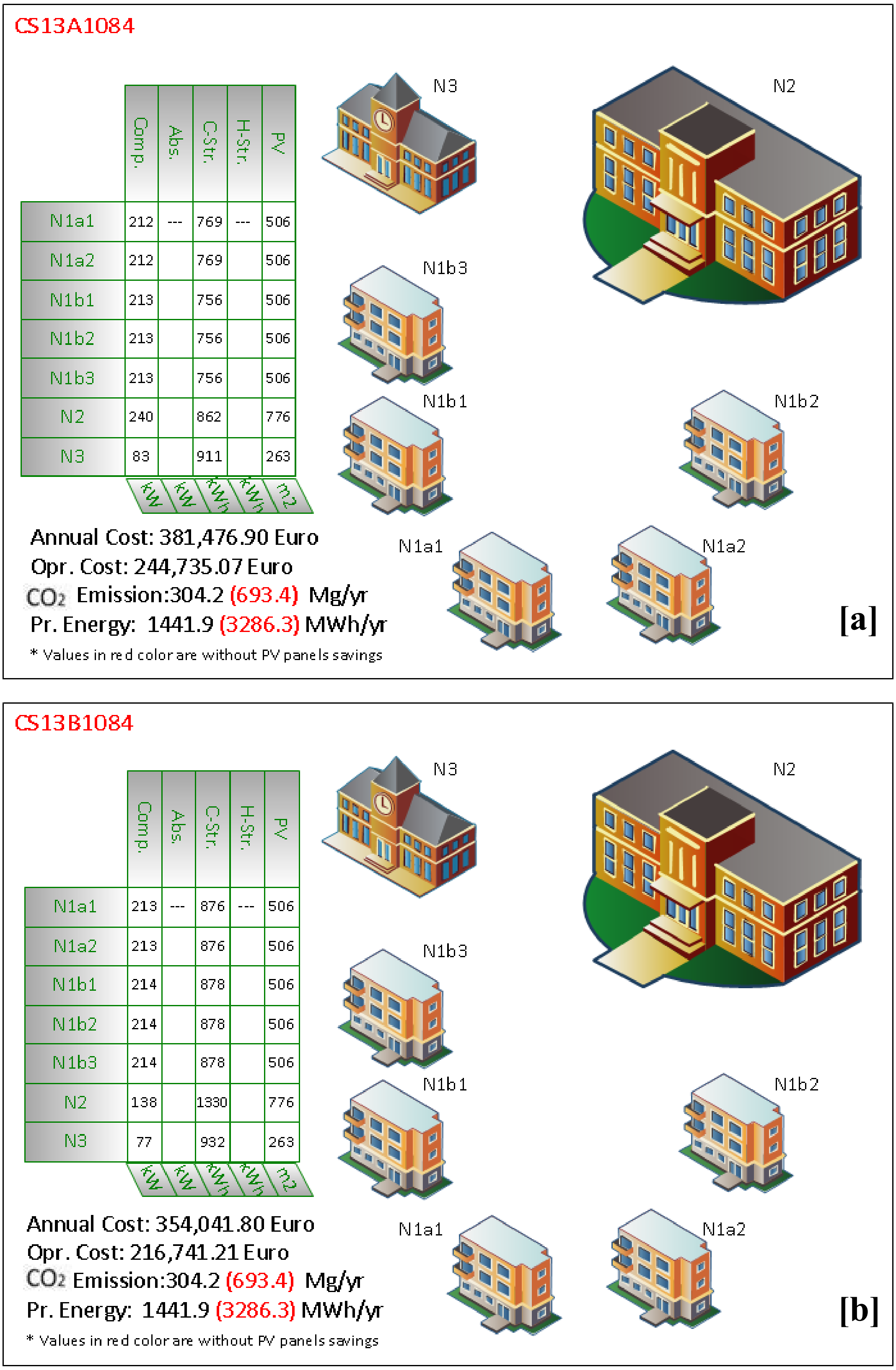
The strategy was implemented throughout a control condition that restricts the summation of all cooling energy productions within the district during the peak energy load period, i.e. from 12:00 to 15:00, to be less than 50% of the total district cooling energy consumption for that period. The individual production of each building is not necessarily to drop to 50% of its cooling load because the constraint is designed to apply for the overall production of all buildings in the case study, regardless if there is a network connecting the buildings or not, and not each building as individual.

The obtained systems for these conditions showed that load shifting strategy had a different impact on the optimized systems for residential buildings from that on none-residential buildings. As shown in Figure 4.41, systems obtained for residential buildings were slightly affected in compare to the reference scenarios (Figures 4.7 and 4.22). Where, the suggested compression chillers were with, slightly, higher capacities for both electricity tariffs. The reference system for tariff B already had bigger storage tanks than that for tariff A which are important to utilize the low electricity prices at night. With applying load shifting strategy, relatively higher capacities for cold storage tanks were required, for both different tariffs scenarios, in order to store the cooling energy required to meet the cooling load at load shifting hours.

When observing the cooling energy production profiles of the compression chillers in residential buildings, presented in Figure 4.42, it is noticed that the cooling load distribution over the whole 24 hours of the day and the relatively small amplitude of the cooling load has limited the possibility of installing smaller chillers which was the expected result of implementing load shifting where load shifting condition has limited the cooling energy production during peak load hours. This requires bigger chiller capacities to produce cooling energy during off-peak periods and meet the peak cooling load through stored energy.

On the other hand, more sufficient measures were implemented when applying load shifting strategy on none-residential buildings, especially on the city council building (N3) due to its relatively smaller cooling load amplitude. Lower capacity for the compression chiller was suggested by the optimizer along with the assistance of storage tanks to meet peak load periods. The high amplitude of the cooling load profile of the school building (N2) has limited the possibility to install smaller chillers which would require electively big storage tanks. This was not the case for tariff B where storage tanks were to be installed either way to utilize the lower night tariff of electricity.

In conclusion, applying load shifting strategy would require the same, if not higher, chiller sizes for residential buildings with relatively bigger storage tanks. None-residential buildings have better potentials to utilize load shifting strategies through installing smaller chillers and store the cooling energy at off-load hours. However, it will be considerable to install the same chiller size, of the optimized scenario without load shifting, for none-residential buildings with high cooling load amplitude even when implementing load shifting strategy. However, such modifications are highly dependent on the adopted strategy of load shifting.



	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	212	---	769	---	506
N1a2	212		769		506
N1b1	213		756		506
N1b2	213		756		506
N1b3	213		756		506
N2	240		862		776
N3	83		911		263
	kW	kW	kWh	kWh	m2

	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	213	---	876	---	506
N1a2	213		876		506
N1b1	214		878		506
N1b2	214		878		506
N1b3	214		878		506
N2	138		1330		776
N3	77		932		263
	kW	kW	kWh	kWh	m2

Figure 4.41: Cost optimization with load shifting strategy for: a) electricity tariff A, and b) electricity tariff B.

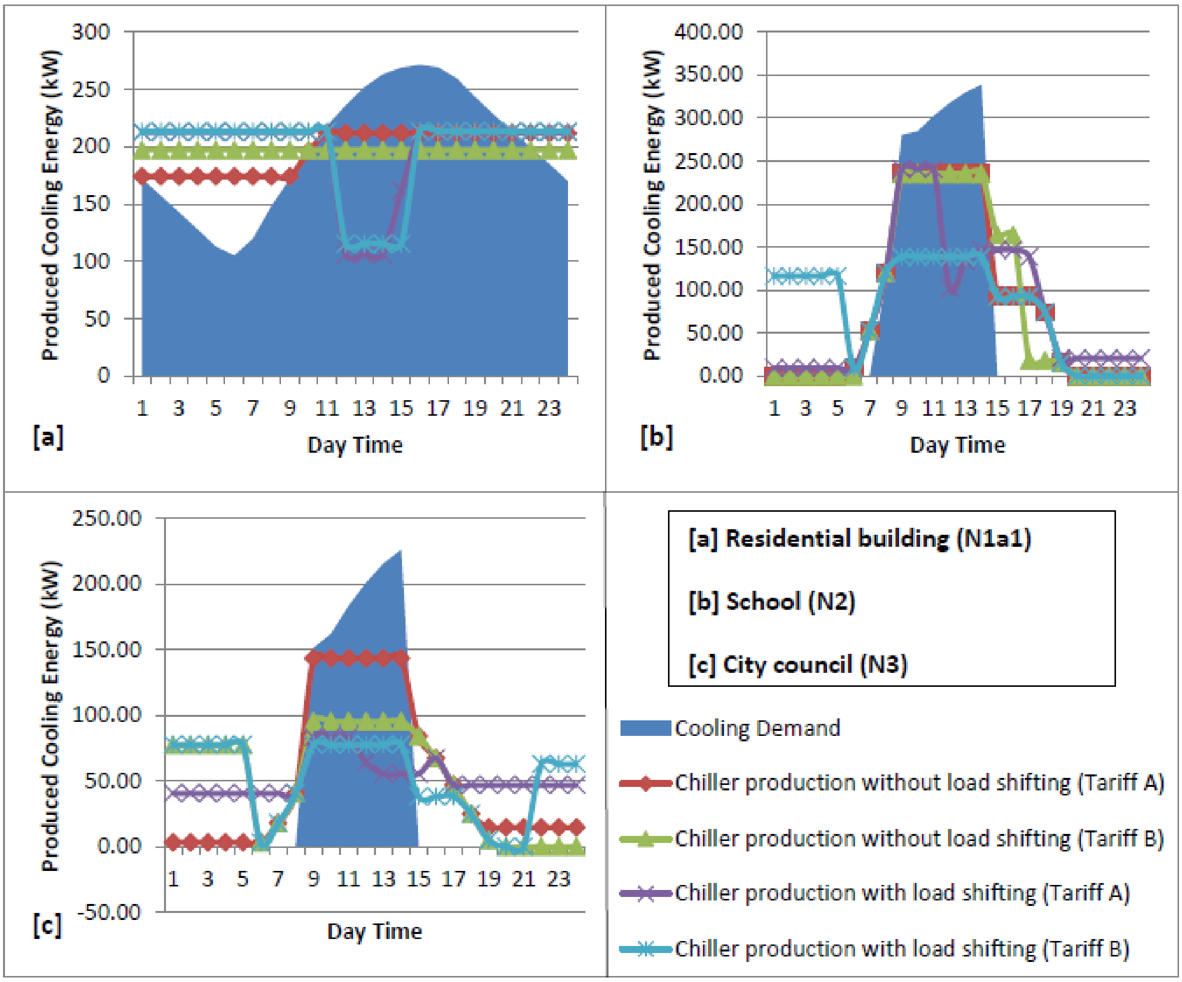


Figure 4.42: Cooling energy provided by individual systems to meet cooling load profiles of three buildings (N1a1, N2 & N3) with and without load shifting at a typical day.

Implementing load shifting strategy would cause a slight increase in total annual cost as shown in Figure 4.43. It is important to keep in mind that the developed optimization model in this work does not count for the reduction in chillers' COPs due to partial cooling load periods which in fact represent the major reason behind adopting load shifting strategies. This result should be investigated further to determine the critical factor producing the difference in response and verify that the result is not spurious. However, the slight increase in total annual cost evident in this work still can be considered as a quite reasonable compromise for the benefits obtained from applying this strategy especially in hot climate regions as it will be explained in the next section (Sec. 4.3.5.4).

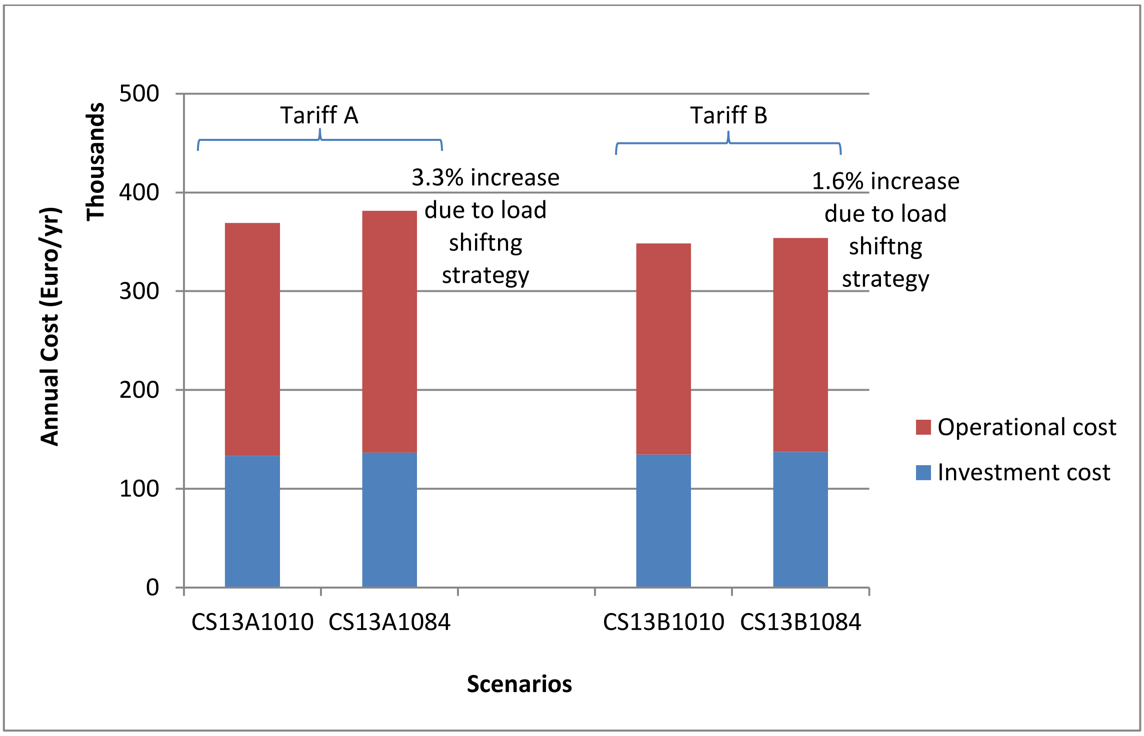
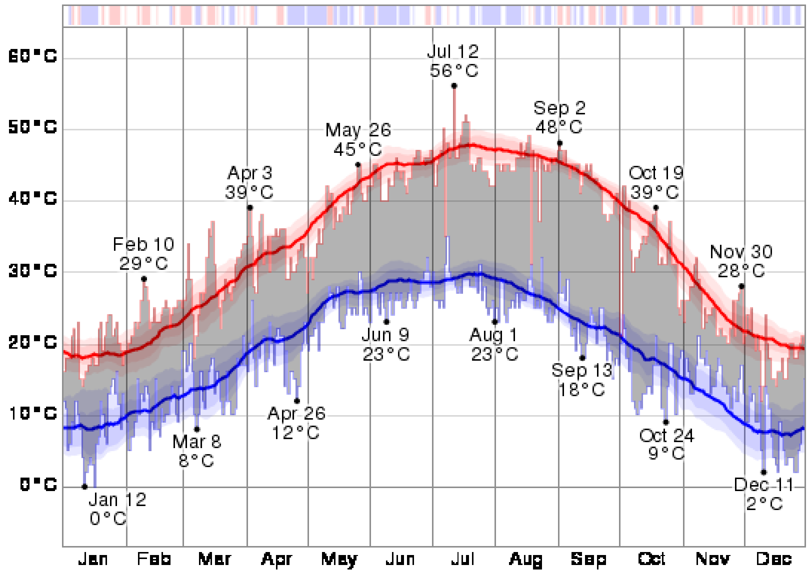


Figure 4.43: Annual investment and operational costs of two reference scenarios (without load shifting) and two load shifting scenarios.

4.3.5.4 Outdoor Temperature Effect Scenarios

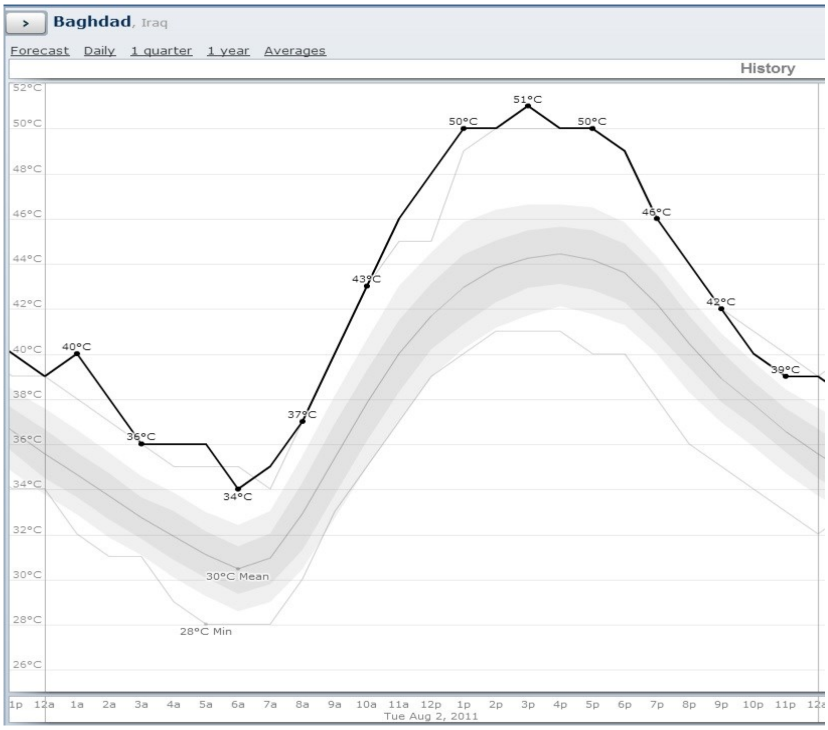
One of the main problems that face cooling systems operating in hot climate regions is the high ambient temperature which has a negative impact on the COP values of the compression chillers. Most of the chillers produced and offered in the market are designed to work with around 30-35°C. However, ambient temperatures in many areas, e.g. sub-tropical regions, exceed the designed ambient temperature. In some cases it reaches up to 55 °C. Figure 4.44 shows the ambient temperature profile for the city of Basra for the entire year of 2013. While, Figure 4.45 present the hourly ambient temperature profile of a typical hot day in Baghdad.

Such high ambient temperatures reduce the compression chiller COP sufficiently. For example, Figure 4.46 introduces the drop in the COP values of chiller produced by carrier (30XA) due to the high out door temperatures. The effect of these phenomena on the district cooling systems was investigated in this study to provide considerable measures for decision makers when designing a DCS in a hot climate region.



Source: http://weatherspark.com/history/32872/2013/Basrah-Al-Basrah-Iraq

Figure 4.44: Ambient temperature profile for the city of Basra, 30°30′N latitude and 47°49′E longitude, at 2013.



Source: https://weatherspark.com/#!graphs;a=Iraq/Baghdad

Figure 4.45: Hourly ambient temperature profile of a typical hot day in Baghdad, 33°20′N latitude and 44°26′E longitude.

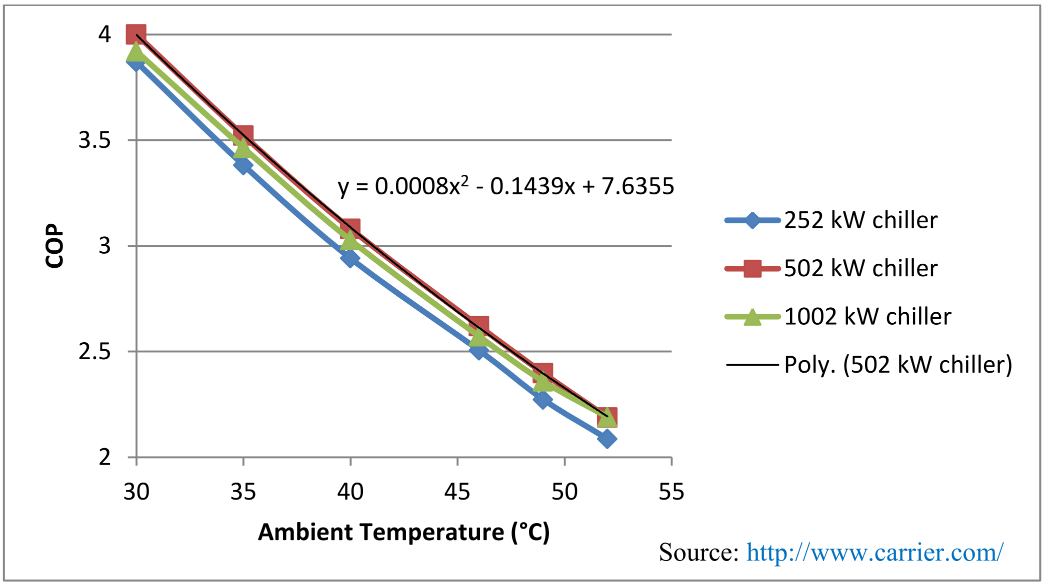


Figure 4.46: COP values of the carrier chiller (30XA) in relation to outdoor temperatures.

By combining the hourly ambient temperature profile for a typical hot day, e.g. Figure 4.45, and the polynomial formula of COP relation to outdoor temperature, presented in Figure 4.46, we can obtain a direct correlation between the two parameters as shown in Figure 4.47.

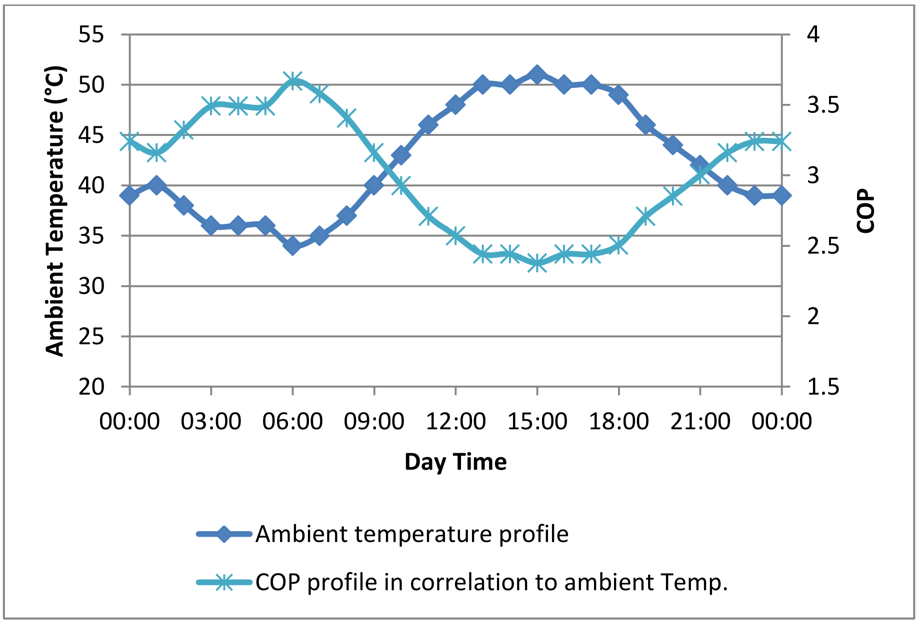


Figure 4.47: Example of COP correlation with daily ambient temperature profile obtained at the city of Baghdad on 2nd August 2011 as an example.

Since that outdoor temperature in subtropical regions often vary between the temperatures of 35°C and 55°C between day and night hours and that the corresponding COP values to these temperatures vary between 3 and 4, the analysis of this phenomena is carried out by comparing the effects of COP variation scenario to the fixed COP scenarios at the values of COP=3 (CS13A/B1010), i.e. Figures 4.7 and 4.22, and COP=4 (CS13A/B1011), i.e. Figure 4.48. The optimal cooling system obtained with the COP variation in correlation to ambient temperature, i.e. sub-scenario CS13A/B0091, is presented in Figure 4.50.

By comparing Figures 4.7, 4.22 and 4.48 it was noticed that increasing the value of the fixed COP from 3 to 4 had an impact on the optimal solution of slightly increasing the sizes of the compression chillers for the residential buildings and selecting smaller storage tanks with around 30 or 40% size reduction. However, such impact was not observed in the optimal solutions obtained for none-residential buildings as explained in section 4.3.5.1.1. On the other hand, the annual total cost of the optimized system was significantly affected by the COP increase where about 16% cost reduction was achieved. Moreover, CO_2 emissions were reduced by 50%. This is due lower primary energy consumption as a result of implementing higher COP value where CO_2 emissions rely mostly on operational energy consumption. However, the value of the emitted CO_2 did not change between the obtained systems for the two electricity tariffs A and B. That is partially due to the adopted assumptions of constant COP and neglecting heat loses in storage tanks. And since that no network was adopted as a result of changing the electricity tariff, the consumed primary energy to meet the cooling load stayed the same and thus CO_2 emissions.

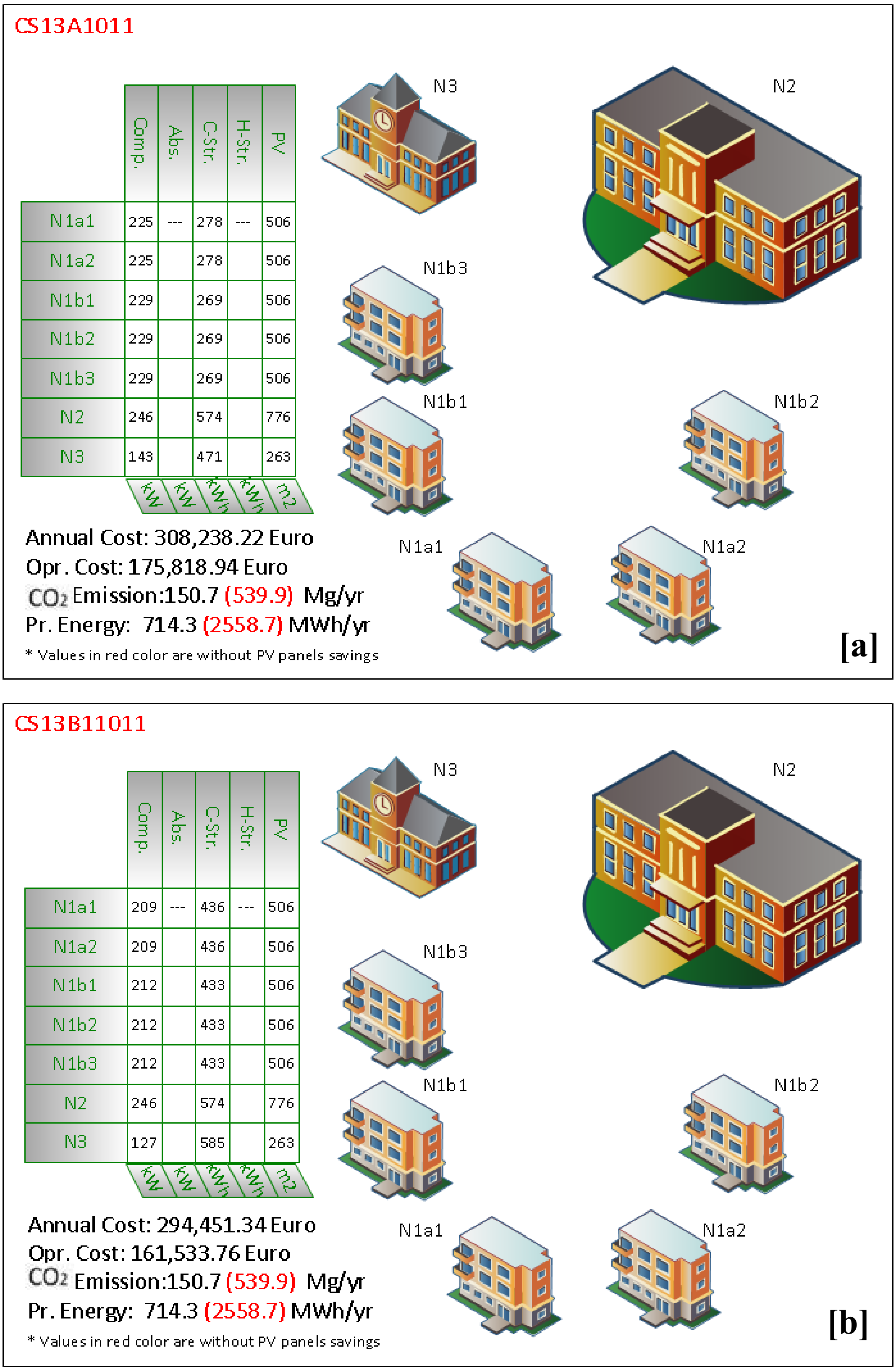


Figure 4.48: Cost optimization with fixed COP =4 for: a) electricity tariff A, and b) electricity tariff B.

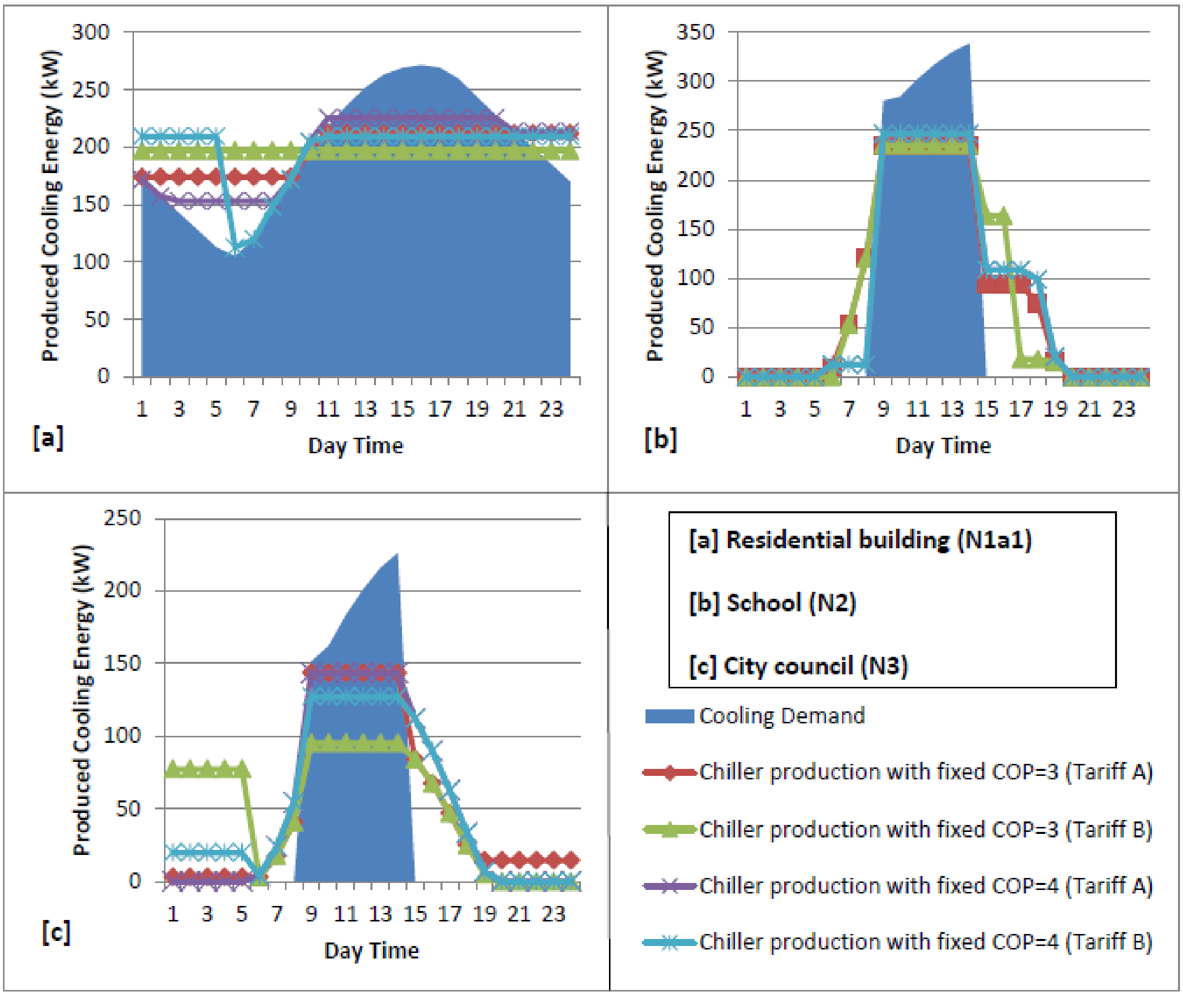


Figure 4.49: Cooling energy provided by individual systems to meet cooling load profiles of three buildings (N1a1, N2 & N3) with fixed COP values of 3 and 4 at a typical hot day.

Including the phenomenon of COP drop in correlation with high ambient temperature resulted in obtaining a new optimized system, presented in Figure 4.50. Comparing this newly obtained system to the system in Figure 4.48 shows that residential and none-residential buildings require different measures to face such phenomenon under the two different electricity tariffs. For electricity tariff A, residential buildings would require a sufficient increase in the installed storage tanks capacity, up to triple the original size, along with a slight decrease in the compression chiller capacity. None-residential buildings witnessed a different impact. Building N3 required a bigger storage tank, almost double the size, and its chiller size was reduced significantly. Where the required energy to meet the cooling demand was produced at off-load hours and particularly when the COP values are high as shown in Figure 4.51. On the other hand, building N2 which has a relatively higher cooling load did not witness such major changes. Only a slight decrease in the chiller size and a corresponding increase in the storage tank were implemented. This indicates that imposing similar changes to those implemented at building N3 on building N2 is not a cost effective option.

A different impact was observed with electricity tariff B where residential buildings required double the sizes for both compression chillers and storage tanks. This is because of the tendency of the model to operate chiller during night hours to utilize low electricity tariff. This tendency were previously, i.e. without the ambient temperature effect, obstructed by the peak cooling load during day hours which would require high capacity storage tanks which in its turn would mean more investment cost. Now, that operating the chiller at night hours would be with higher COP values which will mean less energy consumption and eventually lower operational cost, installing high capacity storage tanks became reasonable. Similar analysis can be used to explain the increase in storage tank sizes for none-residential building as well. However, smaller compression chillers were installed at none-residential building which is due to the possibility of operating them at off-load hours as presented in Figure 4.52.

As a general conclusion for choosing compression chiller capacity when designing under outdoor temperature effect in a hot climate, it is recommended to choose:

- For residential buildings: A chiller capacity that covers around 70% of the peak load of the building at constant electricity tariff. This capacity may be changed significantly when the electricity tariff is variable depending on the tariffs amplitude and at which hours of the day does the electricity price drop.
- For none-residential buildings: A chiller capacity that covers around 50% of the peak load of the building within both electricity tariffs. However, individual cost investigation for each building is recommended especially for building with high peak cooling load.

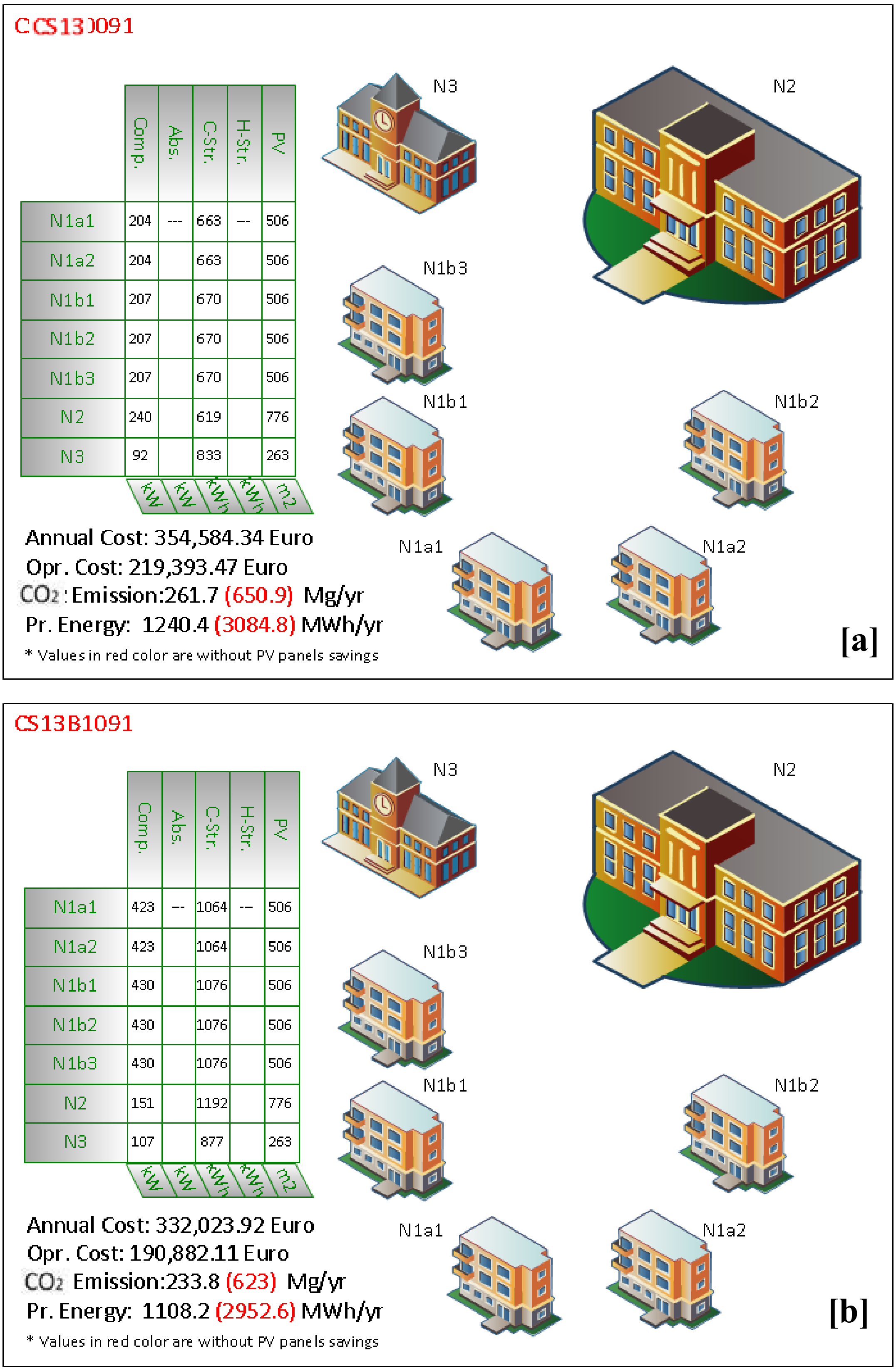


Figure 4.50: Cost optimization with COP drop due to ambient temperature variation for: a) electricity tariff A, and b) electricity tariff B.

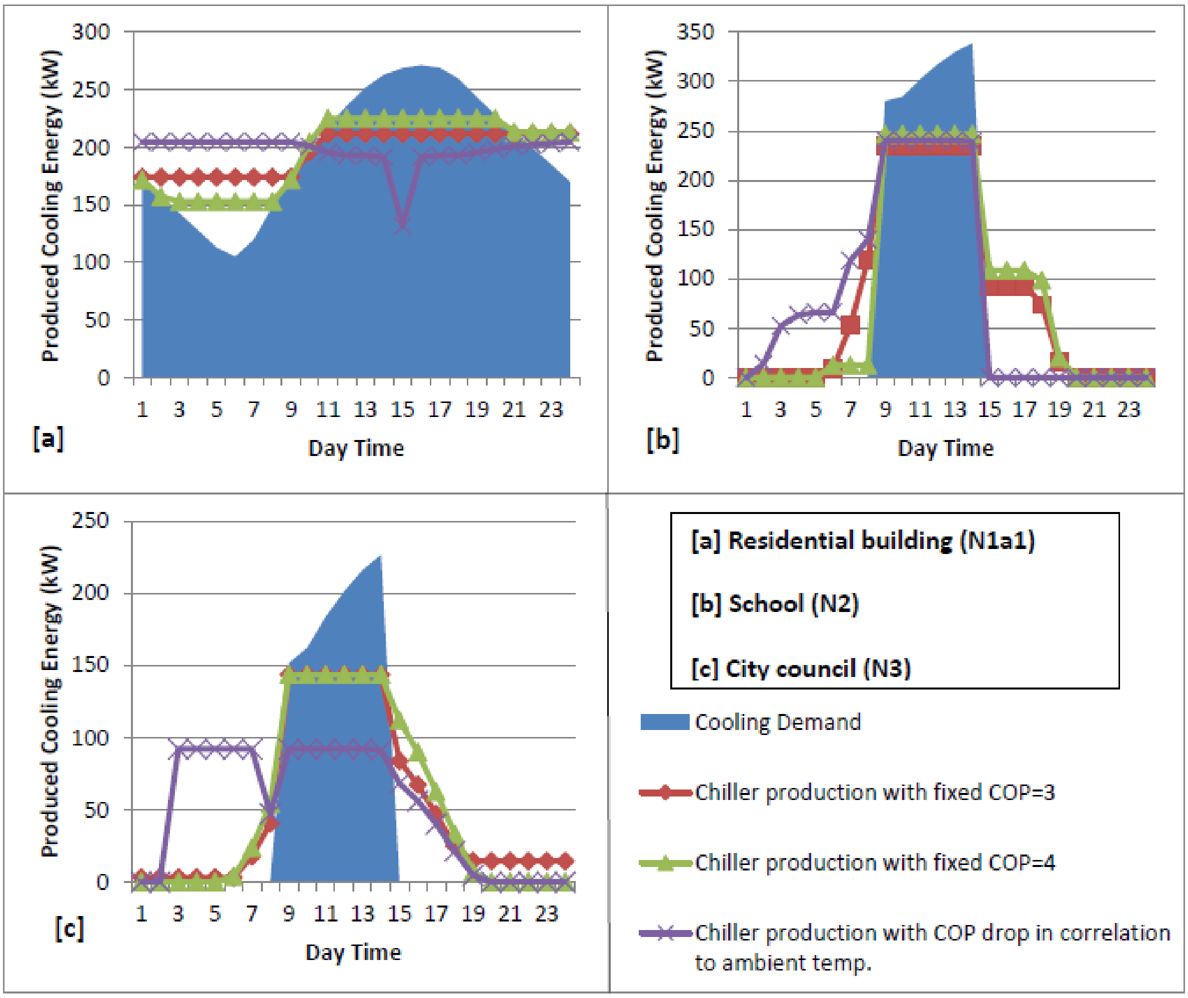


Figure 4.51: Cooling energy provided by individual systems to meet cooling load profiles of three buildings (N1a1, N2 & N3) with fixed COP values of 3 and 4 and variable COP in correlation to ambient temperature within electricity tariff A investigation at a typical hot day.

Figure 4.53Figure 4.53 presents the annual total costs of investigated COP drop phenomenon in comparison to the reference scenarios at COP=3 and 4. It is noticed that this phenomenon has a considerable impact on the optimized total cost. Although its total costs are slightly lower than that of the reference sub-scenario with COP=3, it has a total cost increase that reaches up to 15% for tariff A and 13 % for tariff B over the reference sub-scenario with COP=4. This phenomenon is not an optional strategy that a decision maker can decide to consider it in the system or not. The obtained systems, shown in Figure 4.50, present the optimal systems for the investigated district in the case that hot climate was taken into consideration. Adopting any other DC system or operation plan would result in additional cost. The reference scenario did not put into consideration the effects of ambient temperature on chillers COP. If the reference scenario is to be implemented in a hot region, the system would probably require some costly design or operational modifications to operate without which the system might fail to operate.

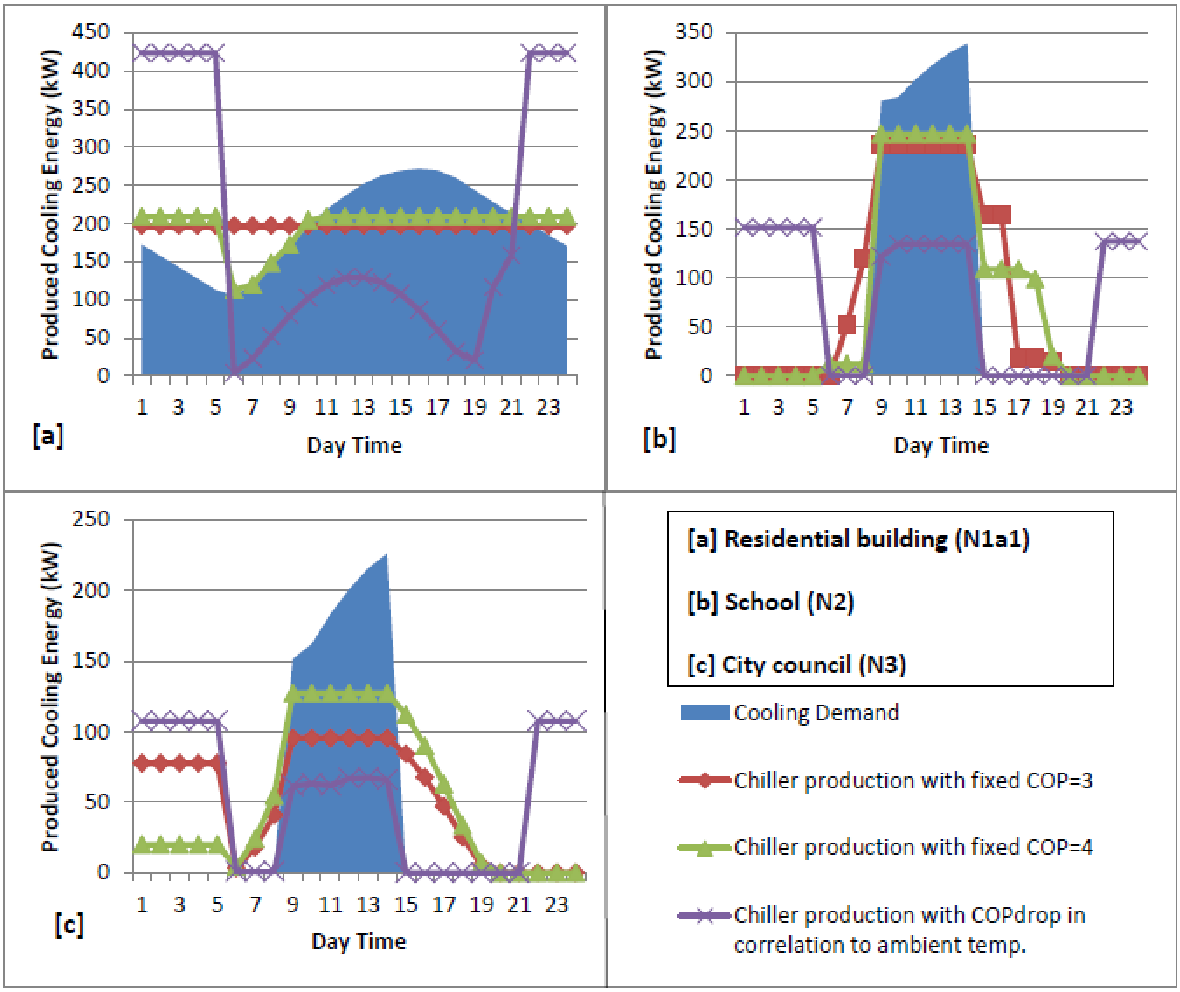


Figure 4.52: Cooling energy provided by individual systems to meet cooling load profiles of three buildings (N1a1, N2 & N3) with fixed COP values of 3 and 4 and variable COP in correlation to ambient temperature within electricity tariff B investigation at a typical hot day.

When comparing the operational plan with implemented load shifting strategy (Figure 4.42) to that obtained with considering COP drop within electricity tariff A (Figure 4.51), similarities between both operational plans are noticeable. Based on all previously described observations, one can conclude that load shaving strategies with smaller chillers and bigger storages can serve effectively to deal with effect of high ambient temperature in hot climate regions especially for non-residential buildings. However, customized operation optimization is highly recommended.

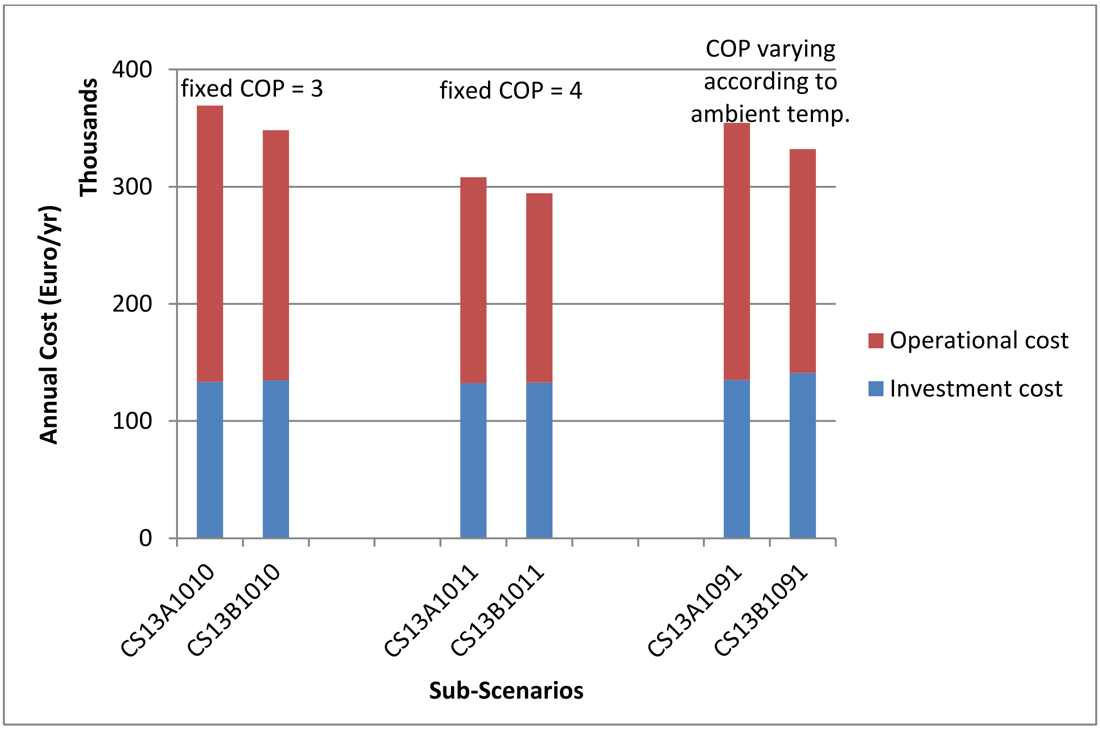


Figure 4.53: Total annual investment and operational costs of 6 sub-scenarios (CS13A1010, CS13A1011, CS13A1091, CS13B1010, CS13B1011 and CS13B1091).

4.3.6 Investigation category 3 (De-Centralized DCS with variable/size-dependent COP) scenarios

One of the advantages of district cooling systems is that high capacity chillers used in these systems usually have higher COP than the small/medium size chillers used in distributed systems for individual buildings. Air-cooled reciprocating chillers have a peak load power requirement of 1.0–1.3 kW per refrigeration ton (TR), thus peak load COP range of 2.70-3.52, depending on capacity and ambient air temperature. They are manufactured in capacities from 0.5 to 150 TR, i.e. 1.8-527.5 kW, [74]. ASHRAE (the American Society of Heating, Refrigerating, and Air-Conditioning Engineers) provide COP value for water cooled reciprocating chillers in its 90.1 standard as 4.2 for capacities less than 150 TR (527.5 kW), see Table 4.18 [75].

Typical water-cooled screw chillers have a COP of 5.0–7.0 and are available with cooling capacities between 70 and 750 TR, i.e. 246-2637 kW, [74]. According to Burba [3], COP values for inverter screw compressors can attain more than 8.0. However, ASHRAE standard has listed lower efficiency specifications in its 90.1, as stated in Table 4.18. Centrifugal chillers are generally manufactured in capacities from 90 to 1,000 TR, i.e. 316.5-3516.8 kW, with most units being in the range of 150 to 300 TR, i.e. 527.5-1055 kW, [74]. They are most efficient at peak load and they consume the least power (kW per TR) at full load operation. Their efficiencies have been improving even further over the past recent years. According to ARI standard rating conditions, centrifugal chillers COP at full design capacity ranges from 5.0-5.8 for capacities bellow 300 TR (1055 kW) to 6.6 for capacities exceeding 300 TR [76].

Table 4.18: ASHRAE 90.1-2001 and 2004 minimum required efficiencies for water-cooled chillers.

Chiller size	Centrifugal	Screw	Reciprocating
Less than 150 TR (i.e. 527.5 kW)	5.0	4.45	4.2
150 – 300 TR (i.e. 527.5-1055 kW)	5.55	4.90	-
Higher than 300 TR (i.e. 1055 kW)	6.10	5.5	-

This variation in compression chillers' COP in regards to their capacities has been implemented in a new model for optimizing decentralized DCS for the case study. A COP value of 4 was chosen for chillers with capacities below 500 kW (142.2 TR), 5.5 for bellow 1000kW (284.3 TR), and 7 for chillers with capacities higher than 1000 kW (285 TR) as shown in Figure 4.54. The aim of this modification in the optimization model was to integrate the advantage of high capacity chillers over small and medium size chillers in consuming less primary energy to provide a certain amount of cooling energy.

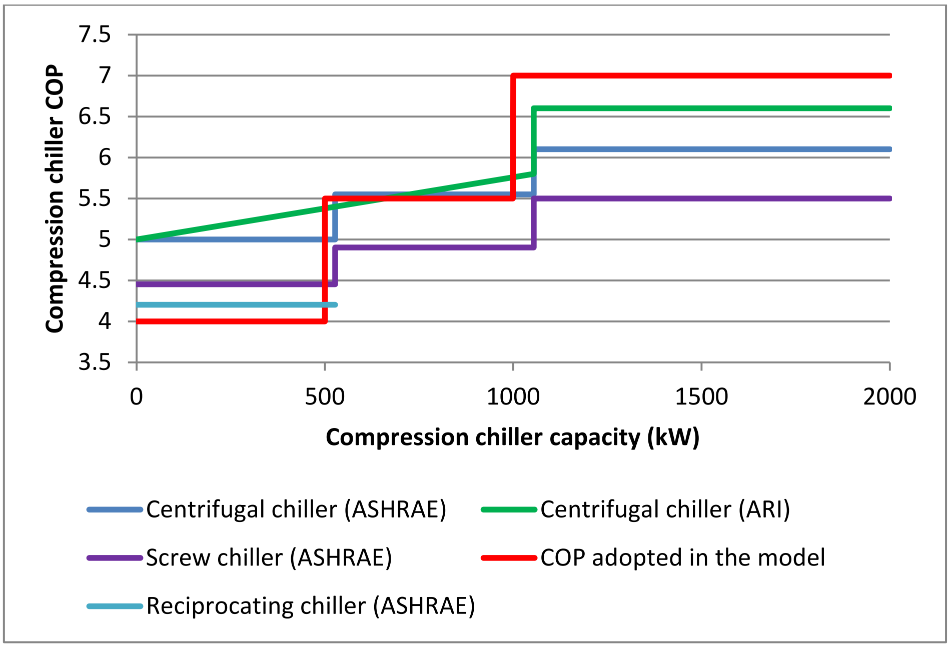


Figure 4.54: adopted COP values for compression chillers in investigation categories 3 and 4.

4.3.6.1 Reference scenario for investigation category 3

The optimization of the reference sub-scenario for investigation category 3 was carried out with the same assumption adopted for investigation category 1 except for the chiller COP values and their variation in regards to the chiller size. Figure 4.55 shows the optimal solution for a reference scenario for case study 1 within investigation category 3 for both electricity tariffs A and B. The major impact on the obtained solution to be noticed is that, unlike the investigation category 1 where separated individual systems were chosen for each building, de-centralized DC networks were implemented in investigation category 3 connecting a group of building to a cooling energy production plant installed at a certain building. Higher COP values for bigger chillers allow saving a certain amount of operational cost by reducing the primary energy consumption needed to produce a certain amount of cooling energy. Thus, by choosing bigger chillers, the model is using the savings in operational costs to install and operate a network connecting a small group of building whose cooling load demand is met by one production plant. However, instead of having one central network a couple of small networks were installed.

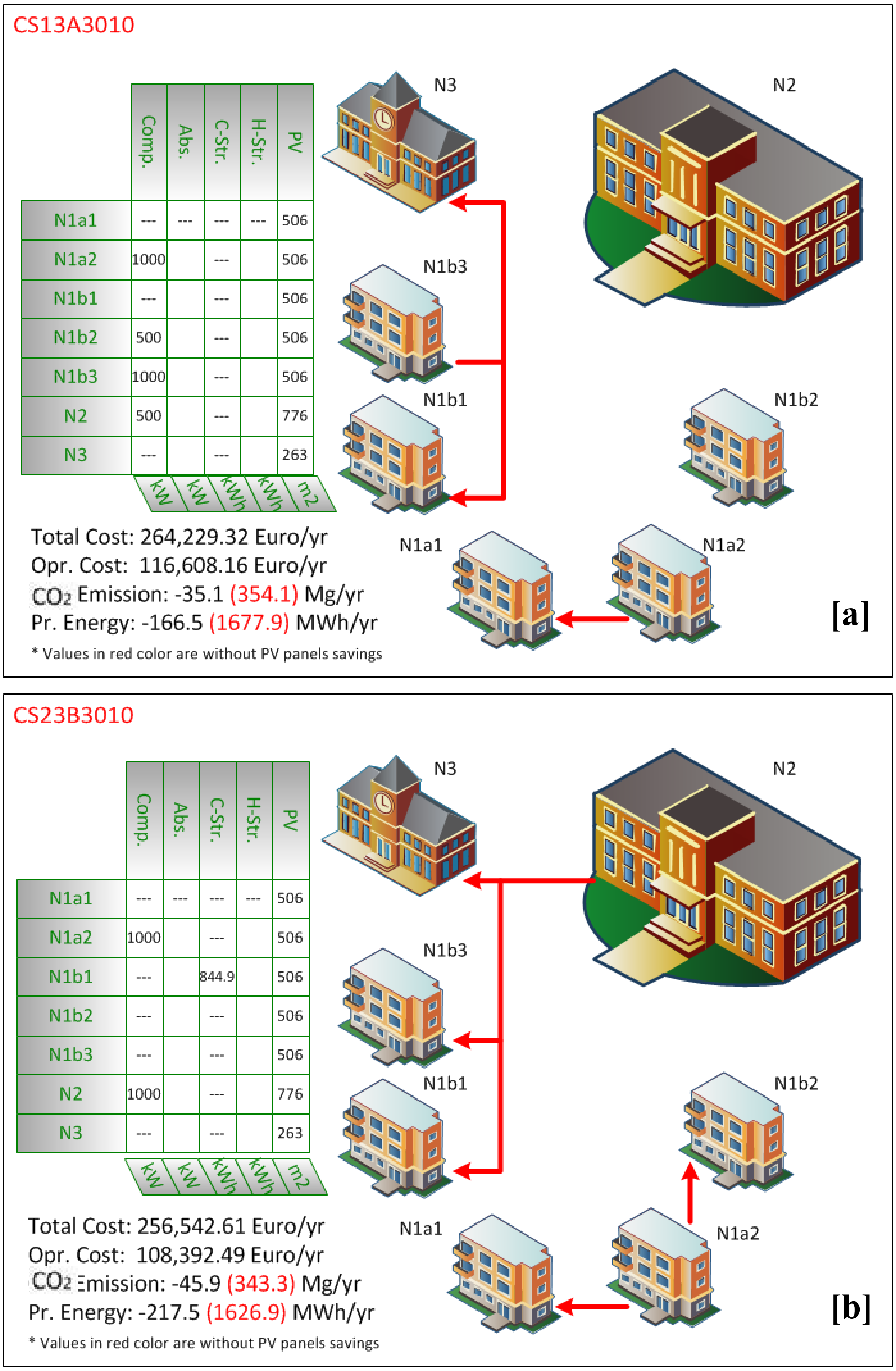


Figure 4.55: Annual cost optimization reference scenario for case study 1 within investigation category 3 for both electricity tariffs A and B.

Some buildings were left unconnected to any network within electricity tariff A as shown in Figure 4.55a. The total installed capacity was 3000 kW where the buildings hosting the energy production plants were equipped with the big size chillers, i.e. 1000 kW, to benefit from the higher COP and the separated buildings were equipped with medium size chillers, i.e. 500 kW. This indicate an extra, not needed, installed cooling capacity were the cooling load of the buildings is lower than the capacity of the installed chillers. However, the model did install such oversized chillers to benefit from the higher COPs. On the other hand, within electricity tariff B, all buildings were connected but into two networks with a production capacity of 1000 kW for each network. Thus the total installed capacity was 2000 kW which is slightly higher than the total peak cooling load of the whole district which is 1929 kW. This indicates that installing an oversized chiller can be more cost efficient than installing a chiller that is the exact same or smaller than the peak cooling load if that oversized chiller would provide a higher COP.

Due to installing oversized chillers, there was no need to install any cold storage tanks within electricity tariff A sub-scenario, CS13A3010, and only one storage tank was installed within electricity tariff B sub-scenario, CS13B3010, as shown in Figure 4.55. This raises the question about the feasibility of these systems and their ability to operate in case of sudden changes in operational conditions. Therefore, an extra optimization was carried out for checking purposes where each on the obtained systems in Figure 4.55 for each electricity tariff was re-optimized under the other electricity tariff. The locations and capacities of the main equipment, e.g. chillers, storage tanks, and DC pipelines, were forced to be the same as in Figure 4.55 throughout this re-optimization process. Capacities of heat exchangers and user site units were allowed to be changed. Re-optimizing the system obtained at electricity tariff A. i.e. CS13A3010, under electricity tariff B sub-scenario was named CS13A3010B. Similarly, re-optimizing the system obtained at electricity tariff B. i.e. CS13B3010, under electricity tariff A sub-scenario was named CS13B3010A. The results have shown that both obtained systems were able to operate with the change of the electricity tariffs with no significant design changes being required. The annual investment and operational costs are shown in Figure 4.56.

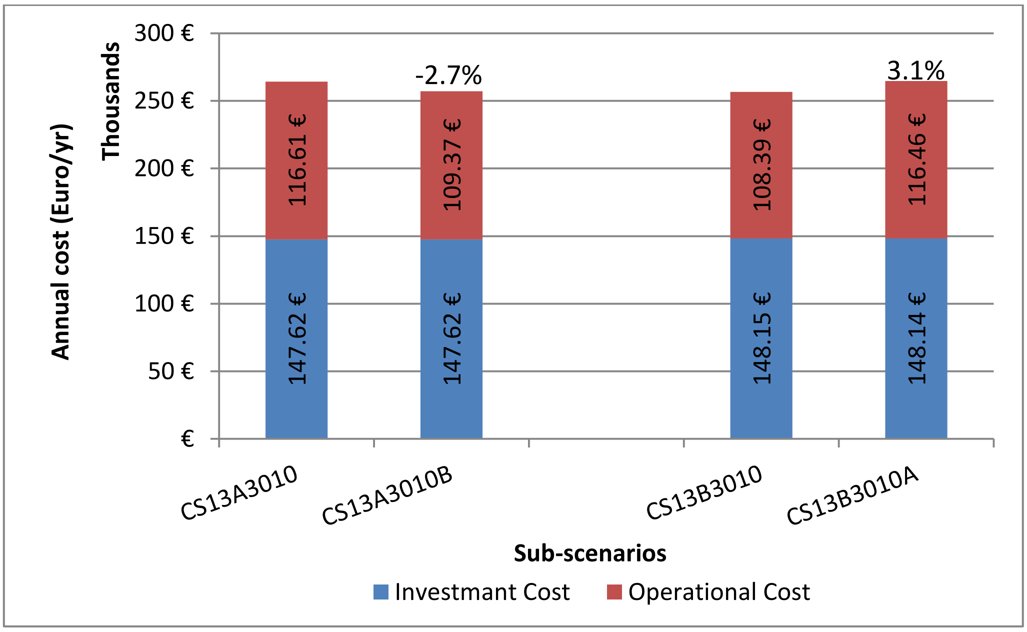
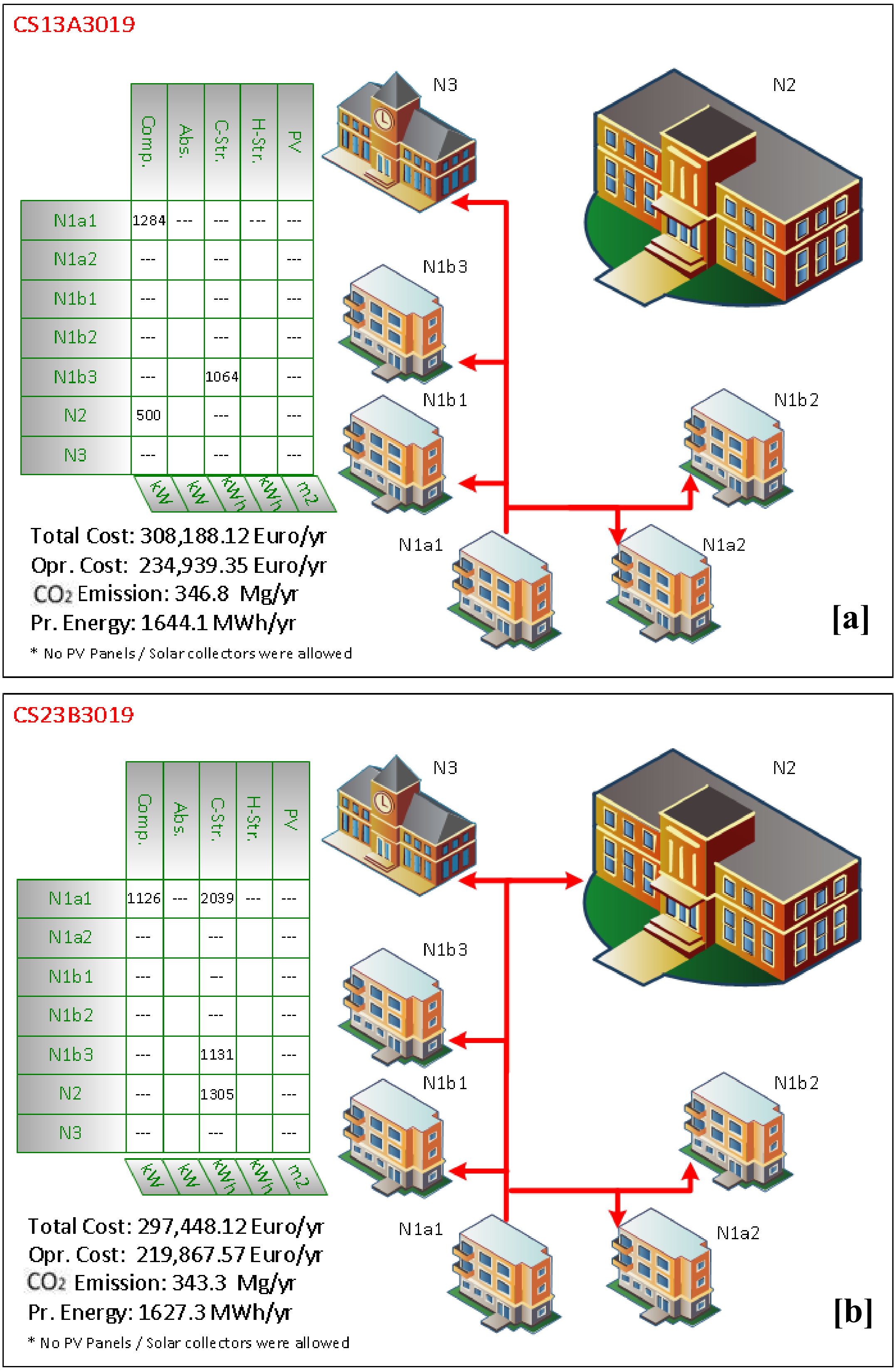


Figure 4.56: Annual costs of the reference scenarios for investigation category 3 in comparison to the same systems operating under switched electricity tariffs.

4.3.6.2 Optimizing without considering solar energy

Since that we have concluded within investigation category 2, i.e. Centralized DC system with constant COP, for both electricity tariffs A and B that installed PV panels have a significant impact on the obtained system, PV panels impact on investigation category 3 was investigated as well. Two new sub-scenarios were carried out for each of the electricity tariffs where no PV panels or solar collectors were allowed to be installed. The adopted coding for these two sub-scenarios were CS13A3019 and CS13B3019 for electricity tariffs A and B, respectively. Excluding PV panels and solar collectors from the design options of the optimization model had a major impact on the obtained systems where new DC networks were adopted as shown in Figure 4.57. An almost full DC network was installed for the district within electricity tariff A with only building N2 being not connected in the network, whereas, within electricity tariff B, all buildings were connected to the network. In both cases building N1a1 was chosen to be the production plant. Table 4.19 presents a cost comparison of the optimized sub-scenarios with and without considering PV panels and solar collector in the optimization. As previously noticed in investigation category 2, systems obtained without utilizing solar energy, i.e. CS13A3019 and CS13B3019, have about half the investment cost of the systems when installing PV panels, i.e. CS13A3010 and CS13B3010, however, it is the operational cost and in particular the electrical plant site cost that is giving the advantage to the sub-scenarios with PV panels due to the amount of locally consumed PV energy, which lowers the amount of electricity purchased from the grid, and also the income of the PV from selling the extra electricity to the grid. Figure 4.58 shows the annual investment and operational costs of the compared sub-scenarios.



[a] CS13A3019

	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1a1	1284	---	---	---	---
N1a2	---		---		---
N1b1	---		---		---
N1b2	---		---		---
N1b3	---		1064		---
N2	500		---		---
N3	---		---		---

[b] CS23B3019

	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1a1	1126	---	2039	---	---
N1a2	---		---		---
N1b1	---		---		---
N1b2	---		---		---
N1b3	---		1131		---
N2	---		1305		---
N3	---		---		---

Figure 4.57: Cost optimization sub-scenarios for investigation category 3 without utilizing solar energy, i.e. PV or solar collectors within a) Electricity tariff A, and b) Electricity tariff B.

Table 4.19: Costs comparison for optimized DC systems obtained with and without utilizing PV panels sub-scenarios for both electricity tariffs A and B.

Type of cost [1]	Tariff A		
	CS13A3010	CS13A3019	Difference
Total annual costs	264,229.33	308,188.13	-43,958.80
7. Total plant investment cost	134,884.01	50,382.09	84,501.91
8. Total Network investment cost	12,737.16	22,866.68	-10,129.52
9. Total operational cost	116,608.16	234,939.36	-118,331.19
9.1. Plant site operational cost	91,776.97	92,463.17	-686.20
9.2. Electrical network (pumping) cost	77.316	250.077	-172.76
9.3. Electrical plant site operational cost	24,753.88	142,226.11	-117,472.23
9.3.1. Comp. chiller electricity cost	50,153.41	104,919.22	-54,765.81
9.3.2. PV panels electricity income [2]	62,840.14	0.00	62,840.14
9.3.3. Heat dissipater electricity cost	37,440.60	37,306.89	133.71
Type of cost [1]	**Tariff B**		
	CS13B3010	CS13B3019	Difference
Total annual costs	256,542.62	297,448.13	-40,905.51
7. Total plant investment cost	123,509.91	48,028.38	75,481.53
8. Total Network investment cost	24,640.21	29,552.17	-4,911.96
9. Total operational cost	108,392.50	219,867.57	-111,475.08
9.1. Plant site operational cost	92,574.52	94,040.83	-1,466.31
9.2. Electrical network (pumping) cost	275.461	294.893	-19.43
9.3. Electrical plant site operational cost	15,542.51	125,531.85	-109,989.34
9.3.1. Comp. chiller electricity cost	49,221.21	92,302.83	-43,081.62
9.3.2. PV panels electricity income [2]	68,735.14	0.00	68,735.14
9.3.3. Heat dissipater electricity cost	35,056.44	33,229.02	1,827.42

[1] All costs are in Euro.
[2] The PV electricity income is to be subtracted when calculating the electrical plant site operational cost.

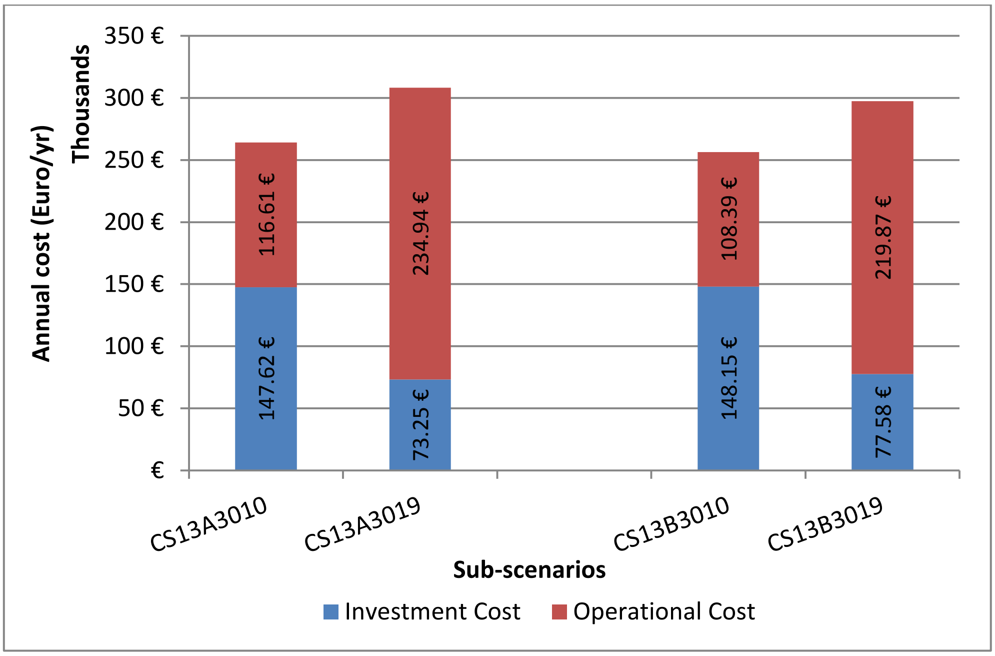


Figure 4.58: Annual investment and operational costs of sub-scenarios with and without PV panels with electricity tariffs A and B for investigation category 3.

4.3.7 Investigation category 4 (Centralized DCS with variable/size-dependent COP) scenarios

As performed in the constant COP investigations, centralized DC systems were optimized for size-dependent COP investigation. The same model and COP variation pattern used in investigation category 3, presented in section 4.3.6, was adopted here. The centralized system was enforced by limiting the number of chillers allowed to be installed to one chiller. However, the location and capacity of the chiller were to be optimized by the model. The purpose of this investigation category is to compare the costs of centralized DC systems to the optimal de-centralized DC systems obtained previously.

4.3.7.1 Reference scenario for investigation category 4

With the same assumptions adopted for the previous investigation categories, optimization of the reference sub-scenario for this investigation category was carried out. Figure 4.59 shows the optimal solution for a reference scenario for the case study within investigation category 4 for both electricity tariffs A and B. Building N2 which has the highest peak cooling load was chosen to be the central production plant for both electricity tariffs. It is noticed that, unlike within investigation category 3, no oversized chillers were installed where the size of the central chiller was already above the minimum chiller capacity that provides the highest COP in the model which is 7 for capacities above 1000kW. Instead the total installed cooling capacities were lower than the peak cooling load. The obtained system for tariff A, shown in Figure 4.59a, was the identical to the system obtained for investigation category 2, labeled CS13A2010 and presented in Figure 4.12b, except for a small design difference in the size of the cooling tower, which was reduced due to higher COP value, causing a slight difference in the total investment cost. However it had a significant reduction in total annual cost as shown in Figure 4.60. This indicated that adopting a size-dependent COP model did not influence the design of the system that much but had a high impact on the operation cost within electricity tariff A. On the other hand, the size-dependent COP model had a bigger impact on the design of the system when optimized within electricity tariff B in comparison to the obtained system for investigation category 2, presented in Figure 4.27b. Similar to tariff A, the total annual cost was reduced by almost 35% as shown in Figure 4.60.

As performed in investigation category 3, an extra optimization was carried out to check the feasibility and reliability of the obtained systems and their ability to operate in case of sudden changes in electricity tariffs. Each on the obtained systems in Figure 4.59 for each electricity tariff was re-optimized under the other electricity tariff. The locations and capacities of the main equipment, e.g. chillers, storage tanks, and DC pipelines, were forced to be the same throughout the re-optimization process except for the capacities of heat exchangers and user site units. The results of the re-optimization, presented in Figure 4.61, show that both obtained systems were able to operate with the change of the electricity tariffs without any design changes being required. This in turn indicates that centralized DC systems have a good reliability towards operating with changing operational conditions.

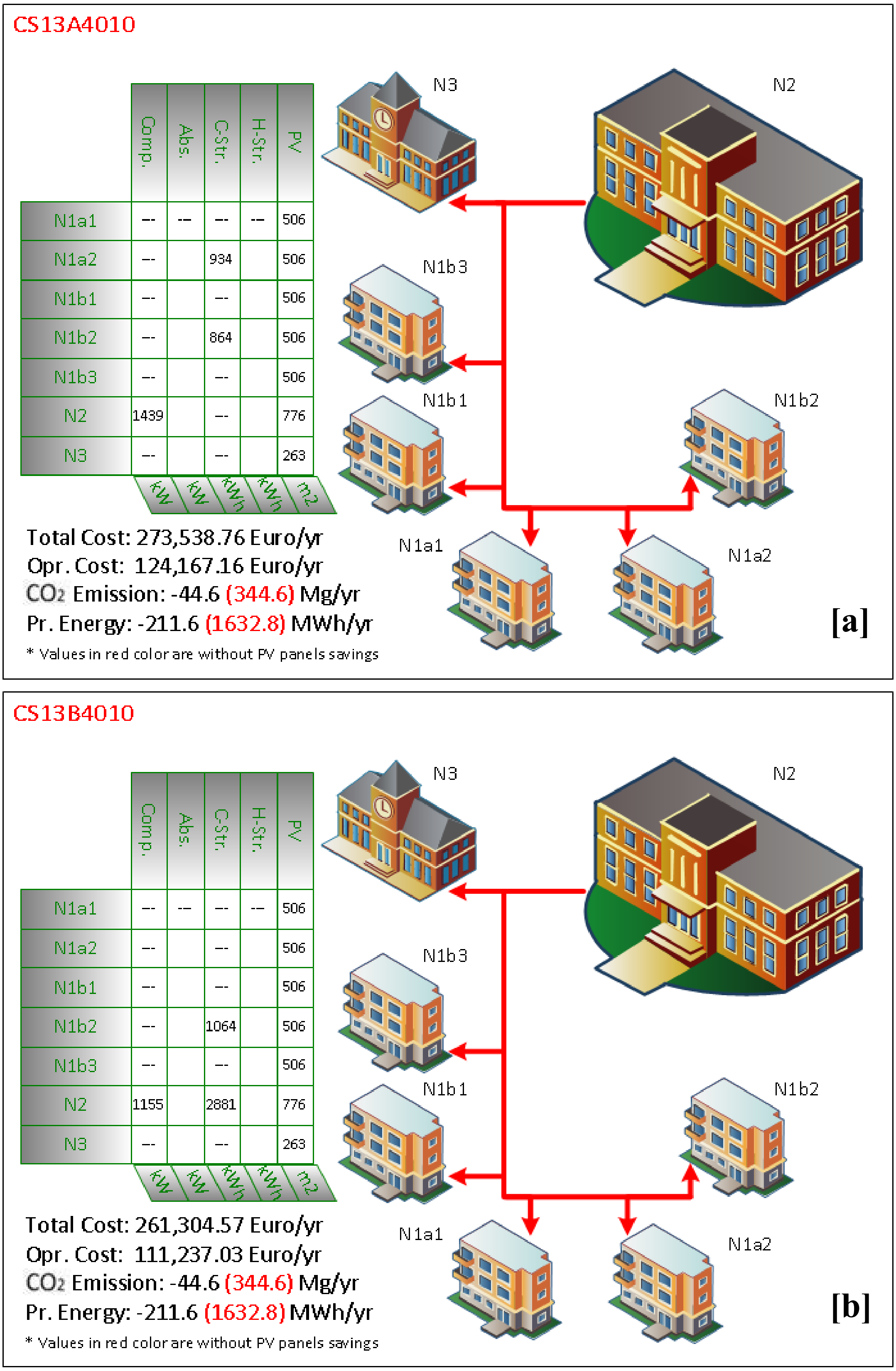


Figure 4.59: Annual cost optimization reference scenario for case study 1 within investigation category 4 for both electricity tariffs A and B.

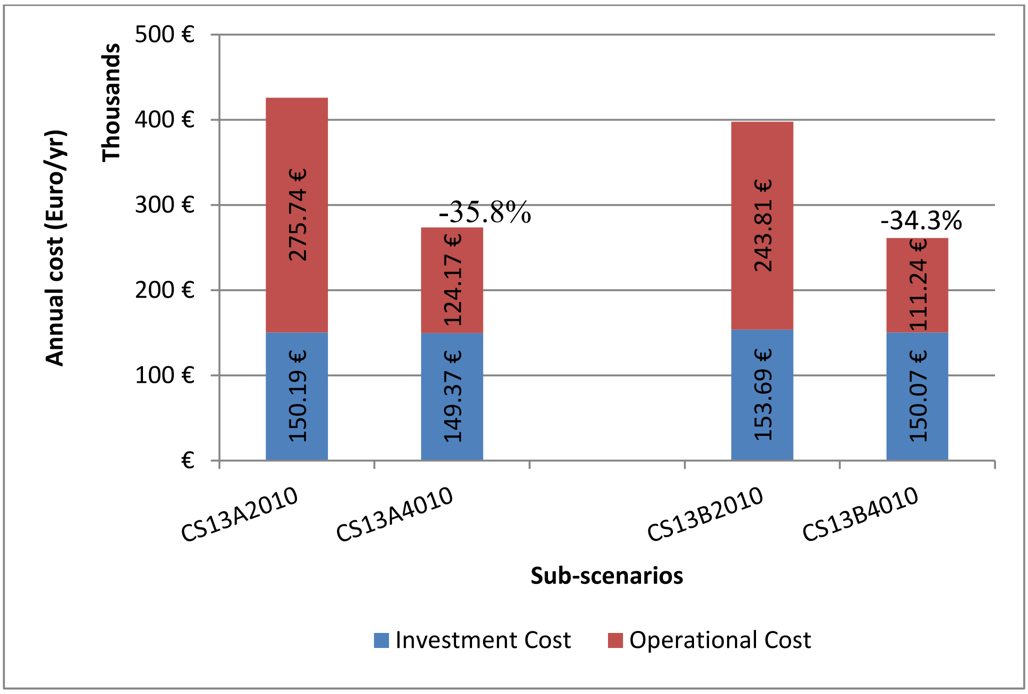


Figure 4.60: Annual costs of the reference scenarios for investigation categories 2 and 4 within under electricity tariffs A and B.

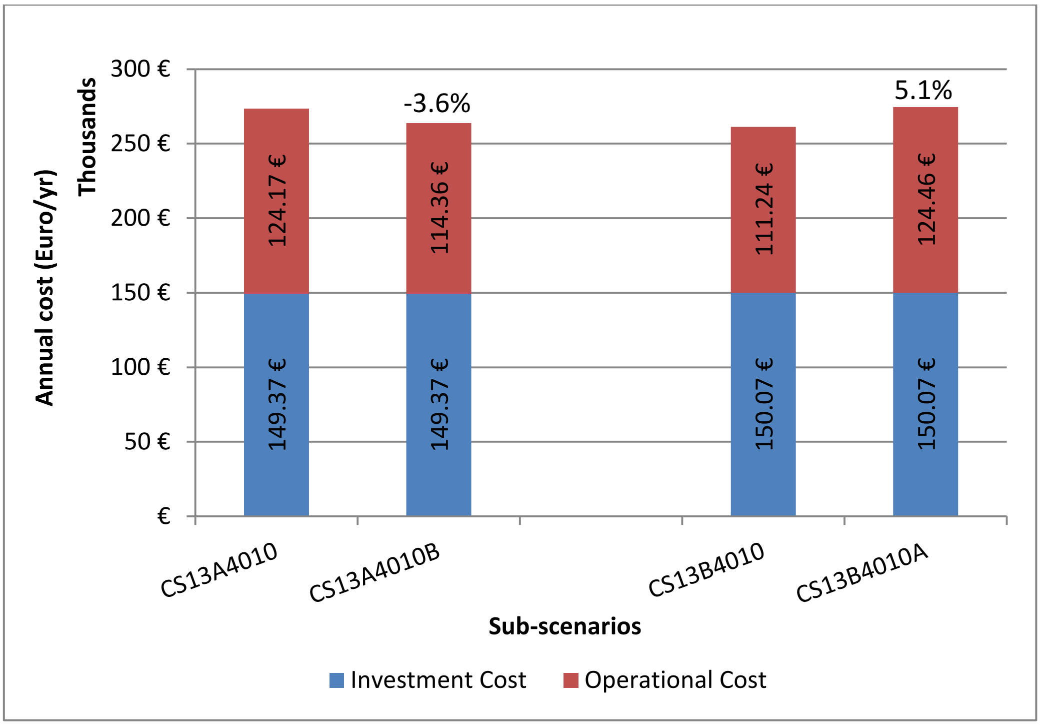
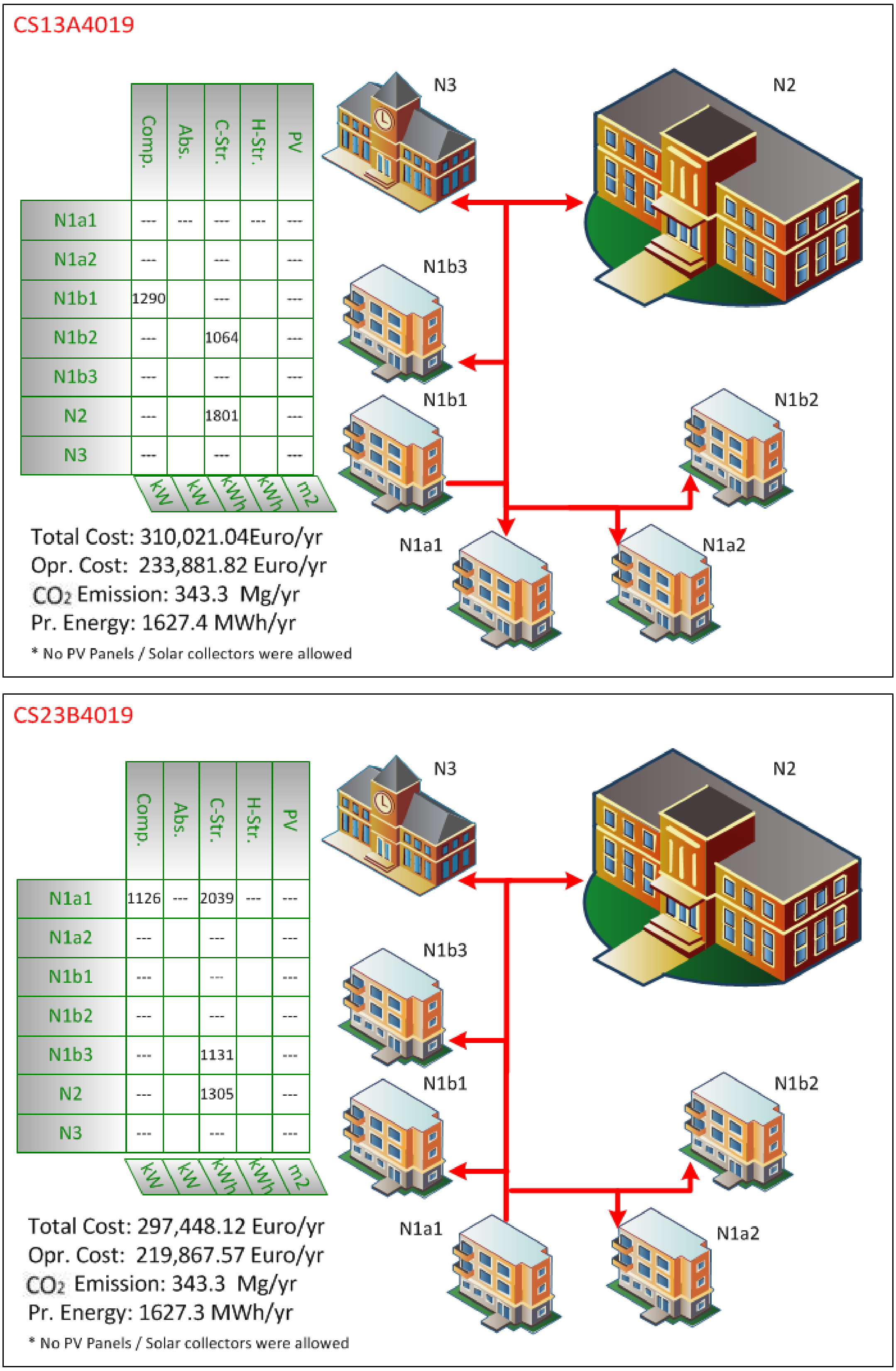


Figure 4.61: Annual costs of the reference scenarios for investigation category 4 in comparison to the same systems operating under switched electricity tariffs.

4.3.7.2 Optimizing without considering solar energy

As performed in the previous investigation categories, the impact of installing PV panels on the design of the reference sub-scenario was investigated by carrying out optimizations where PV panels and solar collectors were not allowed to be installed. The model was still forced to install a centralized DC network by the one chiller constraint. The adopted coding for these two sub-scenarios were CS13A4019 and CS13B4019 for electricity tariffs A and B, respectively. Observing the obtained new DC systems under the mentioned conditions, which are presented in Figure 4.62, show that locations of the central production plants were changes for both electricity tariffs. Building N1b1 was chosen for electricity tariff A and building N1a1 for electricity tariff B. Both of these buildings are central buildings, geographically, in the case study.

A cost comparison of the optimized sub-scenarios with and without considering PV panels and solar collectors is presented in Table 4.20. Once again it was noticed that systems obtained without utilizing solar energy have about half the investment cost of the systems when installing PV panels but a much higher operational cost. On the other scenario, the advantage of having locally consumed PV energy is reducing amount of electricity purchased from the grid. Another advantage is PV income from selling the extra electricity to the grid when PV energy is not consumed by the chillers directly. These two advantages are reducing the electrical plant site cost and thus the operational costs of the systems with PV panels. This attribute residence in most of the investigations carried out so far. The annual investment and operational costs of the sub-scenarios with and without solar energy utilization within investigation categories 3 and 4 are shown in Figure 4.63.



	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	---	---	---	---	---
N1a2	---		---		---
N1b1	1290		---		---
N1b2	---		1064		---
N1b3	---		---		---
N2	---		1801		---
N3	---		---		---
	kW	kW	kWh	kWh	m2

	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	1126	---	2039	---	---
N1a2	---		---		---
N1b1	---		---		---
N1b2	---		---		---
N1b3	---		1131		---
N2	---		1305		---
N3	---		---		---
	kW	kW	kWh	kWh	m2

Figure 4.62: Cost optimization sub-scenarios for investigation category 4 without utilizing solar energy, i.e. PV or solar collectors within a) Electricity tariff A, and b) Electricity tariff B.

Table 4.20: Costs comparison for optimized Centralized DCSs obtained with and without utilizing PV panels sub-scenarios for both electricity tariffs A and B.

Type of cost [1]	Tariff A		
	CS13A4010	CS13A4019	Difference
Total annual costs	273,538.77	310,021.05	-36,482.28
10. Total plant investment cost	117,701.80	46,529.54	71,172.26
11. Total Network investment cost	31,668.78	29,608.92	2,059.86
12. Total operational cost	124,167.16	233,881.83	-109,714.67
12.1. Plant site operational cost	92,835.83	92,859.30	-23.47
12.2. Electrical network (pumping) cost	806.139	335.827	470.31
12.3. Electrical plant site operational cost	30,525.19	140,686.71	-110,161.51
12.3.1. Comp. chiller electricity cost	72,790.01	103,446.11	-30,656.10
12.3.2. PV panels electricity income [2]	79,505.41	0.00	79,505.41
12.3.3. Heat dissipater electricity cost	37,240.60	37,240.60	0.00
Type of cost [1]	**Tariff B**		
	CS13B4010	CS13B4019	Difference
Total annual costs	261,304.57	297,448.13	-36,143.56
10. Total plant investment cost	118,339.68	48,027.46	70,312.21
11. Total Network investment cost	31,726.87	29,552.17	2,174.70
12. Total operational cost	111,237.03	219,867.57	-108,630.54
12.1. Plant site operational cost	94,008.40	94,040.83	-32.43
12.2. Electrical network (pumping) cost	741.935	294.893	447.04
12.3. Electrical plant site operational cost	16,486.69	125,531.85	-109,045.16
12.3.1. Comp. chiller electricity cost	62,467.58	92,302.83	-29,835.25
12.3.2. PV panels electricity income [2]	79,505.41	0.00	79,505.41
12.3.3. Heat dissipater electricity cost	33,524.53	33,229.02	295.51

[1] All costs are in Euro.
[2] The PV electricity income is to be subtracted when calculating the electrical plant site operational cost.

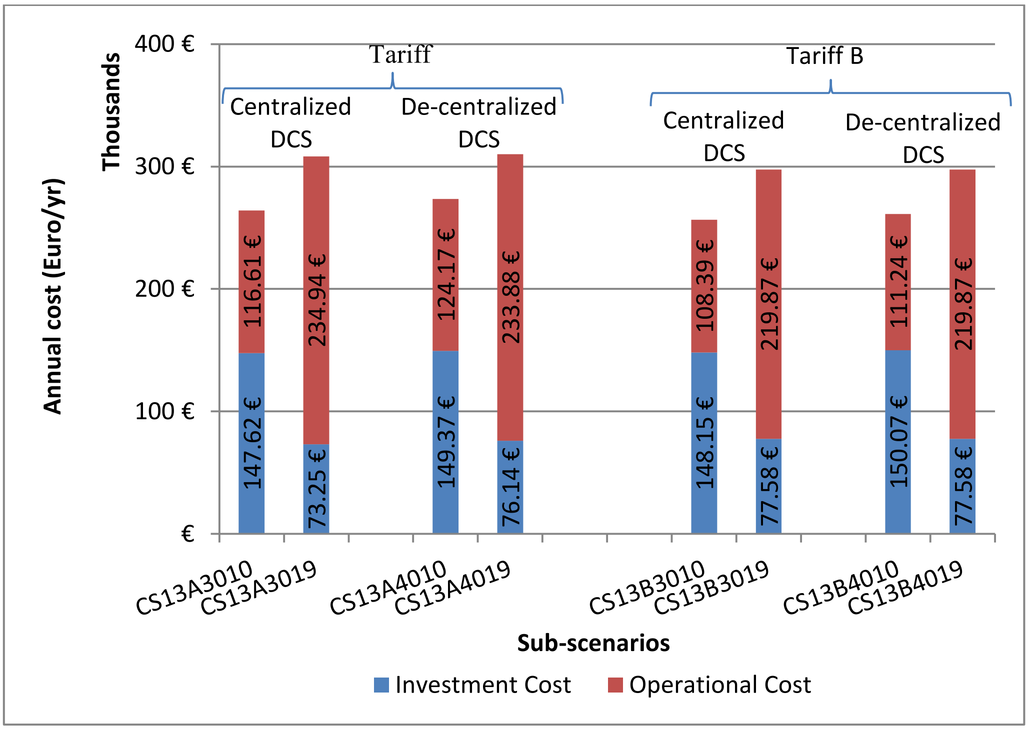


Figure 4.63: Annual investment and operational costs of sub-scenarios with and without PV panels with electricity tariffs A and B for investigation categories 3 and 4.

4.3.8 Operation Constraints Scenarios for investigation categories 3 and 4

Comparing the annual cost of the sub-scenarios presented in Figure 4.63 show that centralized systems have slightly higher costs than de-centralized. This raises the question if such a slight cost difference, 2- 4%, is enough to make a decision to adopt the optimal solution obtained by the model, i.e de-centralized DCS. Therefore, reliability investigations were carried out concerning two operational constrains that often has a big impact on any operating system:

- Load shifting strategy.
- Outdoor temperature effect, i.e. variation of COP values between day and night due to a change in ambient temperature.

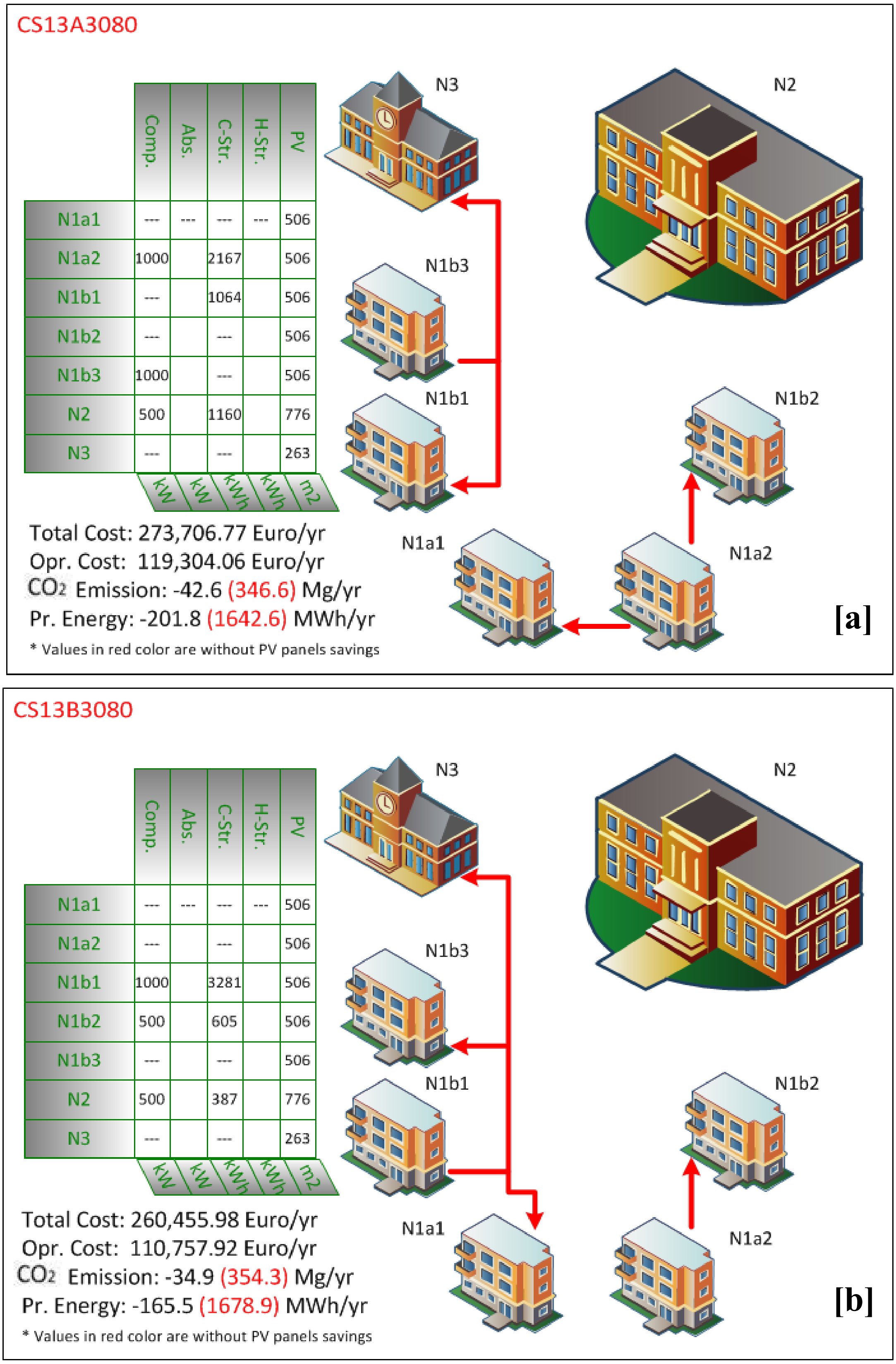
As explained previously, load shifting is an optional strategy adopted by decision makers and system operators when needed while the second constraint, i.e. outdoor temperature effect, is a special phenomenon that occurs in hot climate regions. The reliability check was carried out in the form of several optimization sub-scenarios, starting with a full optimization of the case study within the applied operational constraint and comparing it to the reference sub-scenario. Later on, the reference sub-scenario would be re-optimized under the operational constraints to see if this system is able to operate under the investigated operational conditions.

4.3.8.1 Load Shifting Strategy

Load shifting strategy has been investigated previously in section 4.3.5.3 to observe its effects on the design, operation pattern and overall annual cost of the obtained systems in comparison to the reference scenarios. The same was be performed here and in addition the reference scenarios, i.e CS13A/B3010 and CS13A/B4010 presented in Figures 4.55 and 4.59 respectively, were re-optimized under the load shifting conditions but their original designs were kept the same in order to check their reliability in operating with load shifting.

The obtained systems through optimizing the case study with considering load shifting strategies are presented in Figures 4.64 and 4.65, for investigation categories 3 and 4, respectively. It is noticed that major design changes have been adopted within investigation category 3, i.e. de-centralized systems shown in Figure 4.64, when compared to the reference sub-scenario of category 3 presented in Figure 4.55. The increase in the total annual costs was around 3.5 % and 1.5% for electricity tariffs A and B, respectively. On the other hand, less extreme design changes were adopted within investigation category 4, i.e. centralized systems shown in Figure 4.64, when compared to the reference sub-scenario of category 4 presented in Figure 4.59, where the increase in the total costs was around 1.7 % and 0.5% for electricity tariffs A and B, respectively. However, these design modifications cannot be added on the system obtained at the reference scenario because they include changing the capacities of the chillers and storage tanks and implementing new pipeline network branches as well. This raises questions regarding the reliability of the reference scenarios

Therefore, the ability of the reference systems to operate when adopting load shifting strategy has been investigated in this work. Reference systems were re-optimized with constraints that the locations and capacities of all major equipment, e.g. chillers, storage tanks, heat exchangers, cooling towers, user site units, and DC pipelines, had to be maintained as the same as in the reference scenario before re-optimization. This make the re-optimization process limited to operational parameters. If the system was successfully optimized without changing the design that means the system was able to operate with load shifting even though such operation strategy was not considered when the system was designed at the beginning. And if no solution was obtained by the optimization model then another sub-scenario was carried out with a single modification being allowed. A set of 6 possible modifications were adopted in this investigation as presented in Table 4.21.



[a] CS13A3080

	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	---	---	---	---	506
N1a2	1000		2167		506
N1b1	---		1064		506
N1b2	---		---		506
N1b3	1000		---		506
N2	500		1160		776
N3	---		---		263
	kW	kW	kWh	kWh	m2

[b] CS13B3080

	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	---	---	---	---	506
N1a2	---		---		506
N1b1	1000		3281		506
N1b2	500		605		506
N1b3	---		---		506
N2	500		387		776
N3	---		---		263
	kW	kW	kWh	kWh	m2

Figure 4.64: Cost optimization sub-scenarios for investigation category 3 with load shifting strategy within: a) Electricity tariff A, and b) Electricity tariff B.

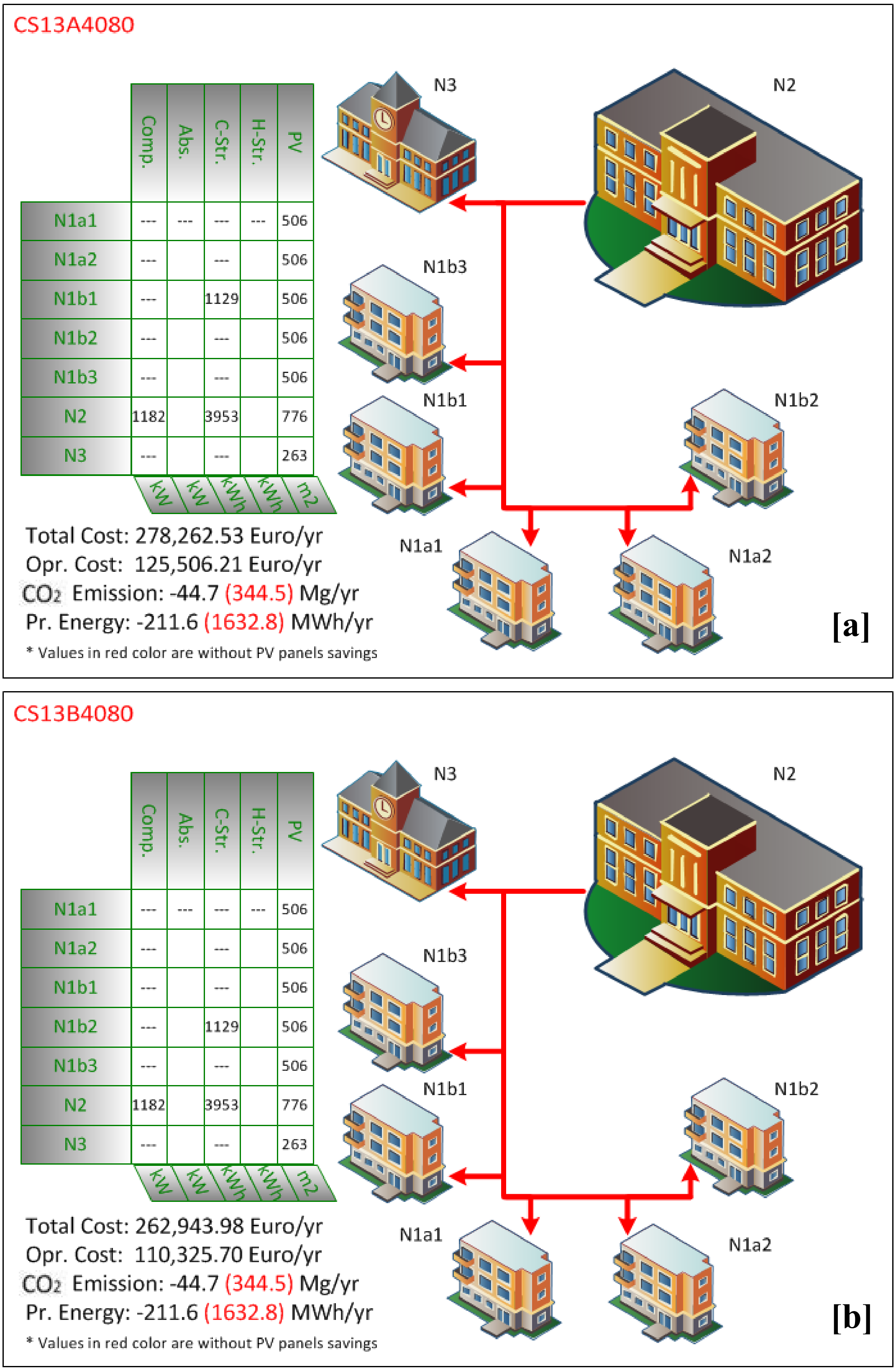
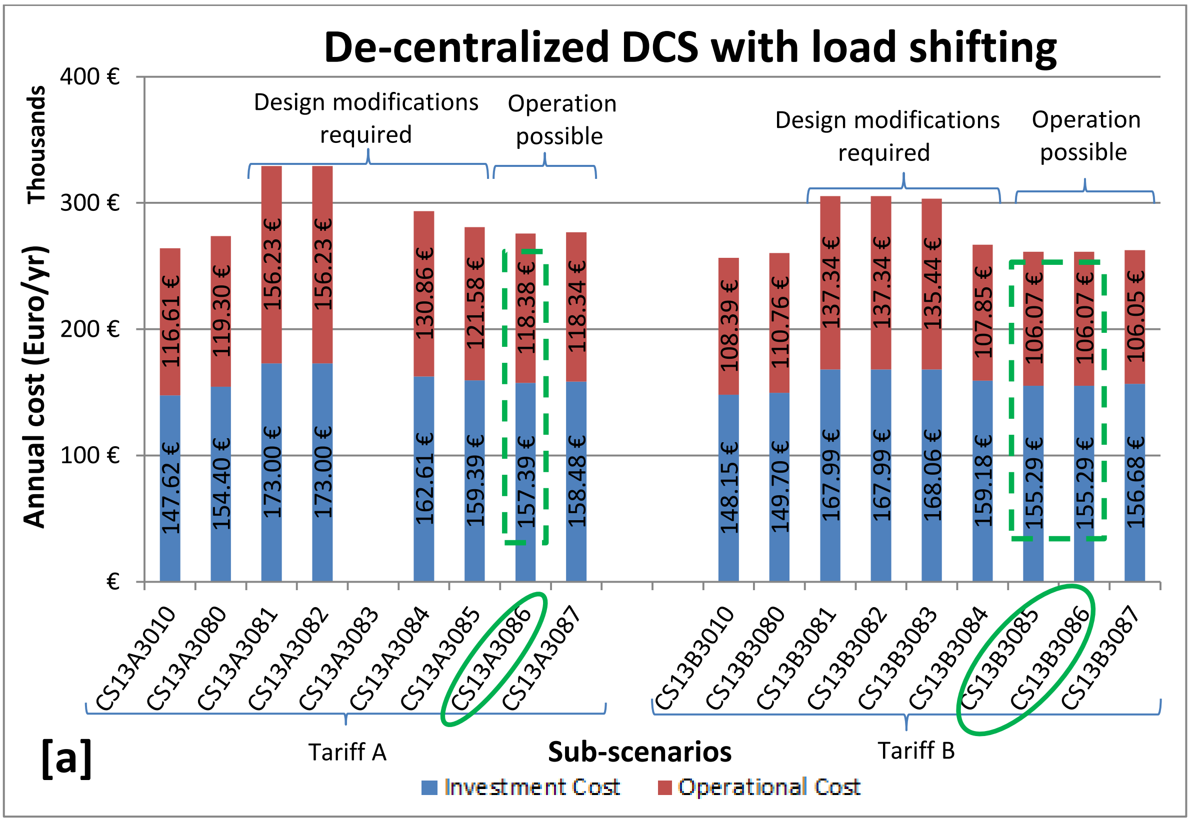


Figure 4.65: Cost optimization sub-scenarios for investigation category 4 with load shifting strategy within: a) Electricity tariff A, and b) Electricity tariff B.

Table 4.21: Description of design modifications adopted in sub-scenarios to investigate applying load shifting strategy on the optimal solutions adopted in investigation categories 3 and 4.

Title of sub-scenario	Code	Description
Reference	CS13A/B (3/4) 010	Optimized without load shifting constraint
Load shifting	CS13A/B (3/4) 080	Optimized with load shifting constraint
M0: Applying load shifting	CS13A/B (3/4) 081	Reference scenario re-optimized under load shifting constraint with no changes allowed
M1: Bigger chillers	CS13A/B (3/4) 082	Reference scenario re-optimized under load shifting constraint with bigger chillers allowed
M2: Bigger storages	CS13A/B (3/4) 083	Reference scenario re-optimized under load shifting constraint with bigger storages allowed
M3: One additional storage	CS13A/B (3/4) 084	Reference scenario re-optimized under load shifting constraint with 1 extra storage allowed
M4: Two additional storages	CS13A/B (3/4) 085	Reference scenario re-optimized under load shifting constraint with 2 extra storages allowed
M5: Opt. storages	CS13A/B (3/4) 086	Reference scenario re-optimized under load shifting constraint with number of extra storages to be optimized
M6: 7 additional storages	CS13A/B (3/4) 087	Reference scenario re-optimized under load shifting constraint with 7 storages being forced

Figure 4.66 shows the total annual costs of the sub-scenarios described in Table 4.21. For the first five sub-scenarios, i.e. M0 to M4, of the de-centralized DCS investigation with electricity tariff A the reference system was not able to operate, even with the implemented changes, unless additional design modification was allowed. Often, these additional design modifications would be changing the capacity of the cooling tower, which can be substituted by adding hot water storage in the heat dissipation circle, or installing additional chillers. Only the last two sub-scenarios, i.e. CS13A3086 & -87, with modifications M5 and M6 were able to operate with the suggested modifications in the system design which was adding an optimized number of cold storage tanks, 4 tanks in this case, to the network without requiring additional modifications. A similar pattern was observed with electricity tariff B except that the optimized number of required cold storage tanks was 2, i.e. one storage tank additional to the original one in the reference system in Figure 4.55b. On the other hand, for the centralized DCS investigation, adding one cold storage tank to the reference system, i.e. M3 sub-scenario, was sufficient to make the reference system able to operate with load shifting strategy. In general, it was noticed for both investigation categories that the total annual cost of the sub-scenarios where the system was able to operate with the suggested changes were very close to the annual cost of the reference scenario systems. This indicates that optimized DCS systems can be adapted to operate with load shifting strategy, even if they were not designed to, with relatively low additional costs.



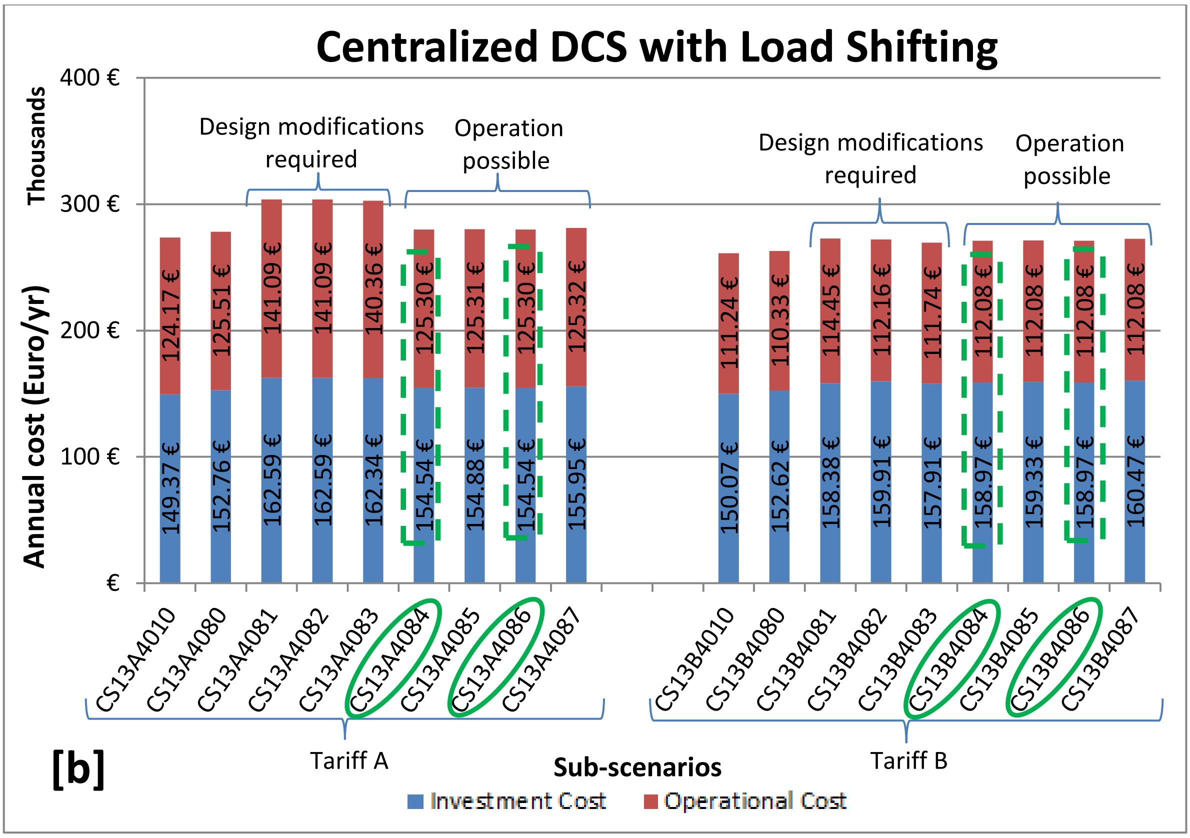
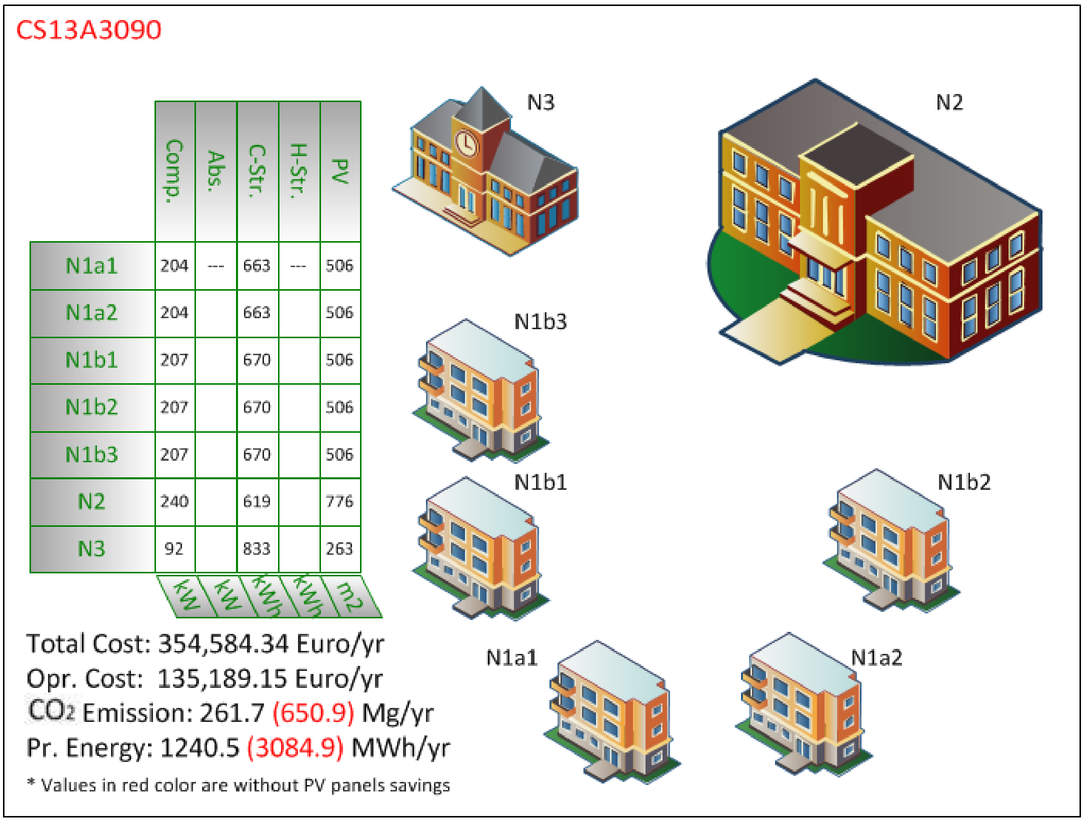


Figure 4.66: Annual investment and operational costs of sub-scenarios of applying load shifting strategy in DCS within: a) Investigation category 3, and b) Investigation category 4.

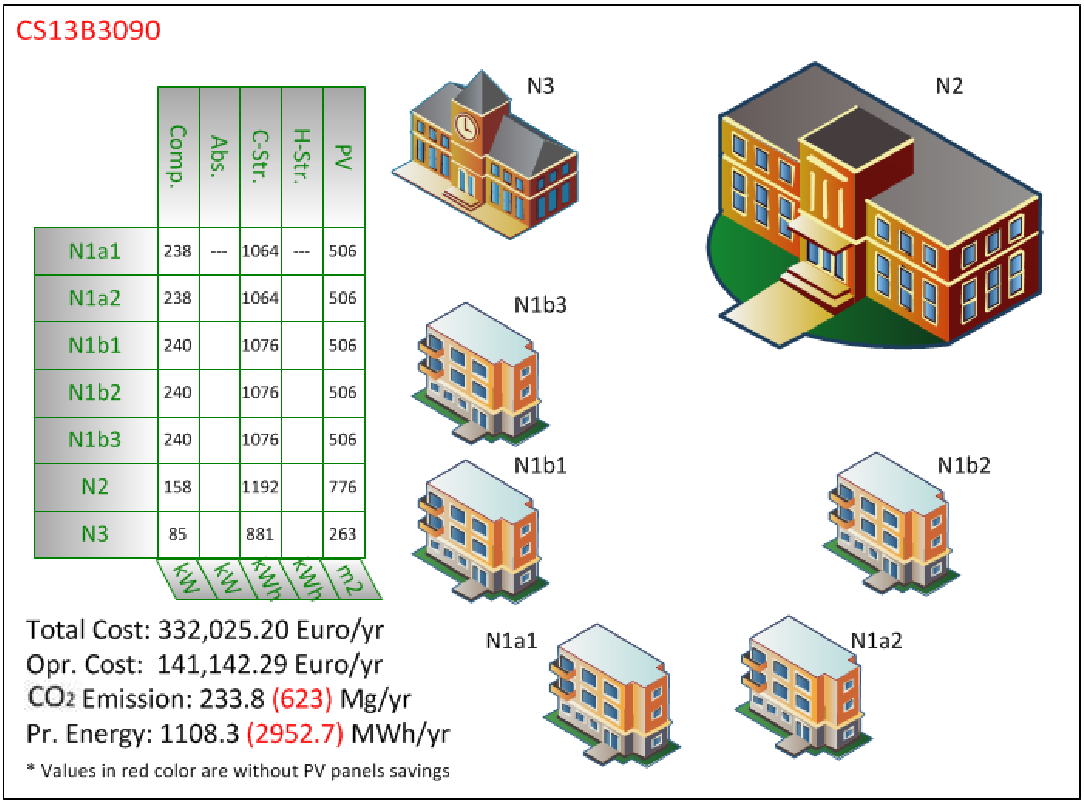
4.3.8.2 Outdoor Temperature Effect

The outdoor temperature effect on compression chillers COP has been explained and investigated in section 4.3.5.4 for investigation categories 1 and 2, i.e. constant COP models. The obtained systems were compared to the reference scenarios of these investigation categories. A similar investigation was carried out for investigation categories 3 and 4, i.e. variable COP models. Where new systems were obtained with the consideration of the outdoor temperature effect and compared to the reference scenarios of these categories. Later on, similar to the previous approach with load shifting, the reference scenarios were re-optimized under the outdoor temperature effect constraints but their original designs were preserved as they were and only operation parameters were subjected to the re-optimization process. The purpose of this re-optimization was to check the ability of the reference systems to operate with this phenomenon.

The obtained systems with considering outdoor temperature phenomenon for investigation categories 3 and 4 are presented in Figures 4.67 and 4.68, respectively. For investigation category 3, no network pipelines were installed. Every building was equipped with a separated individual system. The absence of any DC network, in comparison to the reference scenario in Figure 4.55, indicates the important impact that this phenomenon has on the optimal design of cooling systems. The sizes of the chosen chillers were in the range of the lowest COP in the model which is 4. The chillers were equipped with relatively big storage tanks in comparison to the separated individual systems obtained with the fixed COP model with a value of 4, i.e. Figure 4.48. This increase in storage capacity was necessary to enable the system to deal with drop in the COP value due to the outdoor temperature effect. Although they had lower investment costs, the total annual costs of the newly obtained systems were higher than the reference systems of investigation category 3, i.e. Figure 4.55, with 34% and 29% for electricity tariffs A and B, respectively. Requiring bigger storage tanks was present in the obtained centralized DC system within investigation category 4 as well as shown in Figure 4.68. However, the route of the DC network was kept the same as in the reference scenario, i.e. Figure 4.59, where building N2 was still chosen by the model as production plant. The increase in the total annual costs was around 47% and 51% for electricity tariffs A and B, respectively, when compared to the reference system of investigation category 4 presented in Figure 4.59.



	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	204	---	663	---	506
N1a2	204		663		506
N1b1	207		670		506
N1b2	207		670		506
N1b3	207		670		506
N2	240		619		776
N3	92		833		263
	kW	kW	kWh	kWh	m2



	Comp.	Abs.	C-Str.	H-Str.	PV
N1a1	238	---	1064	---	506
N1a2	238		1064		506
N1b1	240		1076		506
N1b2	240		1076		506
N1b3	240		1076		506
N2	158		1192		776
N3	85		881		263
	kW	kW	kWh	kWh	m2

Figure 4.67: Cost optimization sub-scenarios for investigation category 3 with COP drop due to ambient temperature variation within: a) Electricity tariff A, and b) Electricity tariff B.

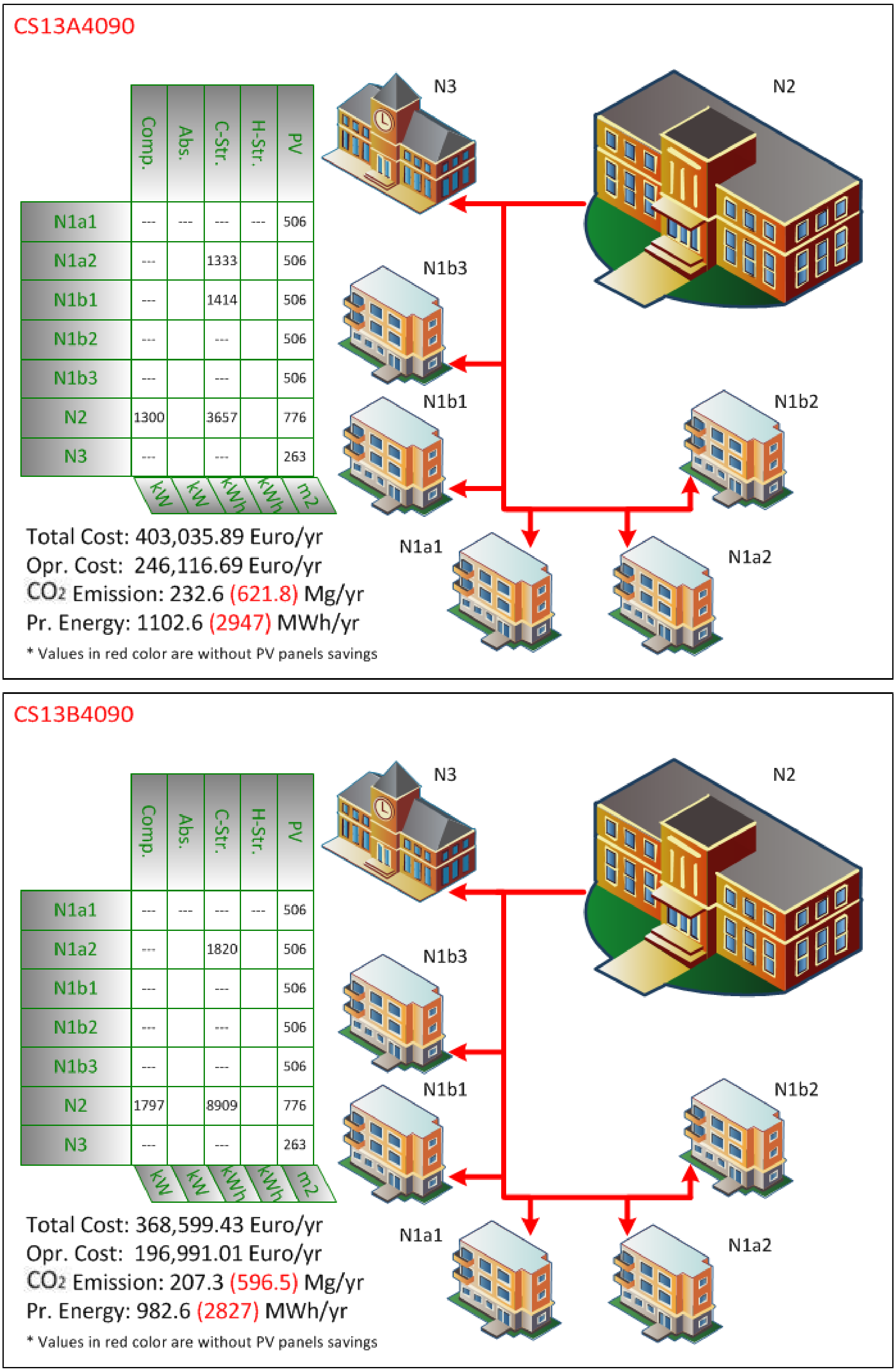


Figure 4.68: Cost optimization sub-scenarios for investigation category 4 with COP drop due to ambient temperature variation within: a) Electricity tariff A, and b) Electricity tariff B.

The same approach used in analyzing the reliability of the obtained reference systems with load shifting strategy was used with the outdoor temperature effect phenomenon as well. Where reference systems were re-optimized with the locations and capacities of all major equipment, e.g. chillers, storage tanks, heat exchangers, cooling towers, user site units, and DC pipelines, being forced to be the same as in the reference scenario system. Table 4.22 shows a list of the sub-scenarios performed in this analysis including the 6 possible modifications adopted in the reliability investigation. The total annual costs of the obtained systems for the described sub-scenarios are presented in Figure 4.69.

Table 4.22: Description of design modifications adopted in sub-scenarios to investigate applying the effect of outdoor temperature on reference systems of investigation categories 3 and 4.

Title of sub-scenario	Code	Description
Reference	CS13A/B (3/4) 010	Optimized without outdoor Temp. effect
Outdoor Temp. Effect	CS13A/B (3/4) 090	Optimized with outdoor Temp. effect
M0: Applying outdoor temperature effect	CS13A/B (3/4) 091	Reference scenario re-optimized under outdoor Temp. effect constraint with no changes allowed
M1: Bigger chillers	CS13A/B (3/4) 092	Reference scenario re-optimized under outdoor Temp. effect constraint with bigger chillers allowed
M2: Bigger storages	CS13A/B (3/4) 093	Reference scenario re-optimized under outdoor Temp. effect constraint with bigger storages allowed
M3: One additional storage	CS13A/B (3/4) 094	Reference scenario re-optimized under outdoor Temp. effect constraint with 1 extra storage allowed
M4: Two additional storages	CS13A/B (3/4) 095	Reference scenario re-optimized under outdoor Temp. effect constraint with 2 extra storages allowed
M5: Opt. storages	CS13A/B (3/4) 096	Reference scenario re-optimized under outdoor Temp. effect constraint with number of extra storages to be optimized
M6: 7 additional storages	CS13A/B (3/4) 097	Reference scenario re-optimized under outdoor Temp. effect constraint with 7 storages forced

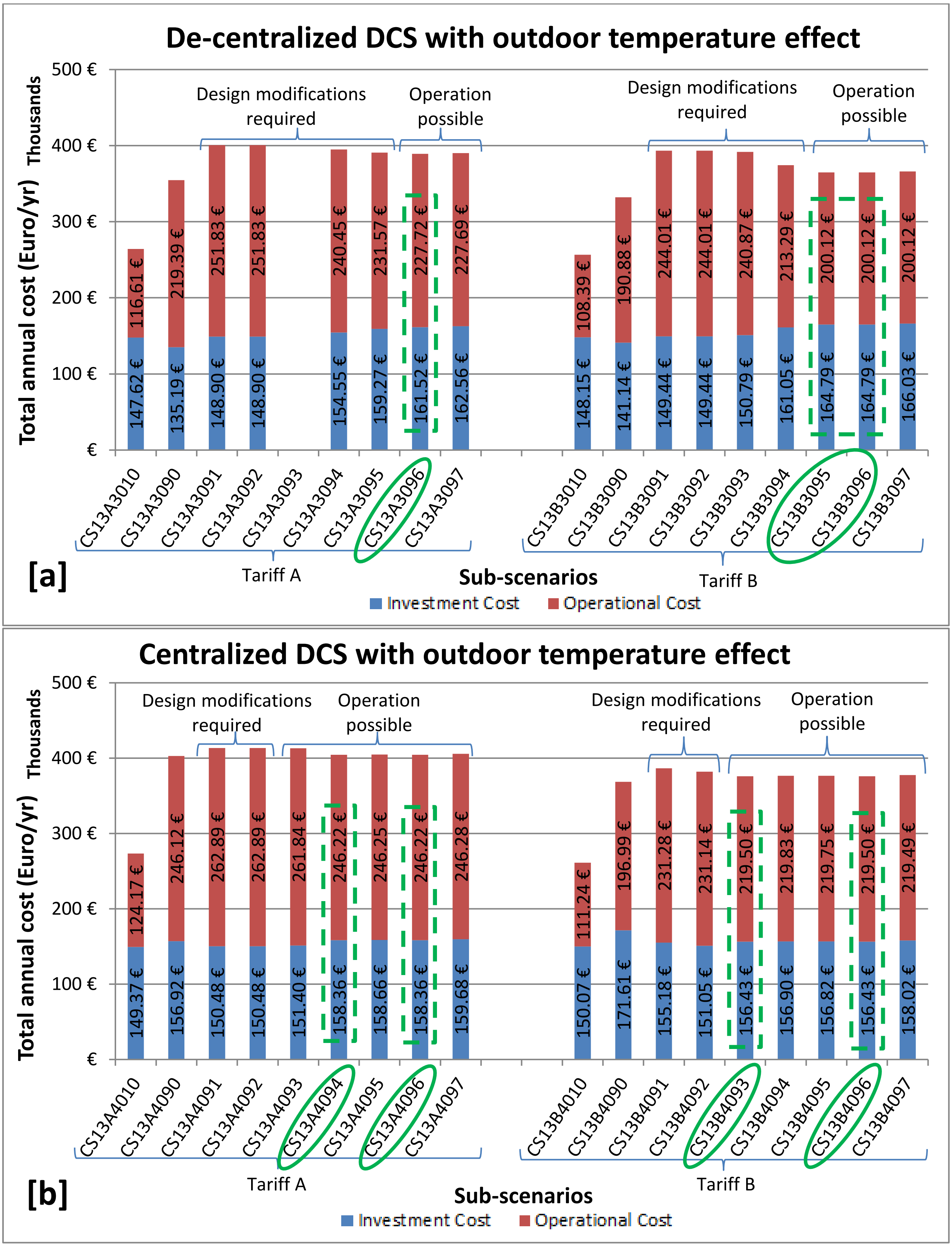


Figure 4.69: Annual investment and operational costs of sub-scenarios of investigating outdoor temperature effect on DCS within: a) Investigation category 3, and b) Investigation category 4.

For the de-centralized DCS investigation within electricity tariff A, only the last two sub-scenarios, i.e. CS13A3096 & -97, were able to operate without any modifications in the design other than the permissible change according to the sub-scenarios themselves, i.e. M5 and M6. The other sub-scenarios required some modifications such as changing the cooling tower capacity. The optimal permissible modification was to add an optimal number of storage tanks, which was 4 in these particular circumstances, to the reference system. The same pattern was observed when re-optimizing the reference scenario within electricity tariff B except that installing two storage tanks, i.e. one storage tank additional to the original one in the reference system in Figure 4.55b, was enough to enable the reference system to operate with considering the outdoor temperature effect on compression chillers COP.

However, for the centralized DCS investigation, it was sufficient to re-optimize the reference system with allowing different sizes for the storage tanks available in the system already to enable the system to operate with the outdoor temperature phenomenon and for both electricity tariffs. The optimal modification for electricity tariff A reference system was to install one additional storage tank to the original two tanks in the reference system CS13A4010 in Figure 4.59a. On the other hand, re-optimizing the capacities of the two existing storage tanks represented the optimal modification for electricity tariff B reference system CS13B4010, shown in Figure 4.59b. In general, it was noticed that although the optimized solutions for the phenomenon, i.e. CS13A/B(3/4)090, has higher total annual cost than the reference systems with a percentage that reaches up to 50%, the total annual cost of the optimized modification to the reference systems were very close to the optimal solutions for the phenomenon especially for the centralized DCS as shown in Table 4.23. Based on this, it was concluded that decision makers need to implement only some simple modifications to the reference systems to make these systems reliable and able to handle the outdoor temperature phenomenon but with a high cost.

Table 4.23: Total costs of optimal solutions and the optimal modified reference systems under the outdoor temp. effect and their percentage of increase in comparison to the reference systems.

Investigation category	Reference system		Optimal solution			Optimal modified reference system		
	Code	Cost (Euro)	Code	Cost (Euro)	%	Code	Cost (Euro)	%
Category 3 with tariff A	CS13A3010	264229.3	CS13A3090	354584.3	34.2	CS13A3096	389244.3	47.3
Category 3 with tariff B	CS13B3010	256542.6	CS13B3090	332025.2	29.4	CS13B3095	364905.2	42.2
Category 4 with tariff A	CS13A4010	273538.7	CS13A4090	403035.8	47.3	CS13A4094	404578.2	47.9
Category 4 with tariff B	CS13B4010	261304.5	CS13B4090	368599.4	41.1	CS13B4093	375928.4	43.8

4.4 CO_2 Emissions Optimization Objective

Over the last few decades, climate change phenomena have driven researchers, designers and DC companies to pay more and more attention to the CO_2 emissions coming out of their cooling systems. Therefore, optimizing CO_2 emission was one of the concerns of this work as part of the adopted multi criteria approach. A single objective optimization model was developed as a preliminary stage to combine both cost and CO_2 emissions objectives in one multi-objective optimization model on a later stage.

The objective function of the CO_2 emissions model is presented in details within Chapter 3 of this work. Generally, the amount of CO_2 emitted from a DCS is mostly related to the type of energy resources being utilized, type of technology being used and the efficiencies of these technologies. The model developed is concerned with optimizing the operational patterns of the selected cooling technologies. CO_2 emissions resulting from design stages such as manufacturing and installing the cooling technologies, network pipelines and other DC equipment were symbolically implemented in the model. For example, for each chiller 1g of CO_2 was assumed to be emitted in manufacturing process for each kW of the chiller capacity and 1kg of CO_2 for the installation process. Similar assumptions were implemented also for other DC equipment and piping. Such assumptions were adopted due to the lack of CO_2 emission parameters for these processes in the literature. However, operational emissions were the dominant factor in the objective function of the model and the values of their parameters are presented in chapter 3.

The approach for investigating optimal CO_2 solutions was carried out on two stages or main scenario groups.

- **First stage:** A de-centralized scenario was investigated to obtain a reference solution to be compared with on a later stage. Several compression chiller COP values and models were adopted in this stage
- **Second stage:** An optimal centralized district cooling system scenario was obtained and compared to the reference system.

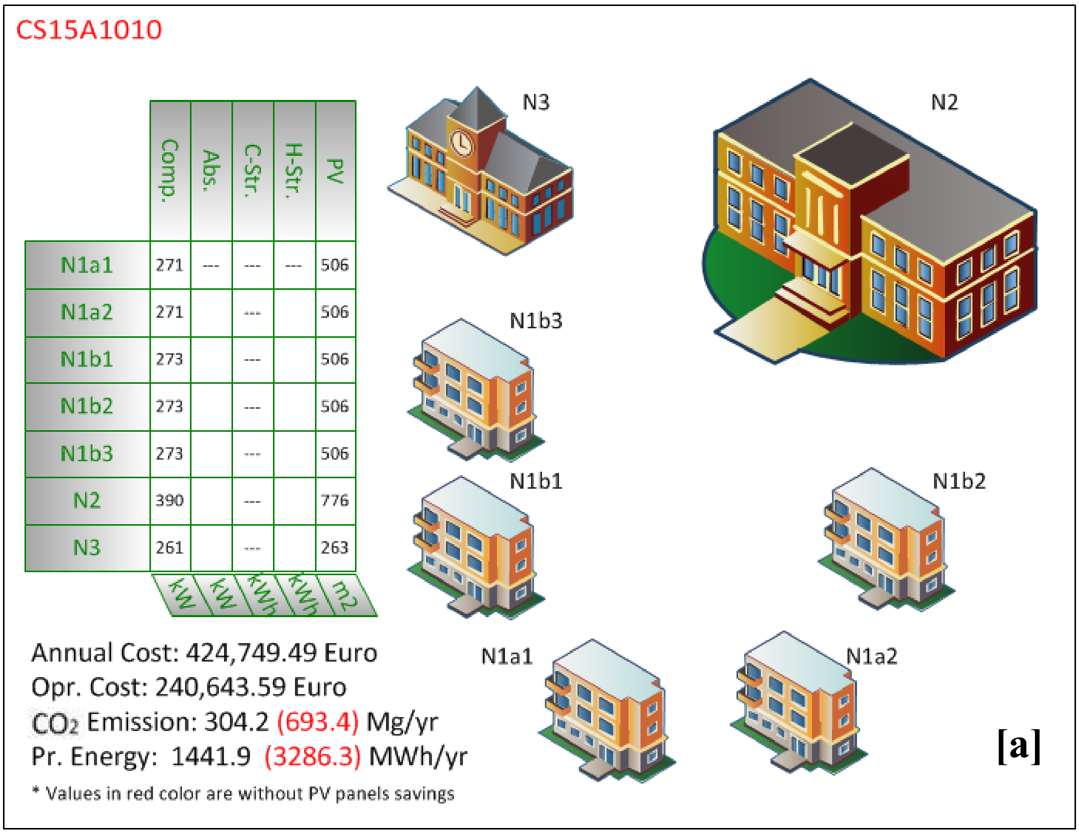
4.4.1 Reference Scenarios

Similar to the adopted approach in the cost minimization objective, a simplified scenario was investigated as a reference for comparison purposes. It is basically an optimization for the case study without considering the restriction and operational conditions that might affect the optimal solution. Waste heat availability was not considered and no other operation conditions such as load shifting were applied. All buildings were assumed to have an entire floor or basement as free space to install the cooling system equipment. Two tariffs for the electricity were investigated and two COP models were adopted:

- Fixed COP model where several COP values were adopted regardless of the size of the chillers.
- Variable COP model where the COP value varies depending on the size of the chiller.

4.4.1.1 Fixed COP model

The system obtained for the first reference sub-scenario for case study 1 with electricity tariff A and a constant COP of a value of 3 for the compression chillers, presented in Figure 4.70a, show that no DC network was installed. Relatively small individual compression chillers were chosen to be installed at each building. The main difference of this system from the one obtained under the same conditions but with cost optimization objective is that no storage tanks were needed since that storing cooling energy for later uses does not alter the primary energy consumption and hence the CO_2 emissions. Thus the cooling load of the building is to be met by the local compression chiller instantly, i.e. hour by hour. Such design can be understood as a result of the CO_2 objective function that relays mainly on the operational patterns of the system. Where selecting a one central chiller for the entire district would not make a significant difference, neither positive nor negative, in terms of CO_2 emissions since that the latest depends majorly on the primary energy consumed during the operation time. This is under the assumed simplification that COP values are fixed for both low and high capacity chillers. On the other hand, a DC network would have additional CO_2 emissions coming out of the energy consumed by the cold water pumps used to circulate the water within the network. PV panels were installed on 70% of the roof area which was also assumed to be free to use. The same amount of PV panels was installed in the cost objective reference scenario, i.e. Figure 4.7, as well. Changing the electricity tariff from tariff A to tariff B did not have any impact on the optimal solution as shown in Figure 4.70b, yet a different total annual cost was obtained. The cost of energy consumed is not considered in the CO_2 objective therefore changing electricity tariff does not have any impact on the amount of CO2 being emitted. However, such change in electricity prices would naturally affect the total cost of the system. For the following sub-scenarios, investigation was focused merely on results obtained with electricity tariff A.



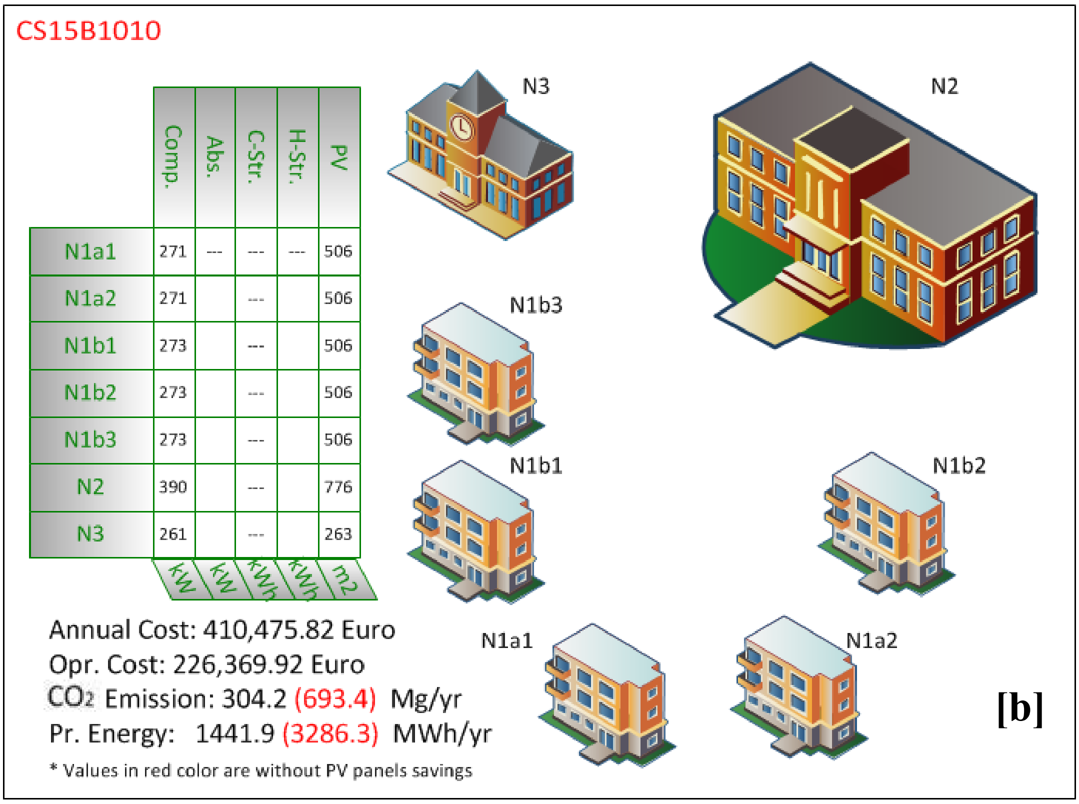


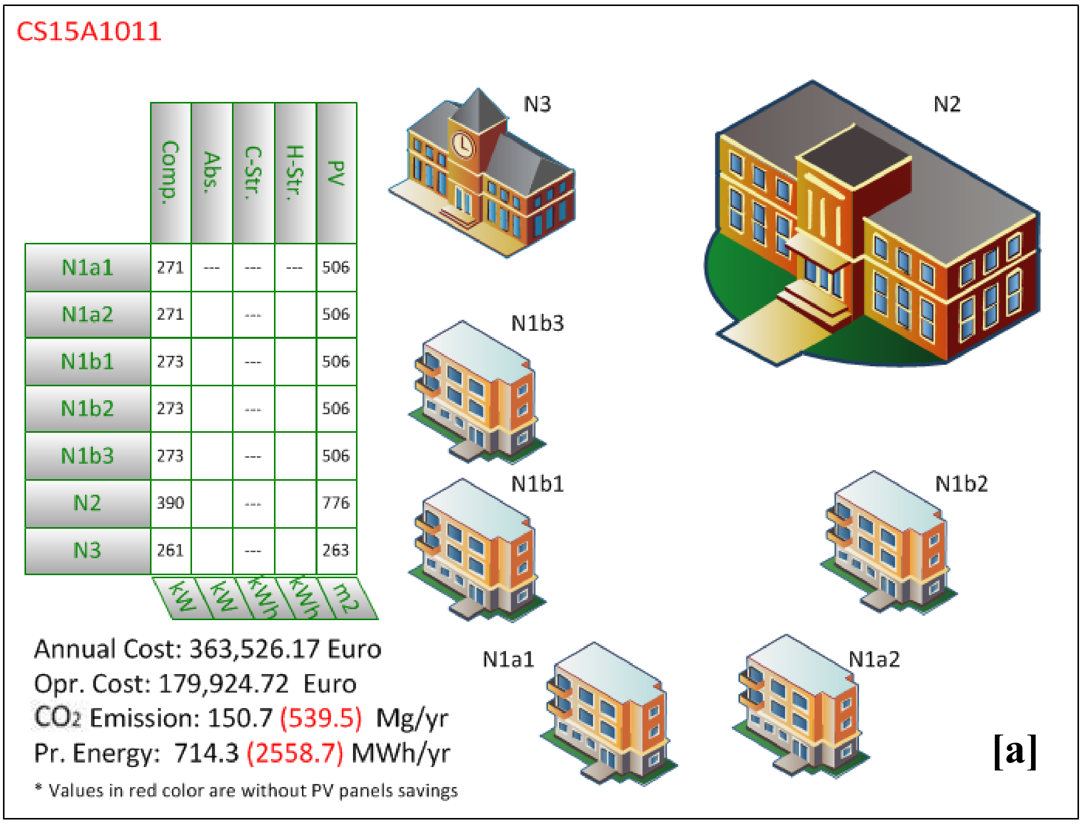
Figure 4.70: CO_2 emissions optimization with compression COP=3 for: a) electricity tariff A, and b) electricity tariff B.

A rough COP sensitivity analysis was carried out to observe the impact of changing compression chillers COPs on the optimal solution. COP was still assumed to be fixed regardless of the installed chiller size and regardless of the outdoor temperature variation. It was observed that the obtained optimized systems with compression chillers with COP values of 4,5,6 and 7, shown in Figures 4.71 and 4.72, represent the same optimized solution obtained for COP=3, presented in Figure 4.70. The amount of CO_2 emitted was reduced whenever a higher COP was adopted since that higher COP means less primary energy would be needed to produce the same amount of cooling energy. However increasing the COP here does not have any impact on the obtained optimized design for the system because these COPs are not changing with the change of the installed chiller sizes. Hereby, installing a bigger chiller at a certain location and connecting the other buildings to that central location would result only in additional CO_2 emissions due to the DC network operational pumps unless that central chiller would have a higher COP due to its bigger size. Based on this remark, centralized DCS investigation was carried out only within the variable COP model in this work.

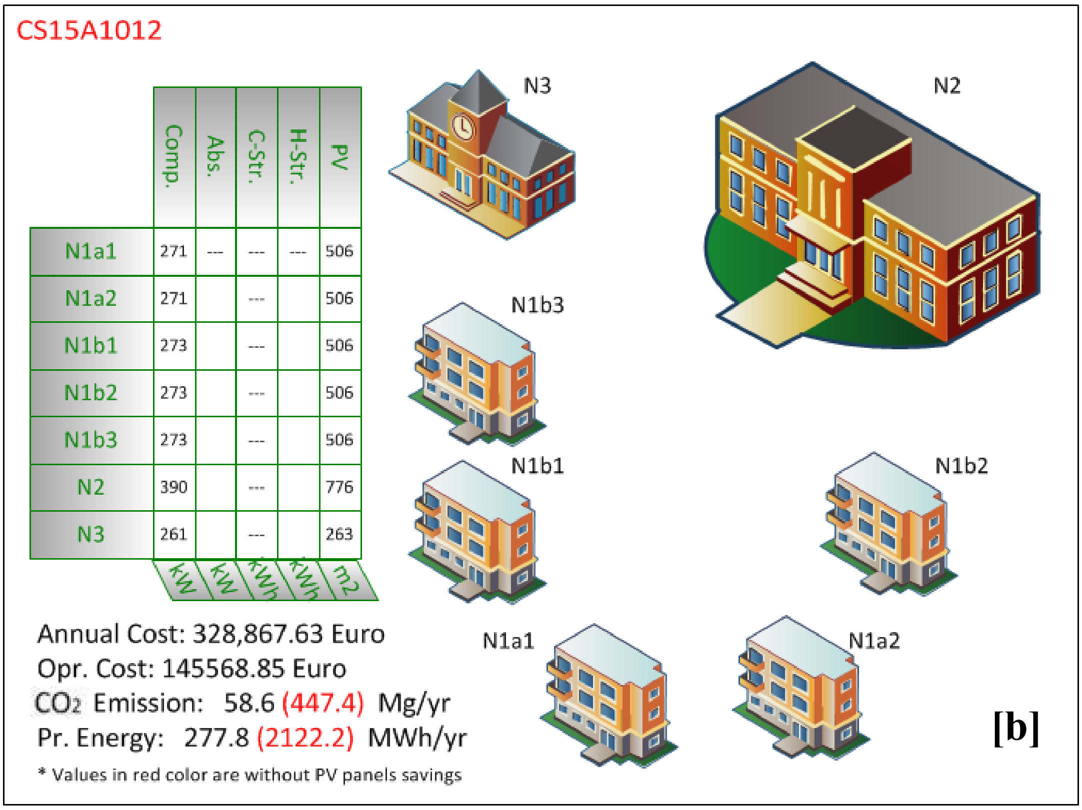
It was noticed that the sub-scenarios with COP values of 6 and 7 (CS25A0013 & CS25A0014) had negative values for the total annual emitted CO_2. This is due to the amount of CO_2 emission avoided by implementing PV-panels into the system. This means that these two scenarios have environment friendly cooling systems.

Figure 4.73 shows the total annual cost and annual CO2 emissions obtained for the investigated sub-scenarios with COP values of 3, 4, 5, 6 and 7 for both cost and CO2 optimization objectives. Changing the optimization objective had a significant impact on the total annual cost. However, it did not have any impact on the CO2 emissions. This is due to the simplifications implemented in the model where the COP was assumed to be fixed and no energy loses from the storage tanks were considered. As a consequence, as long as no DC network is installed, the mount of primary energy consumption and thus CO2 emissions would be the same for the same total sum of cooling energy demand regardless of the number and capacities of chillers and storage tanks installed as long as these assumptions are maintained.

The values of percentage decrease in the total annual cost and CO_2 emissions of these systems in reference to the COP=3 sub-scenario are presented in Figure 4.74. Adopting a compression chiller with COP=7 instead of 3 can cause a 31% reduction in the total annual cost under CO_2 emission optimization and 35% reduction under cost optimization objective.



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1a1	271	---	---	---	506
N1a2	271		---		506
N1b1	273		---		506
N1b2	273		---		506
N1b3	273		---		506
N2	390		---		776
N3	261		---		263



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1a1	271	---	---	---	506
N1a2	271		---		506
N1b1	273		---		506
N1b2	273		---		506
N1b3	273		---		506
N2	390		---		776
N3	261		---		263

Figure 4.71: CO_2 emissions optimization with: a) Compression chiller COP=4 and, b) Compression chiller COP=5.

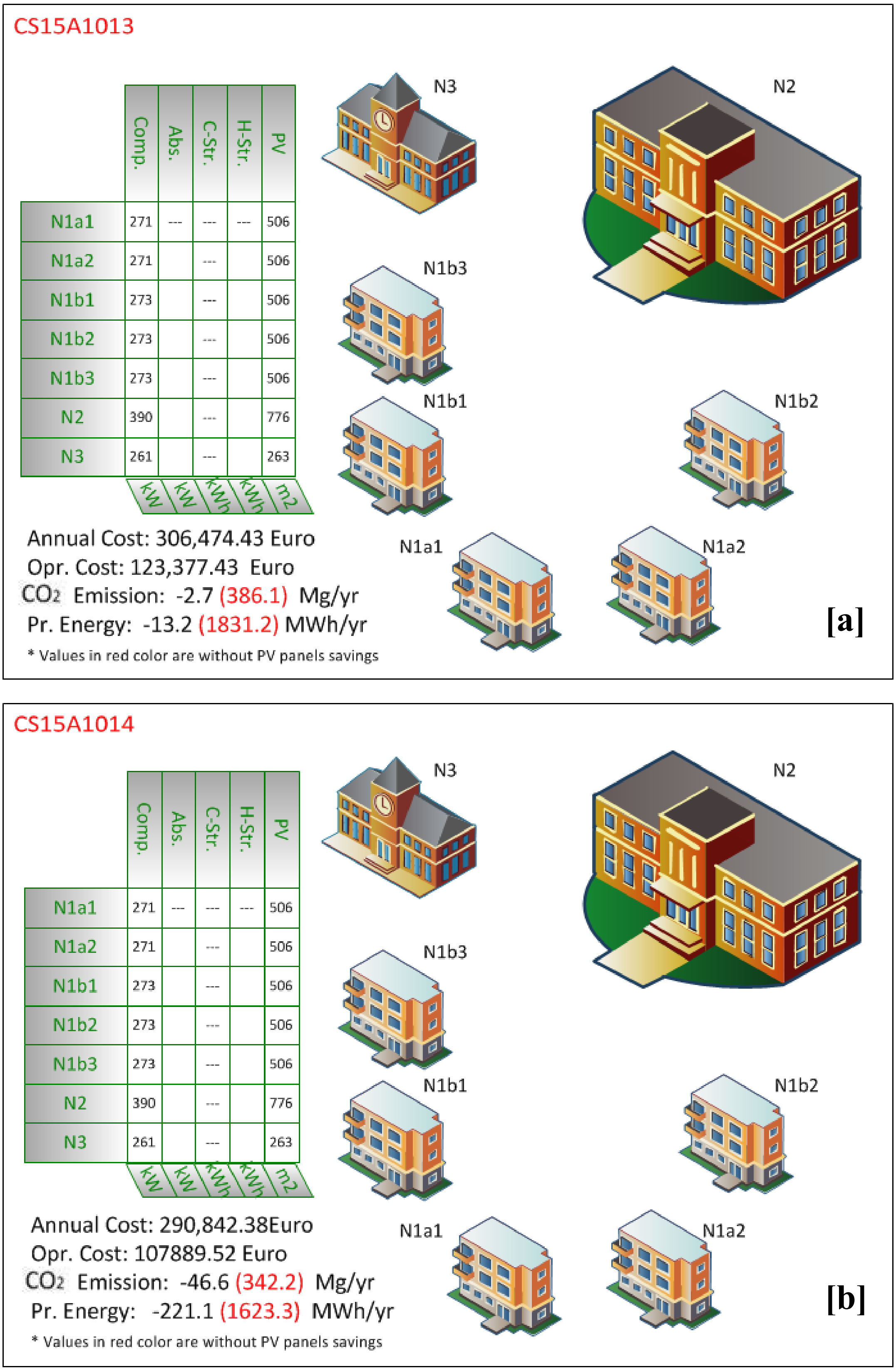


Figure 4.72: CO_2 emissions optimization with: a) Compression chiller COP=6 and, b) Compression chiller COP=7.

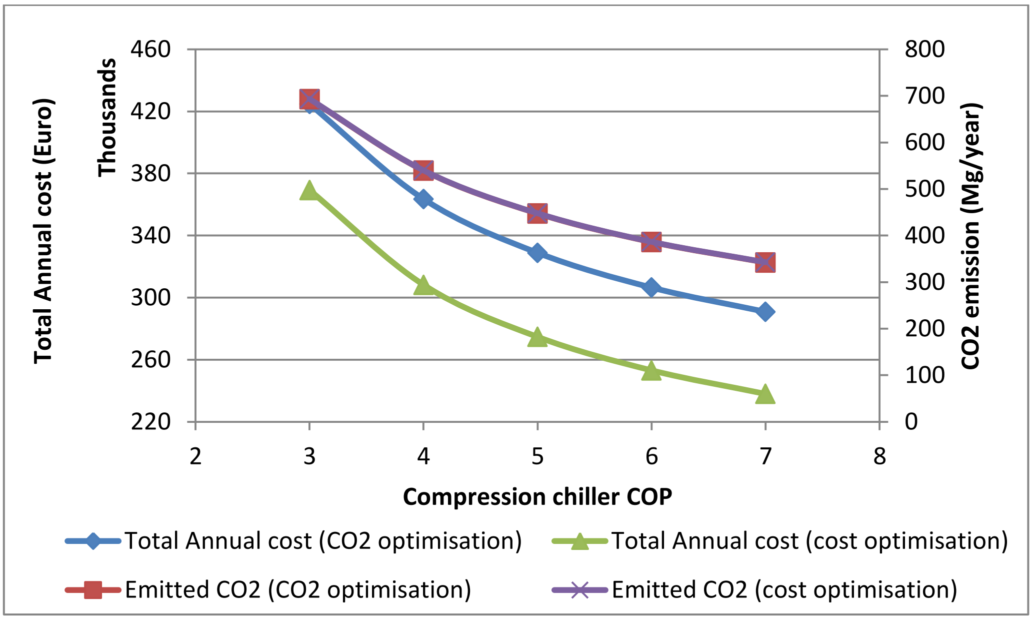


Figure 4.73: Total annual cost and CO_2 emission (without avoided CO_2 by PV panels) obtained for the COP sensitivity analysis for both cost and CO_2 emissions minimization objectives.

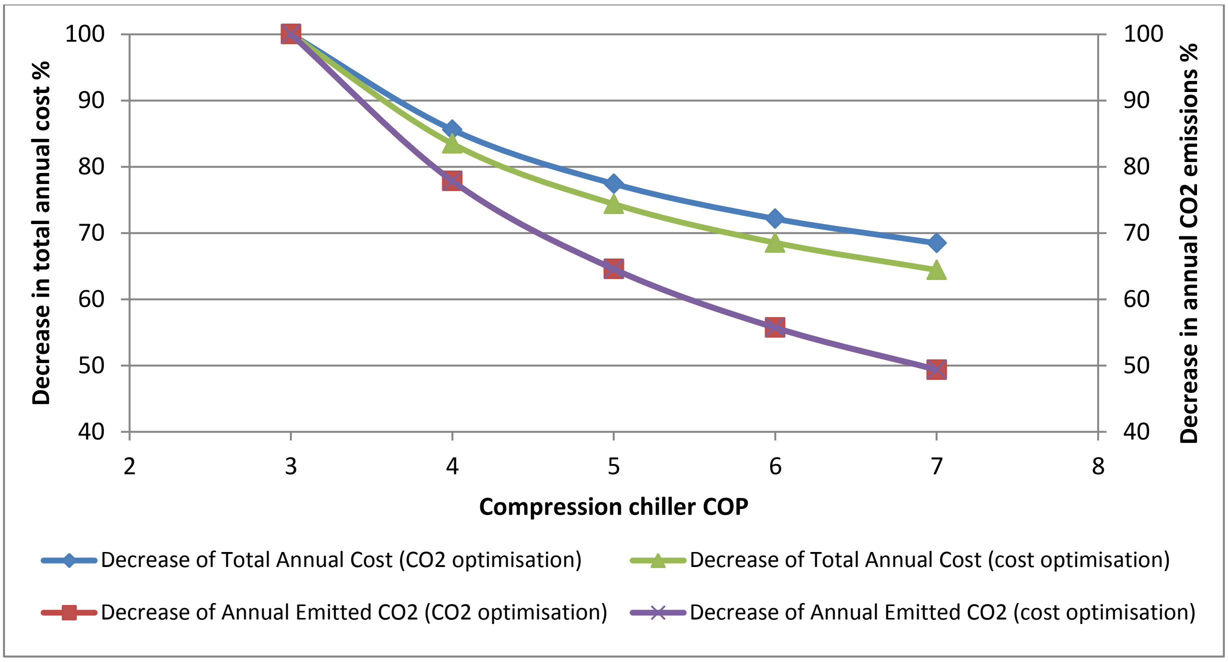


Figure 4.74: Reduction in total annual cost and CO_2 emission obtained for the different COP sub-scenarios with minimizing CO_2 as the objective in reference to COP=3 sub-scenario.

4.4.1.2 Variable COP model

Since it was concluded that changing the objective function into optimizing the CO_2 rather than cost did not affect the amount of emitted CO_2 due to the fixed COP assumption and the absence of DC network, investigation was carried out with a variable COP model. The same model and COP variation pattern used in section 4.3.6, was adopted here. The same three values of compression chiller COPs were introduced according to the chiller capacity as presented in Figure 4.54. The higher chiller capacity chosen by the model the higher COP implemented which would lead to less CO_2 emissions.

Figure 4.75 shows the obtained system by the variable COP model with CO_2 minimization objective. Although the amount of CO_2 emissions was reduced in comparison to the variable COP reference scenario under cost optimization objective, i.e CS13A3010 presented in Figure 4.55a, it was the same amount of emissions obtained by the fixed COP model at COP=7 as shown in Figure 4.76. This is due to the obtained individual systems where each building has been provided with a separated individual chiller with a capacity of 1000 kW to ensure maximum COP possible in the model. These high chiller sizes are considered as oversizing of the system in order to benefit from higher values of COP as explained previously in section (4.3.6.1). Such oversizing attitude is expected in a CO_2 optimization model since that the additional cost of installing bigger chillers do not influence the CO_2 objective function.

Although, installing DC network pipelines would not result in significant extra CO_2 emissions, no DC network was installed because operating this network would result some CO_2 emission due to energy consumption for pumping the cold water throughout the network. In general, it is concluded that optimizing the de-centralized DC system with a variable COP model under CO_2 objective function would result in obtaining as much high capacity as possible for the chillers to secure a higher COP and that such oversizing would eliminate the need of installing storage tanks or DC networks.

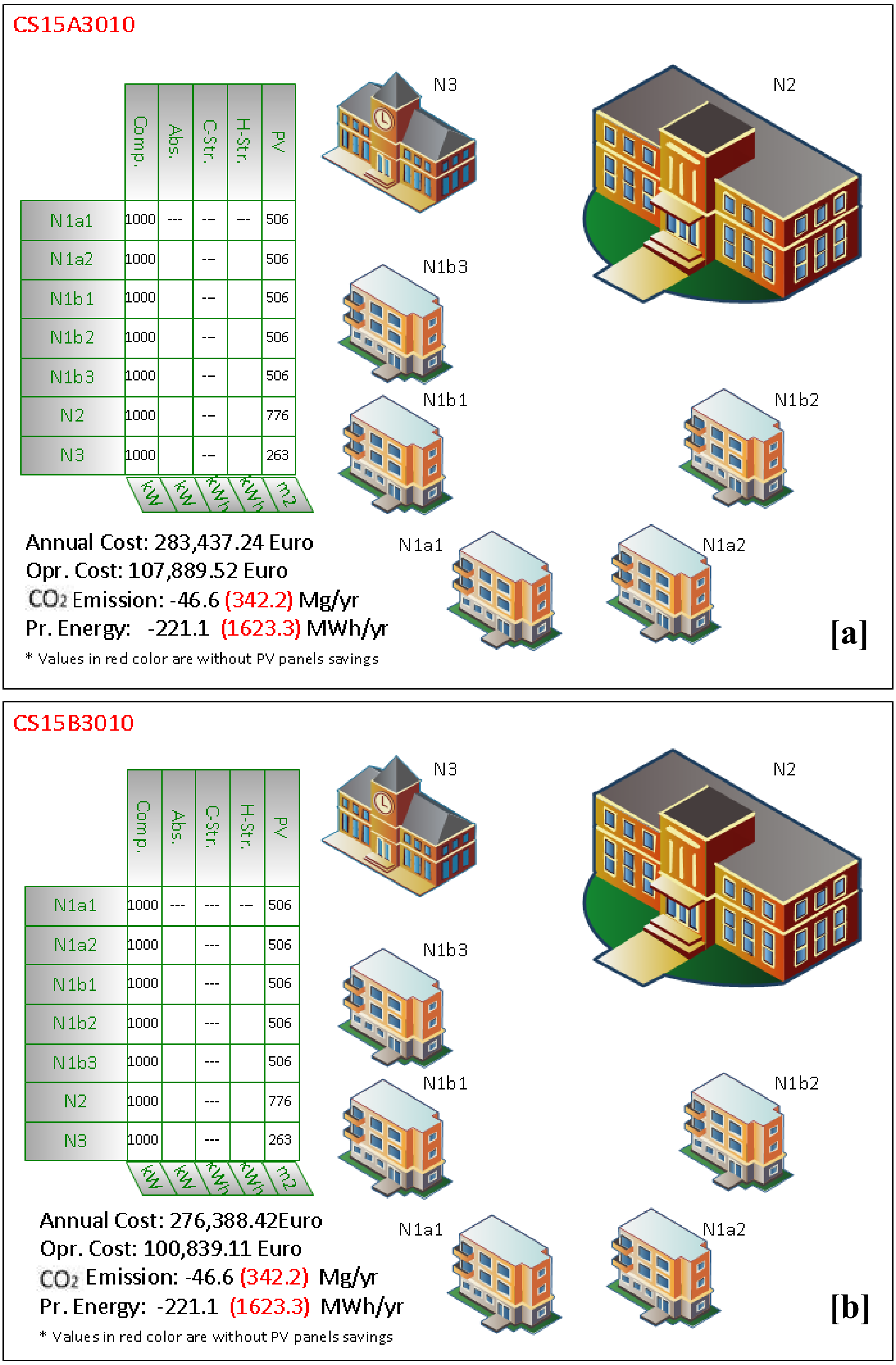


Figure 4.75: CO_2 emissions optimization for a de-centralized DC reference system with variable COP model for: a) electricity tariff A, and b) electricity tariff B

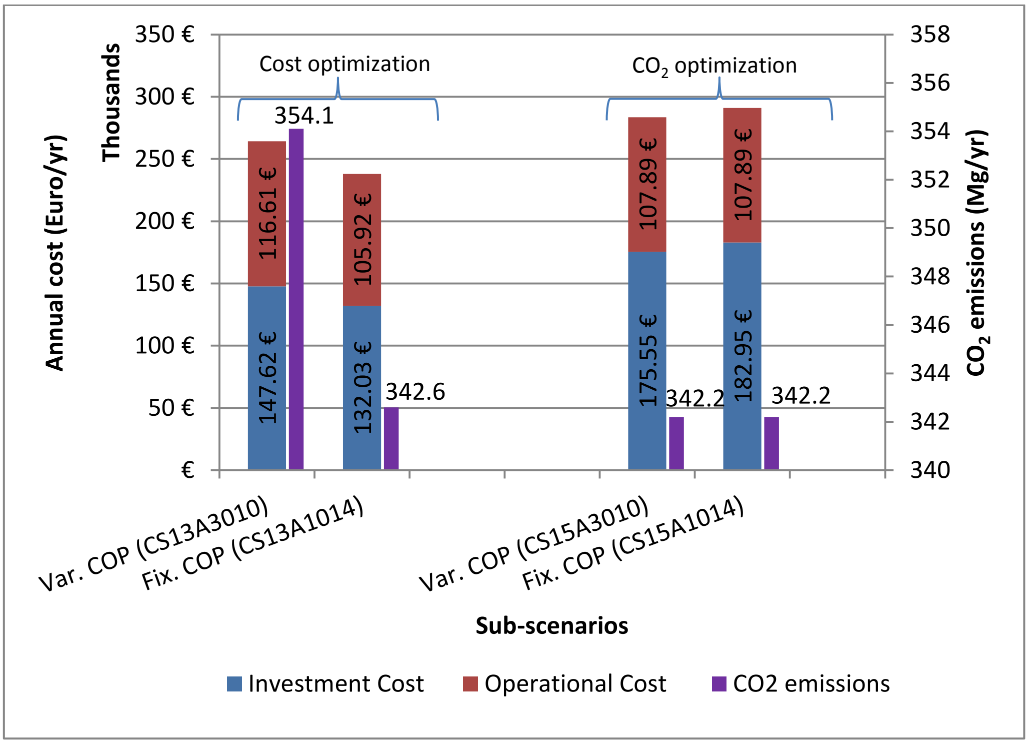


Figure 4.76: Investment and Operational costs and CO_2 emissions for the variable COP and fixed COP (at COP=7) models for both total costs and CO_2 emissions optimization objectives.

4.4.2 Centralized DC system

After the results and conclusions obtained from optimizing the case study for a de-centralized DC system with a CO_2 minimization objective, it was necessary to investigate optimizing the case study for a centralized DC system for comparison and conclusion validation purposes. The centralized DC system was imposed by limiting the number of chillers to be installed to one chiller. The model was free to choose the location and capacity of the central chiller.

Figure 4.77 shows the obtained centralized DC system by the variable COP model with CO2 minimization objective. As it was expected, forcing the model to obtain a centralized system, i.e. CS15A4010, has increased the total annual CO2 emissions in comparison to the variable COP reference scenario CS15A3010, i.e. Figure 4.75. These additional CO2 emissions are results of implementing and operating the DC network. However, the obtained total annual costs were very close to each other as presented in Figure 4.78.

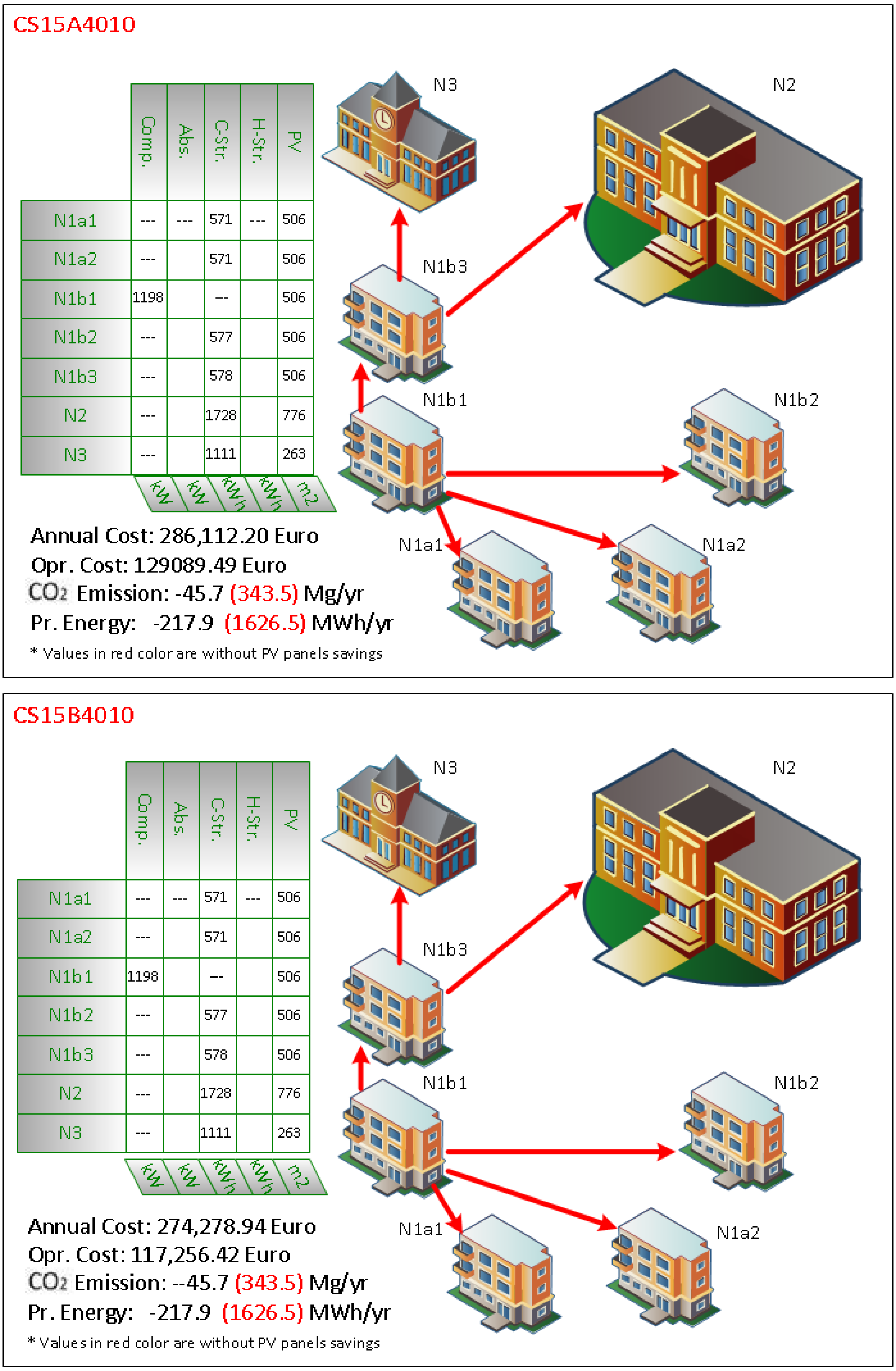


Figure 4.77: CO_2 emissions optimization for a centralized DC system with variable COP model for: a) electricity tariff A, and b) electricity tariff B

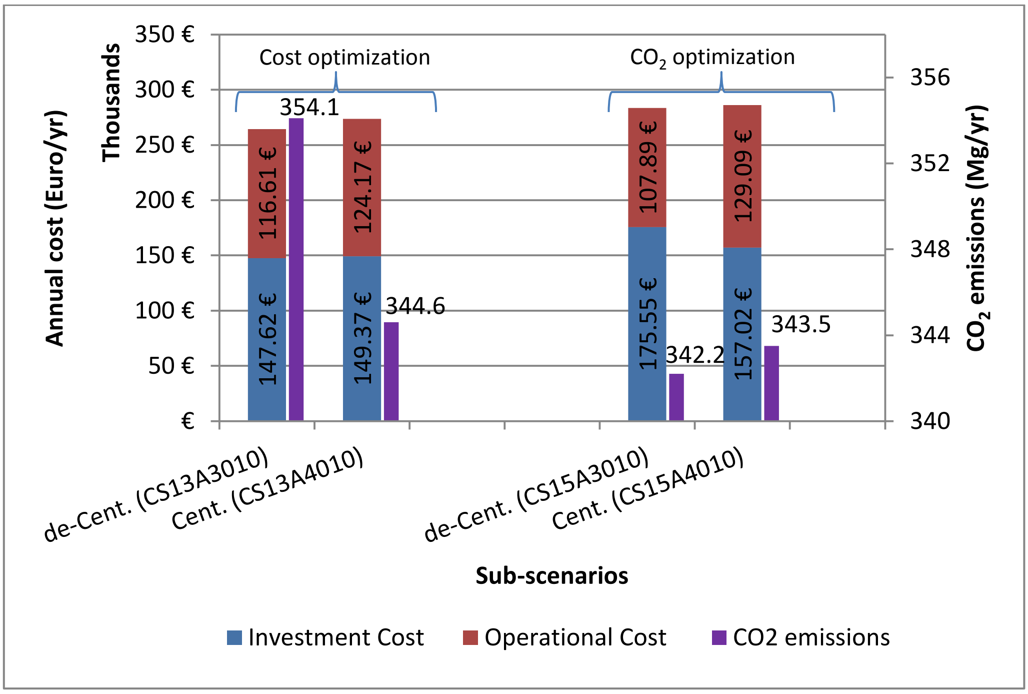


Figure 4.78: Investment and Operational costs and CO_2 emissions for centralized and de-centralized DCS obtained with variable COP model for both total costs and CO_2 emissions optimization objectives.

Observing the obtained centralized system, we notice that the size of the central chiller is above 1000 kW, above the minimum capacity required to achieve the highest COP, which eliminates the oversizing phenomenon. However, the adopted DC network was a point of interest where the adopted pipelines were connecting the central production plant to several buildings in a form of a star network rather than connect each building to the one next to it. This is because the length of the pipeline has not so much of a significant impact on the CO_2 optimization objective. Rather it is amount of the energy flow rate being transmitted throughout the pipeline that can cause additional CO_2 emissions. Therefore, the model has selected a network of direct narrow pipelines in a star form, regardless of pipeline lengths, and equipped every building with a storage tank to ensure minimum cooling energy transmission through the DC pipelines. It is logical that such a system would have higher investment and operational cost than the DC network obtained for the centralized system with cost optimization objective, i.e. CS13A4010 presented in Figure 4.59. A cost and CO_2 emissions comparison between the systems obtained at both objective functions is demonstrated in Figure 4.78. In this comparison, there are two very important observations:

- The cost deference between the centralized and de-centralized systems is so low (3.5% increase for the cost objective function and less than 1% increase for the CO_2 emissions objective function). This validates the previous conclusion obtained in this work that optimized centralized DC systems do not cost that much higher than optimized de-centralized systems. That slight increase in total annual cost can be easily deemed as reasonable in return of all the benefits that centralized DC systems offer such as higher operating reliability and availability, higher energy efficiency, lower maintenance costs, lower construction cost of buildings, and a more environment friendly impact.

- The deference in CO_2 emissions between the centralized and de-centralized systems gives another insight. The CO_2 emissions level for the centralized DC systems under the two objective functions were almost the same. However, they were not that far from the de-centralized systems levels. Deciding for centralized DC system has lowered the total annual CO_2 emissions by 2.8% within the cost optimization objective function, yet caused an increase of 0.4% within the CO_2 emission optimization objective function. Such a low impact of choosing centralized systems can be explained by that the comparison is being carried out against optimized systems, which in this case study happened to be de-centralized DC system. Most statistical studies and reports in the literature has reported that centralized DC systems can reduces CO_2 emissions by high margins because they were comparing it to un-optimized conventional cooling systems, often distributed stand-alone systems, which are known for having high energy consumption rates. In fact, these results lead to the conclusion that investing in centralized DC systems will automatically reduce CO_2 emissions even when optimizing annual cost is the objective.

- More importantly, the highest possible reduction in CO_2 emission when optimizing de-centralized DC system under CO_2 emission objective function, i.e. CS15A3010 which is supposed to present the lowest emissions level possible, has a value of 3.3% only when compared to the de-centralized DC system obtained within cost optimization objective function, i.e. C13A3010. This indicates that optimizing this case study under reducing CO_2 emissions objective does not achieve a significant impact. Again, this is because the cost optimizing process already includes reducing operational cost by lowering the amount of primary energy being consumed. Such a low impact of the second objective function raises question regarding its role in the multi objective optimization stage and whether such a stage is actually needed or reasonable.

4.5 Multi-Objective Optimization: Annual Cost and CO_2 Emissions

The main goal of this work is to provide decision makers with a tool that assist them in obtaining preliminary design configuration and operation strategies for district cooling energy systems based on multi objective optimization considering both environmental and economic aspects. Single objective optimizations have been carried out for both total annual cost and CO_2 emissions objectives in two separated optimization stages. The results obtained at the second stage have raised questions regarding whether such a stage is actually needed or reasonable to be considered at decision making process. In the third stage the tool will be upgraded into multi objective optimization model by combining both total annual cost and CO_2 emissions objectives into one objective function. At this stage of the investigation the same assumptions adopted in both cost and CO_2 emission optimizations were adopted as well. Most importantly, COPs were considered constant in regards to the partial load and outdoor temperature variation however the investigation was carried out with the variable COP model, in regards to the chiller size, only. Investigations were performed for de-centralized DC systems for both electricity tariffs A and B. The purpose of this stage is to investigate the impact of combining the two objectives on optimized solutions. A much more detailed investigation concerning multi objective optimization is to be carried out in the second case study investigated within the scope of this work. The combination of the two objectives has been performed by adopting the Normalized Weighted Sum method where the two contradicting objective functions were turned into a one normalized objective function by means of normalizing weights, as demonstrated in eq. (3.88):

$$Z_{Multi} = W_C \, . Z_C + W_{CO2} \, . Z_{CO2} \qquad \text{Eq. (3.88)}$$

These weights were calculated in correlation with the difference between each objectives magnitude when the other objective is minimized (also known as Nadir value Z^N) and each objectives minimum value when optimized alone (Utopia value Z^U):

$$W_C = U_C \cdot \frac{1}{Z_C^N - Z_C^U}$$

$$W_{CO2} = U_{CO2} \cdot \frac{1}{Z_{CO2}^N - Z_{CO2}^U}$$

Where U_C and U_{CO2} are importance weights assigned by the decision maker according to the importance of each objective in the decision making process. Table 4.24 shows the Nadir and Utopia value obtained at each single objective optimization.

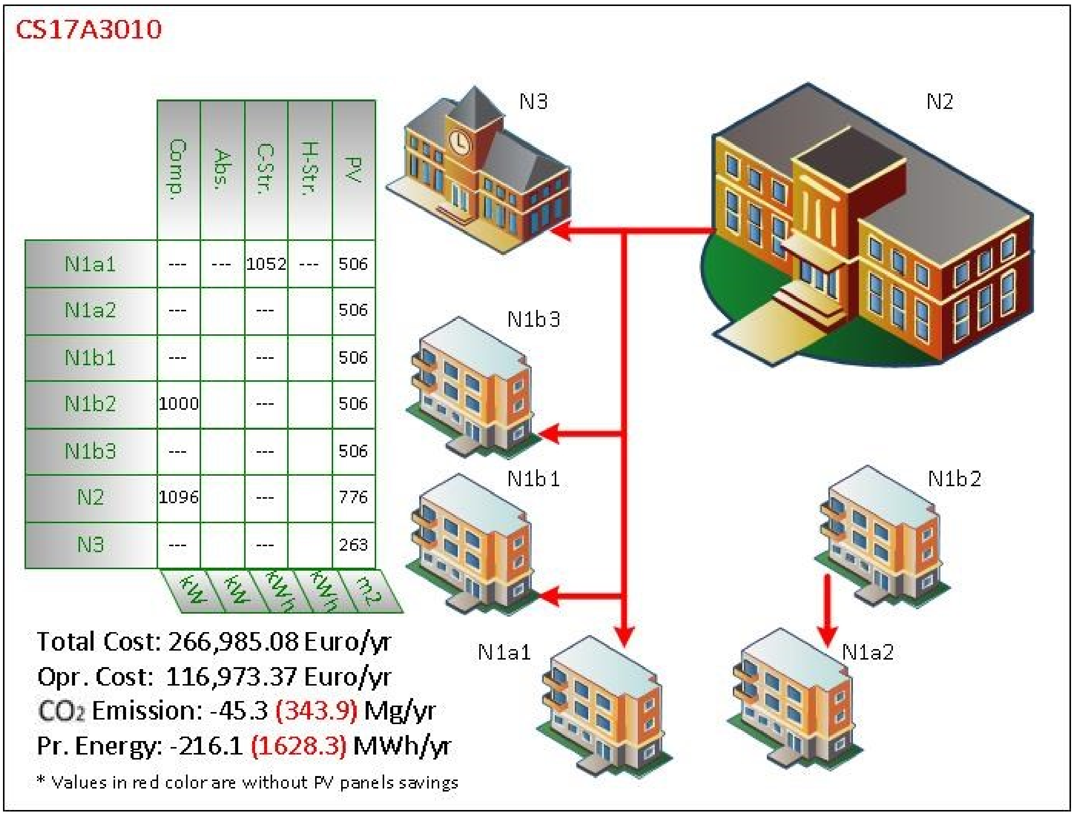
Table 4.24: Nadir and Utopia values obtained at each single objective optimization for the de-centralized DC systems in case study 1.

Single objective optimization		Total annual cost (Euro/yr)	Total annual CO_2 emission (Ton/yr)
Total annual cost objective	CS13A3010	Z_C^U = 264,229.32	Z_{CO2}^N = -35.1
	CS13B3010	Z_C^U = 256,542.61	Z_{CO2}^N = -45.9
CO_2 emission objective	CS15A5010	Z_C^N = 283,437.24	Z_{CO2}^U = -46.6
	CS15B5010	Z_C^N = 276,388.42	Z_{CO2}^U = -46.6

The Utopia and Nadir values of the single objective optimization scenarios represent the far limits, i.e. best results, one can obtain in regards to that particular objective. Any obtained system under multi-objective optimization would be somewhere between these two far limits. These two far limits along with a certain number of multi objective optimization scenarios can give a clear imagination of Pareto Frontier. Based on several importance weights assigned by decision makers, a group of Pareto solutions can be obtained. Generating Pareto solutions is an objective task that seeks to objectively generate Pareto points in the design space regardless of their desirability. On the other hand, selecting a specific Pareto solution is a subjective task that depends extremely on the decision maker preferences. Since that the (Nadir-Utopia) gap is not so big for both objectives, only one multi objective scenario, with importance weights of (1-1), was investigated. The aim is to see the impact that considering both objectives together in a multi objective optimization would have on each single objective solution.

The Utopia and Nadir values, presented in Table 4.24, give a good overview about possible enhancement on both objectives. The gap between the two values for the CO2 objective is 11.5 ton/year for electricity tariff A and 0.7 ton/year for electricity tariff B. This gap represent the maximum possible enhancement in CO_2 emissions which can only be achieved when the optimization is completely shifted from optimizing merely annual cost to optimizing CO_2 emissions only. Similarly, the gap in the Utopia and Nadir values for the annual cost at each electricity tariff, which is 19207.92 and 19845.81 Euro/year, respectively, represent the maximum possible enhancement in annual cost that can only be achieved when the optimization is completely shifted from optimizing merely CO_2 emissions to optimizing annual cost only. Figure 4.79 shows the obtained solution for de-centralized DC systems at multi objective optimization with (1-1) importance weights. Observing these DC systems confirms the expectations that a multi objective optimization solution will be somewhere between the two single objective optimization scenarios. The obtained DC system when optimizing CO_2 emissions, i.e. Figure 4.75, consist of separated over-sized individual systems at each building, whereas the obtained system at the annual cost optimization, i.e. Figure 4.55, contains a de-centralized DC network. The obtained system under multi-objective optimization was somewhere between these two options where de-centralized DC was implemented while the phenomena of oversizing some chillers was preserved for certain buildings. Figure 4.80 presents the total annual costs and CO_2 emissions of the multi objective scenario. The value of the two objectives lay between the Nadir and Utopia values of the two objectives. Pareto Frontier can be obtained by adopting CO_2 emissions as X-axis and annual cost as Y-axis as demonstrated in Figure 4.81. All solutions lying on the Pareto Frontier are known as non-dominated solutions where no enhancement to one of the objectives is possible without harming the other objectives. Solutions in the area to the right-upper side of Pareto frontier are known as dominated solutions. It is not possible to obtain any solution at the left-lower side of Pareto Frontier in reality.

The gap between the Nadir and Utopia values for this case study was relatively small, 0-3% of the Utopia value for CO_2 emissions objective and about 7-8% of the Utopia value for the total annual cost objective. Adopting a multi objective optimization with importance weights of (1-1) has reduced the Nadir-Utopia gap of the CO2 emissions and total cost objectives by around 88 and 85%, respectively at the electricity tariff A investigations. The reduction the Nadir-Utopia gaps for both objectives at electricity tariff B were around 57 and 70%, respectively. Thus, the total annual cost and CO2 emissions of the obtained solution were very close to the Utopia values of both objectives. This indicates that decision makers can avoid a significant loss both economically and environmentally if multi objective optimization is to be adopted.



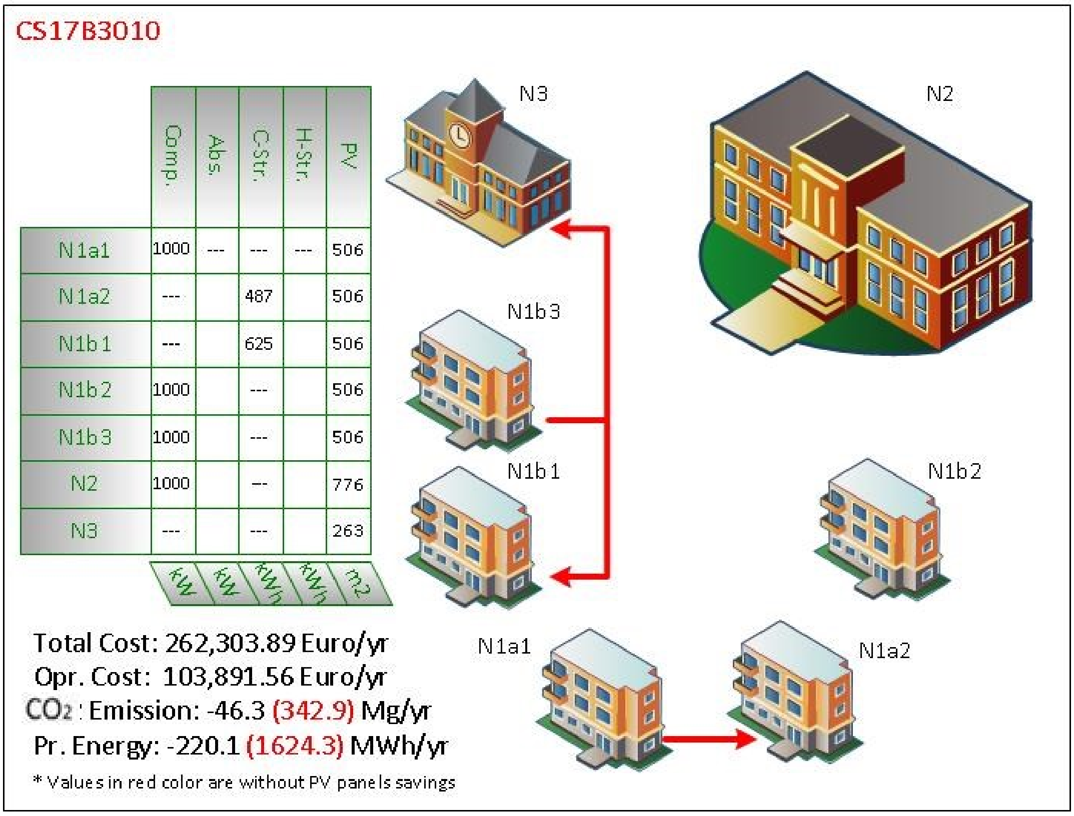


Figure 4.79: De-centralized DC network scenario at Multi objective (cost 1-1 CO_2) optimization stage for case study 1 with electricity tariffs A and B.

This multi objective investigation can be expanded into several importance weights allowing decision makers more options and more flexibility in the decision making process. However, since that the Nadir-Utopia gaps for both objectives were relatively small, and since that the (1-1) weights scenario has managed to reduce both Nadir-Utopia gaps with significant margins already, deciding to be content with this solution as a final choice is recommended. A detailed multi objective optimization investigation a long with a decision making approach are presented in the next chapter.

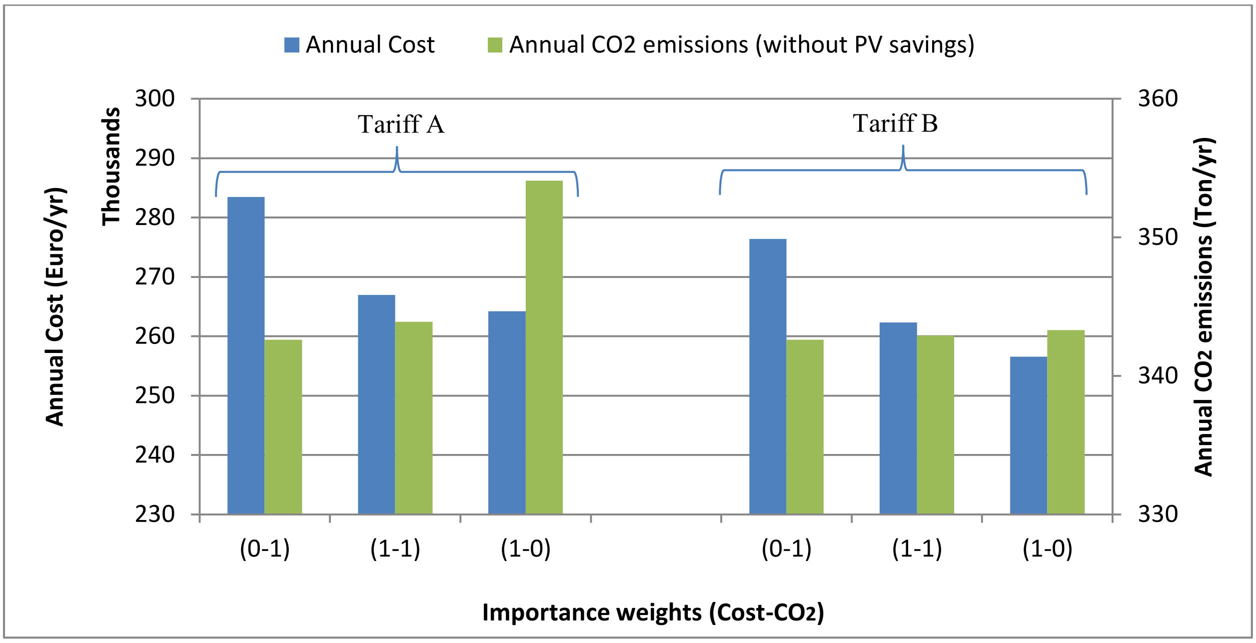


Figure 4.80: Annual cost and CO2 emissions for the multi objectives de-centralized & centralized DC scenarios at different importance weights for case study 2

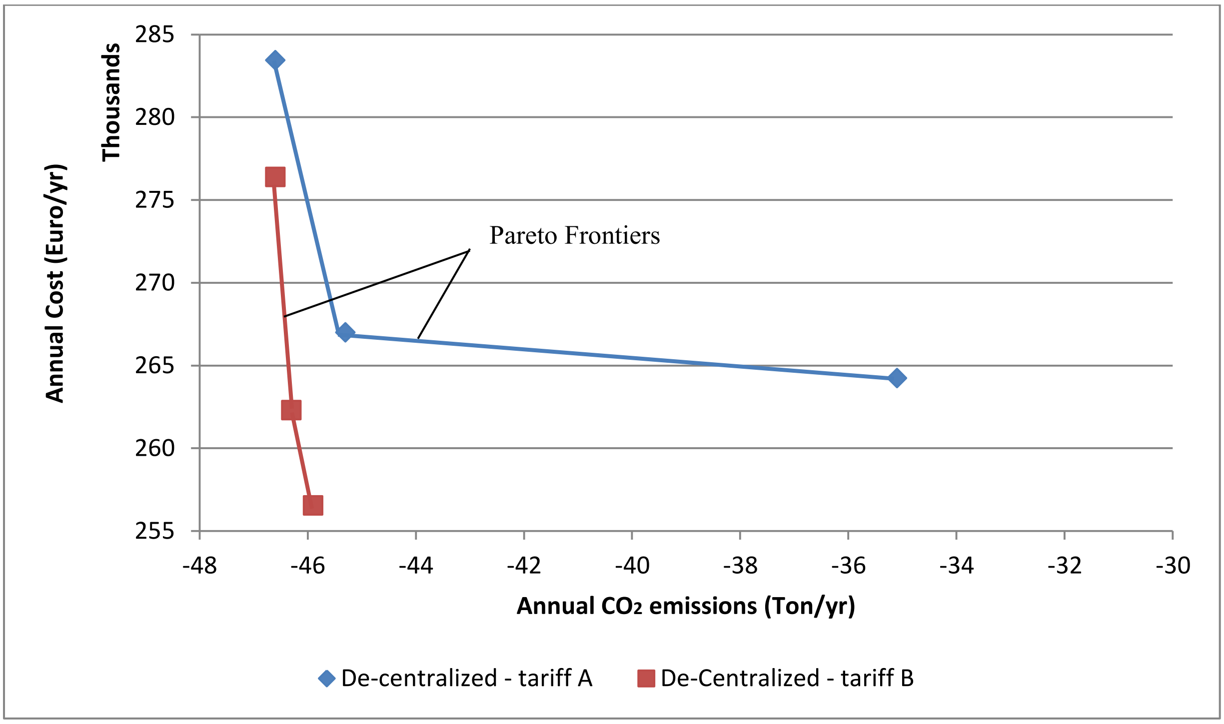


Figure 4.81: Pareto Frontiers for De-centralized DC systems for case study 1.

4.6 Summary

A small area was chosen out of a prospective planned residential district in a hot climate region as the first case study in this work. The selected district includes seven buildings where two of them were public none-residential buildings, a school and a town council while the other five buildings were multi-residents apartments with almost identical cooling load profiles. Detailed description of the chosen district including building characteristics and the cooling load profiles of the buildings is presented. A criterion for selecting representative days for each building was developed. An optimization approach consisting of three stages was introduced with total annual cost and CO2 emissions being the first two single objective optimization stages. The third stage was a multi objective optimization combining the two single objectives.

The developed optimization model went through a major upgrade throughout the investigation. At first, a constant COP model for the compression chillers was adopted. Later on, a variable COP model depending on the chiller size was introduced. The investigation examined the possibility of implementing both Centralized and De-centralized DC systems. The study was carried out for several groups of scenarios; each of them being analyzed for the sensitivity of the optimal solution toward a certain design parameter or operation conditions including: Available area, Production plant location, Cold storage location Constraints, Piping prices, Investment cost, Constant and variable electricity tariffs, Waste heat availability, Load shifting strategies, and the Effect of outdoor temperature in hot regions on the DC system performance.

The results obtained for several scenarios within the case study have showed that the results were highly affected by the type of the buildings in general and their occupation pattern in particular. It was noted that the well-known strategy of installing relatively small chiller capacity, e.g. 60 or 70 % of the peak load, accompanied with storage tanks is more desired at non-residential buildings due to the several zero load hours such buildings usually have in their load profile. It was noticed that compression chillers come ahead of absorption chillers in terms of both investment and operational costs for the market prices provided in the case studies investigated. However, there are other sufficient cases where absorption chillers might be a cost-effective solution such as when electricity prices are high and fuel can be provided at adequate prices or when sufficient amount of waste heat is available. Moreover, constant COP investigations have concluded that carrying out preliminary DCS design investigation with the simplification of assuming constant COPs for the compression chillers would overlook one of the major advances of DC that is high capacity chillers operate with higher COP than stand-alone systems. Adopting several values for chiller COP depending on the chiller capacity has lowered the total annual cost of the fully centralized DC systems by around 35% for both electricity tariffs and made adopting DC network a favorable option.

It was found that operation cost has a higher impact on the optimization process and, consequently, the resulting cooling system designs. In fact, optimizing the investment cost alone causes an increase of around 20% in the total cost. Therefore, making decisions based on optimizing investment cost only is not recommended.

Investigating load shifting strategy has showed that optimized DCS systems can be adapted to operate with load shifting strategy, even if they were not designed to, with relatively low additional costs. Noting that Centralized DC systems require much less modifications than de-centralized DC systems. On the other hand, investigating the outdoor temperature effect on chiller performance has showed that it is very crucial for decision makers to count for this effect where it cause up to 50% increase in total annual cost. However, it was found that some simple, but expensive, modification on the reference scenario, such as replacing the storage tanks with bigger ones, is sufficient to adapt the system to operate with the effect especially for the Centralized DC systems which have shown more flexibility and reliability in dealing with this phenomenon. In addition, adopting load shaving strategies can serve effectively to deal with effect of high ambient temperature in hot climate regions for non-residential buildings. However, residential buildings might require different measure to deal with the phenomenon. As a general conclusion for choosing compression chiller capacity when designing under outdoor temperature effect in a hot climate, it is recommended to choose:

a. For residential buildings: A chiller capacity that covers around 70% of the peak load of the building at constant electricity tariff. This capacity may be changed significantly when the electricity tariff is variable depending on the tariffs amplitude and at which hours of the day does the electricity price drop.
b. For none-residential buildings: A chiller capacity that covers around 50% of the peak load of the building within both electricity tariffs. However, individual cost investigation for each building is recommended especially for building with high peak cooling load.

It was noticed that the two objective functions, i.e. total annual cost and annual CO_2 emissions, had a close influence on the optimization process. Both objectives seek to reduce the amount of primary energy consumed by adopting the highest COP possible and reducing the amount of operation hours as much as possible. Thus, optimizing the system under one of the objectives would automatically improve the other one. For example, adopting a compression chiller with COP=7 instead of 3 can cause a 31% reduction in the total annual cost under CO2 emission optimization and 35% reduction under cost optimization objective and in the same time achieving the same amount of minimal annual emitted CO_2 at both objectives. Analyzing the obtained annual cost and CO_2 emissions at both single objective optimizations for this case study has led to some important observations:

a. Optimized centralized DC systems cost slightly higher than optimized de-centralized systems. This slight increase in total annual cost can be easily deemed as reasonable in return of all the benefits that centralized DC systems offer such as higher operating reliability and availability, higher energy efficiency, lower maintenance costs, lower construction cost of buildings, and a more environment friendly impact.
b. The CO_2 emissions level for the centralized DC systems under the two objective functions were almost the same. However, they were not that far from the de-centralized systems levels. These results lead to the conclusion that investing in centralized DC systems will automatically reduce CO_2 emissions even when optimizing annual cost is the objective.
c. Optimizing the first case study under reducing CO_2 emissions objective did not achieve a significant impact in compare to cost optimization reference scenario. This is due to that cost optimizing process already includes reducing operational cost by lowering the amount of primary energy being consumed.

Observing the obtained DC systems at the single objective optimizations and their Utopia and Nadir values can provide a sufficient help for decision makers. The gap between the Nadir and Utopia values for this case study was relatively small, 0-3% of the Utopia value for CO_2 emissions objective and about 7-8% of the Utopia value for the total annual cost objective. Adopting a multi objective optimization with importance weights of (1-1) has reduced the Nadir-Utopia gap of the CO2 emissions and total cost objectives by around 88 and 85%, respectively at the electricity tariff A investigations. The reduction the Nadir-Utopia gaps for both objectives at electricity tariff B were around 57 and 70%, respectively. Thus, the total annual cost and CO2 emissions of the obtained solution were very close to the Utopia values of both objectives. This indicates that decision makers can avoid a significant loss both economically and environmentally if multi objective optimization is to be adopted. This multi objective investigation can be expanded into several importance weights allowing decision makers more options and more flexibility in the decision making process. However, since that the Nadir-Utopia gaps for both objectives were relatively small, and since that the (1-1) weights scenario has managed to reduce both Nadir-Utopia gaps with significant margins already, deciding to be content with the (1-1) solution as a final choice was recommended.

Chapter Five

Case Study II

Chapter Five

Case Study II

5.1 Introduction

Through observing and analyzing optimized systems obtained at the various scenarios for the first case study, shown in the previous chapter, it was concluded that the results obtained are highly affected by the type of the buildings in general and their occupation pattern in particular. As residential buildings were the dominant type of the buildings investigated within case study 1, it was obvious that there is a significant need to focus on optimizing a district dominated with office buildings and compare the obtained results in an attempt to further validate the obtained conclusions from the first case study. Thus, a university campus with dominantly office buildings was chosen to be investigated as case study 2 within this work. The chosen district consists of four buildings where three of them are university buildings, containing staff offices and lecture halls, and one student dormitory building. As in the first case study, several scenarios were investigated with some major assumptions to obtain optimized cooling systems taking into consideration changes in design parameters and operation conditions. More focus was paid in this case study on investigating scenarios that help further investigating or validating the results and conclusions obtained within case study 1 such as the effect of the PV connection strategy within the cooling system on the obtained location for the cooling energy production plant. Outdoor temperature effect was also investigated but within the multi criteria optimization stage.

In this chapter, section 5.2 presents a detail description of the second case study and the characteristics of the buildings along with their cooling load profiles. An overview to the optimization approach adopted is explained within this section as well. The results of the cost optimization and CO_2 emissions optimization are discussed in sections 5.3 and 5.4, respectively. Deeper focus investigating the multi objective optimization scenarios, that combine both cost and CO_2 objectives, is presented in section 5.5.

5.2 Overview of the case study

Although urban cities consist mostly of residential districts, it is logically understandable that newly established urban would contain many non-residential districts as well and for various utilizations. Common examples of such non-residential districts are: governmental compounds, multi-building hospitals, university campuses, commercial and industrial districts …etc. This kind of district is more likely to require a complete different approach when designing a cooling system for it. It was noticed, when investigating case study 1, that the existence of office buildings can have a great impact on the obtained optimized cooling system depending on the location, size, and cooling load profile of the building. In order to further validate these conclusions and investigate if a non-residential district would acquire similar solutions to those obtained for residential district, a part of a university campus was selected to be investigated as case study 2 in this work. The following sections offer a detailed description of the selected district, the cooling load profiles of the buildings and an explanation of the optimization approach.

5.2.1 Description of Selected District

Four buildings from a university campus, see Figure 5.1a, which is located in a hot climate region were selected. Three of the four chosen buildings represent the engineering departments of Mechanics (N1), electronics (N2) and Architecture (N3), respectively. These three university buildings consist majorly of staff offices, labors and lecture halls. The fourth building is a student's dormitory (N4). The selected buildings are presented in Figure 5.1b. The distances between the buildings in this case study are relatively big, in comparison to case study 1, and the peak cooling loads are in a range of 490-560 kW.

5.2.2 Buildings' occupation and cooling load profiles

The same cooling load profile estimation methodology used in case study 1 was used in case study 2 as well where each of the investigated buildings was assumed to have an amount of available area that can be used to install cooling system equipment and auxiliaries. The occupation pattern for the three non-residential buildings was assumed to be the same while the dormitory (N4) a quite different occupation pastern. Two of the non-residential buildings, N1 and N2, have a similar construction with a difference in the orientation. Table 5.1 shows the buildings' construction data, occupation profiles, lightening and other design assumptions. TRNSYS was used to simulate the four buildings in order to obtain their annual cooling load profile. Out of this annual cooling load profile, six days were chosen to represent the summer season, April-September, in the optimization process.

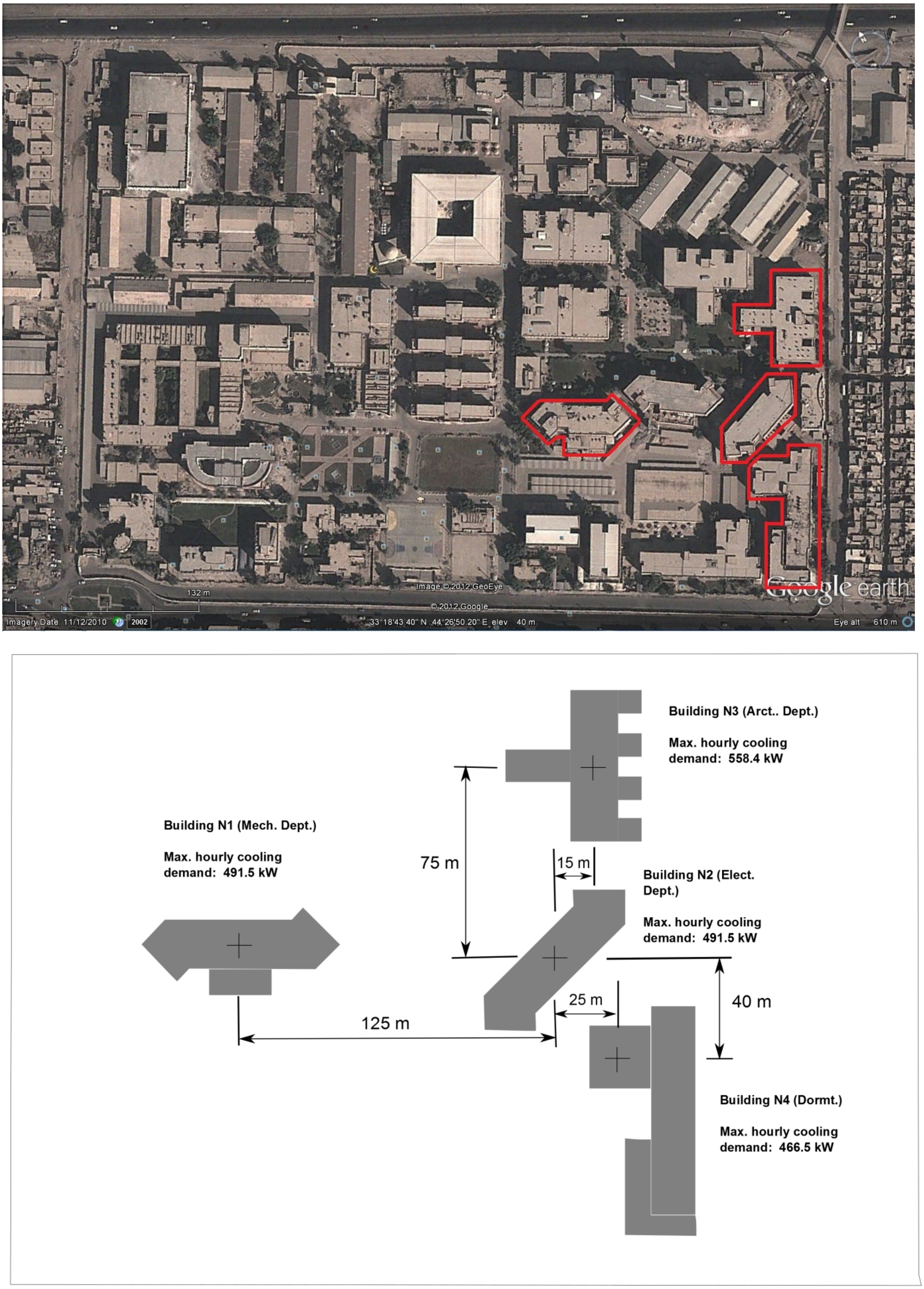


Figure 5.1: a) Map of university campus emphasizing the selected buildings to be investigated within case study 2; b) a schematic map for Case Study 2.

Table 5.1: Construction, occupation and design data of the buildings of case study 2.

Building name/code	N1	N2	N3	N4
Building type	None- residential Building	None-residential Building	None-residential Building	Residential Building
Floor Area	1,380 m^2	1,380 m^2	2,018 m^2	2,310 m^2
Building Height	14 m	14	14 m	12 m
Wall Orientation and Area	E, W = 238m^2 NE, SW = 700m^2 NW , SE = 35m^2 N, S = 210m^2	N, S = 700m^2 NE, SW = 238m^2 NW, SE = 210m^2	SE, NW = 840 m^2 NE, SW=1134 m^2	SE,NW=1140m^2 NE, SW=636 m^2
Total glass area percentage of the outside surface area	25.6 %	25.6 %	27 %	29.5 %
Max. number of occupants	1000	1000	1000	400
Occupancy schedule at week days	1000 P. (7 am - 3 pm)	1000 P. (7 am - 3 pm)	1000 P. (7 am - 3 pm)	400 Per. * (3 pm – 7 am)
Occupancy schedule at weekend days	0 P. (for 24 hours)	0 P. (for 24 hours)	0 P. (for 24 hours)	200 Per. (for 24 hours)
Ventilation	0.5 A-ch/hr (7 am - 3 pm)	0.5 A-ch/hr (7 am - 3 pm)	0.5 A-ch/hr (7 am - 3 pm)	0.5 A-ch/hr (for 24 hours)
Lightening	5 W/m^2	5 W/m^2	5 W/m^2	5 W/m^2
Infiltration	0.5 A-ch/hr	0.5 A-ch/hr	0.5 A-ch/hr	0.5 A-ch/hr
Computers, equipment & printers	300 devices (7 am - 3 pm)	300 devices (7 am - 3 pm)	300 devices (7 am - 3 pm)	500 devices * (3 pm – 7 am)
Cooling set temperature	24 ºC (7 am - 3 pm)	24 ºC (7 am - 3 pm)	24 ºC (7 am - 3 pm)	24 ºC (for 24 hours)

* These numbers are reduced to the half for N4 during the working hours (7 am - 3 pm) due to students attending lectures.

The selection of a representative day for each month was performed using the same method used for the first case study in the previous chapter. The Method is based on finding the best match of a daily cooling load profile within the month to the average cooling load profile of that month, by calculating the minimum sum of the hourly square difference between each day and the average cooling load profile of the month, as shown in Figure 5.2.

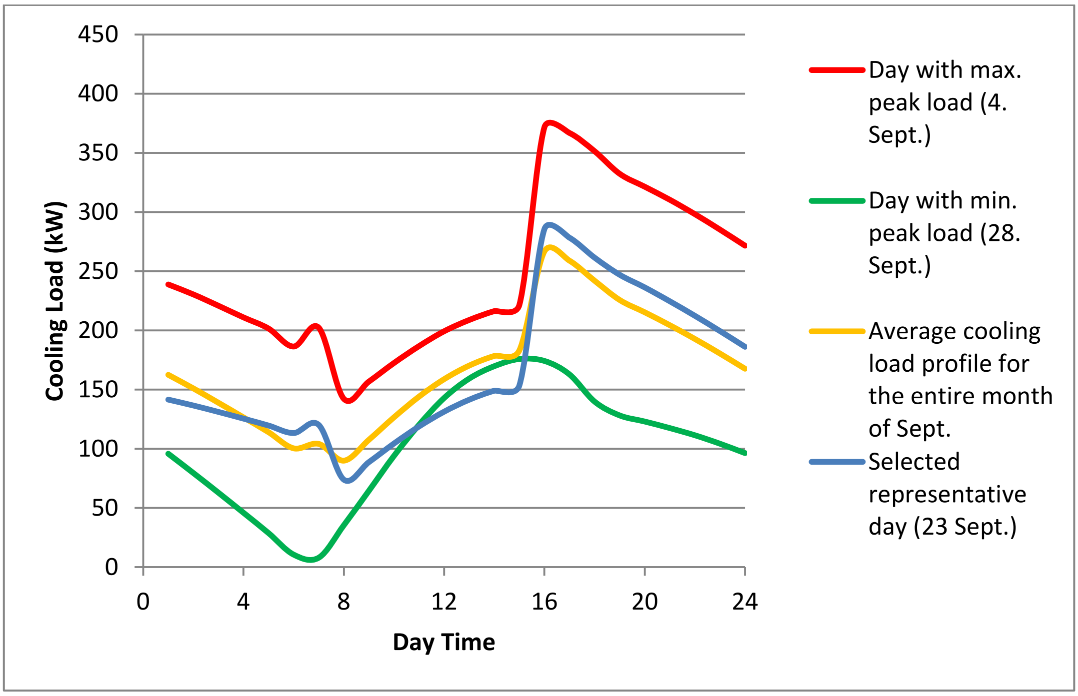


Figure 5.2: Selection of a representative day for September based on the minimum sum of square differences to the average cooling profile of the month

Figure 5.3 shows the estimated cooling load profiles for the four buildings (N1, N2, N3 and N4) at six representative days for each building. Building N2 has almost the same architectural construction and occupation pattern as Building N1. Therefore their cooling load profiles are almost identical with a peak cooling load of around 500 kW occurring in July. Building N3 had a slightly higher peak load with a value around 550 kW. The representative days of these buildings were chosen among the working days since their cooling loads at holidays are null. The remaining buildings (N4) is a residential building, student dormitory, and since that it was assumed that at least half of the occupants will be leaving the building during working hours 7:00am to 3:00pm, to attend the lectures, a significant drop down in its cooling load profile can be noticed during the working hours. Their peak cooling load of this building is estimated to be around 460 kW occurring in July as well.

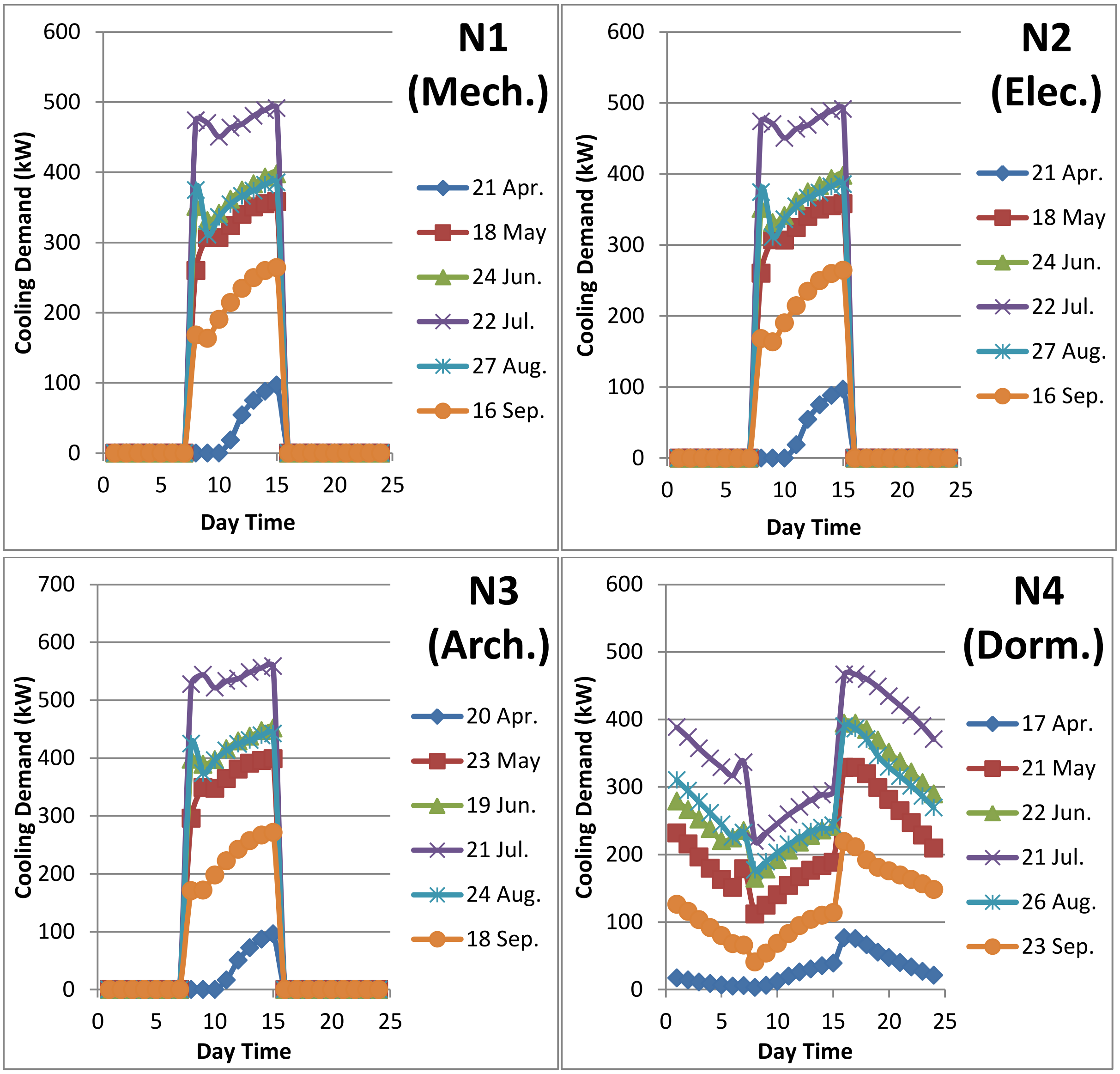


Figure 5.3: Cooling load profiles for 6 representative days for the buildings of case study 2.

5.2.3 Optimization Methodology and Approach

The same MILP optimization model, developed in chapter 3 and used in case study 1, was utilized to investigate case study 2. GAMS modeling language was used to implement the model and the optimization was carried out by the commercial solver CPLEX12. As in case study1, a three stages optimization approach was adopted: 1) Total annual cost optimization, 2) Annual CO_2 emissions optimization, and finally 3) Multi-objective optimization combining both total cost and CO_2 emission objectives. While first and second stages focus on the effect of the integrating solar energy equipment, e.g. PV panels, into the optimization process and their effect on the obtained systems, the third stage was dedicated to further investigate specific operation strategies related to hot climate regions such as the outdoor temperature effect phenomena.

The investigation within case study 1 was categorized into four investigation categories based on two major assumptions. The first was the decision between to have either a centralized district cooling system (DCS) or a de-centralized DCS where a group of, or all, buildings can have their own separated individual cooling systems and the second was the decision between to adopt either a constant COP for the compression chillers or a variable COP depending on the chiller size. The first assumption is further investigated within case study 2 in order to draw more general conclusions based on the results obtained in both case studies regarding the issue of centralized or de-centralized DCS. However, only variable COP for the compression chillers is to be investigated from now on. The investigation of case study 1 has concluded that adopting constant COP will eliminate one of the major advantages of investing in high capacity chillers which has resulted in showing that a group separated individual cooling systems would be more cost efficient than a district cooling system, when COP was considered to be constant, while district cooling systems appeared to be a better choice, with lower total annual cost, when COP is dependent on chiller size. And since variable COPs are the actual case in reality, a decision was made drop the constant COP investigation categories and focus on variable COP scenarios. Therefore, there are two investigation categories within case study2:

- Category 1: De-centralized DCS with variable COP.
- Category 1: Centralized DCS with variable COP.

In the de-centralized DCS investigations the optimization model was given a free choice to install a full network connecting all buildings, a group of small networks or no network at all leaving all building with individual systems. On the other hand, only one network, connecting all buildings, with one production site was allowed in the centralized DCS investigations. These major investigation categories were implemented in all three stages of optimization: Cost, CO_2 and Multi-objective optimizations.

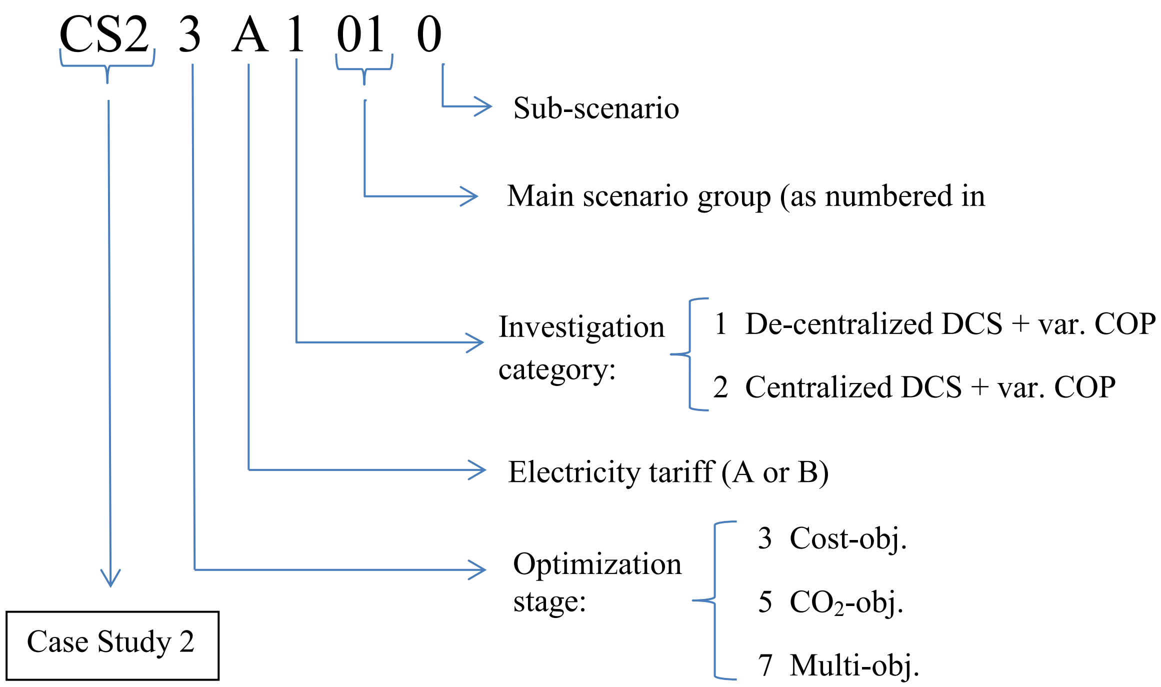
The study was carried out for several groups of scenarios; each of them being analyzed for the sensitivity of the optimal solution toward a certain design parameter or operation conditions. The analysis approach for the case study was designed in a way that starts with a reference scenario with certain set of design and operational constraints. Later on, more realistic constraints were integrated in each new scenario depending on the type of design parameter or operation condition being investigated. As shown in

Table 5.2, the first two optimization stages will focus mainly on the solar energy integration policy while the third stage will investigate some of the hot climate operation conditions as well.

Table 5.2: Main scenario groups investigated at each investigation category in case study 2.

Optimization stages	Main Scenario Groups
Cost Opt.	10. Reference Scenario
	11. Solar energy integration policy
CO_2 Opt.	1. Reference Scenario
	2. Solar energy integration policy
Multi-Objective Opt.	1. Reference Scenario
	2. Solar energy integration policy
	3. Outdoor Temperature Effect Scenarios

The coding system adopted to label each of these scenarios in case study 2 is:



5.3 Cost Optimization Objective

Total annual cost is considered the main decision making criteria in most cooling systems design application. As it was obvious in the previous chapter, both investment and operational costs have major impact of the decision making process. Therefore, total annual cost was chosen as the objective function of the first optimization stage in case study 2 as well. The objective cost function is explained in details in chapter 3 of this work. This objective was used to obtain optimized cooling systems for case study 2 with the different scenario conditions and investigation categories.

5.3.1 Reference Scenario

A reference scenario was obtained at first with a certain set of assumptions for the purpose of investigating the effect of changing other design and operation parameters later on. The assumptions adopted to obtain the reference scenario are:

- All buildings were assumed to have an entire floor or basement as free space to install the cooling system equipment.
- 30% of the roof area was preserved for installing heat dissipaters, e.g. cooling towers, while the rest was utilized by the optimization model.
- Chilled water entering the buildings at 6°C and leaving at 12°C.
- Two different electricity tariffs were implemented (Tariff A and B).
- Waste heat availability was not considered.
- No operation conditions such as load shifting were applied.
- Fixed COPs for the chillers regardless of partial load and outdoor temperature variation were considered within the reference scenario.
- Variable COP values for the chillers depending on the chiller size, which is to be determined by the model, were implemented in this case study.

The variation in compression chillers' COP in regards to their capacities has been implemented in optimization model as explained in Chapter 4. A COP value of 4 was chosen for chillers with capacities below 500 kW (142.2 TR), 5.5 for below 1000kW (284.3 TR), and 7 for chillers with capacities higher than 1000 kW (285 TR) as shown in Figure 5.4. Thus, the realistic advantage of high capacity chiller over small and middle size chillers in consuming less primary energy to provide a certain amount of cooling energy was firmly implemented in the model used to investigate this case study.

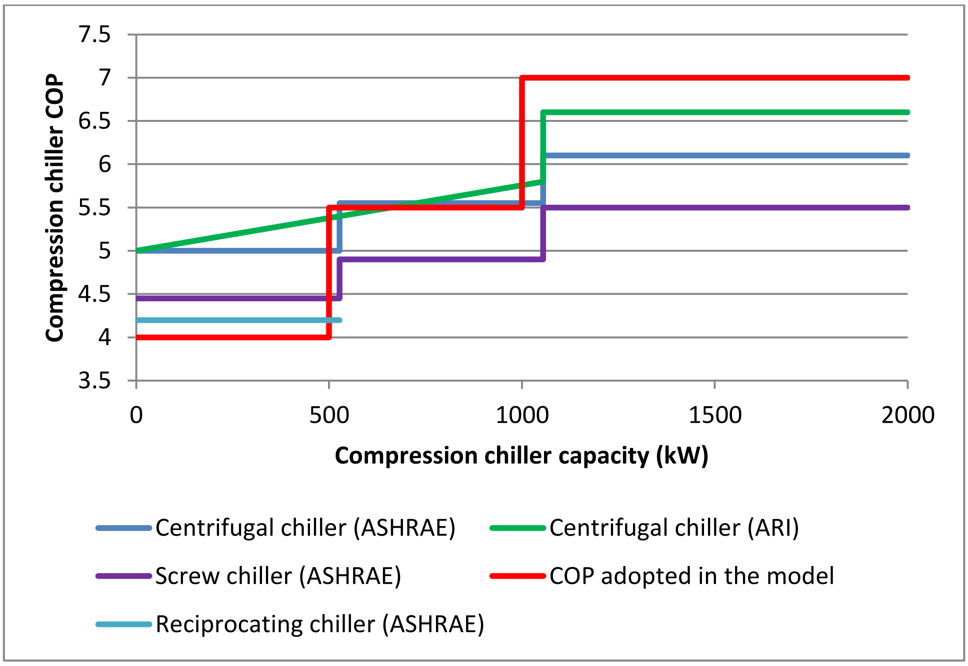


Figure 5.4: Adopted COP values for compression chillers in case study 2.

The obtained optimized system for the reference scenario for case study 2 is presented in Figure 5.5. A de-centralized DC cooling system was implemented where two buildings, N2 and N4, were connected in a small network with building N4 being the production plant. The two other buildings, N1 and N3, were equipped with separated individual cooling systems. It is also noticed that no cold storage were installed. This was against the expectations where non-residential building are more likely expected to be equipped with storage tanks that make use of the no-load hours by storing cooling energy produced by the chillers during these periods and use it at load hours which in turn allow for the installing chillers smaller than the peak load of the system and thus reducing the investment costs. However this was not the case here. Instead the installed chillers were either the exact capacity needed to meet the peak cooling load or oversized. Higher COP values for bigger chillers allow saving a certain amount of operational cost by reducing the primary energy consumption needed to produce a certain amount of cooling energy. Since the peak loads of the building in this case study where somewhere around 500 kW which the value of shifting the COP from 4 to 5.5 in the model, installing chillers with capacities over 500 kW was preferred. In other words, choosing relatively high chillers capacities, that offer higher COP, seems to be, in this case study, more cost effective than the option of installing small chillers, i.e. smaller COP, with storage tanks due the saving potentials in operational cost. Such an attribute might have occurred because the developed model for implementing COP variation, depending on the chiller capacity, was a step by step linear model.

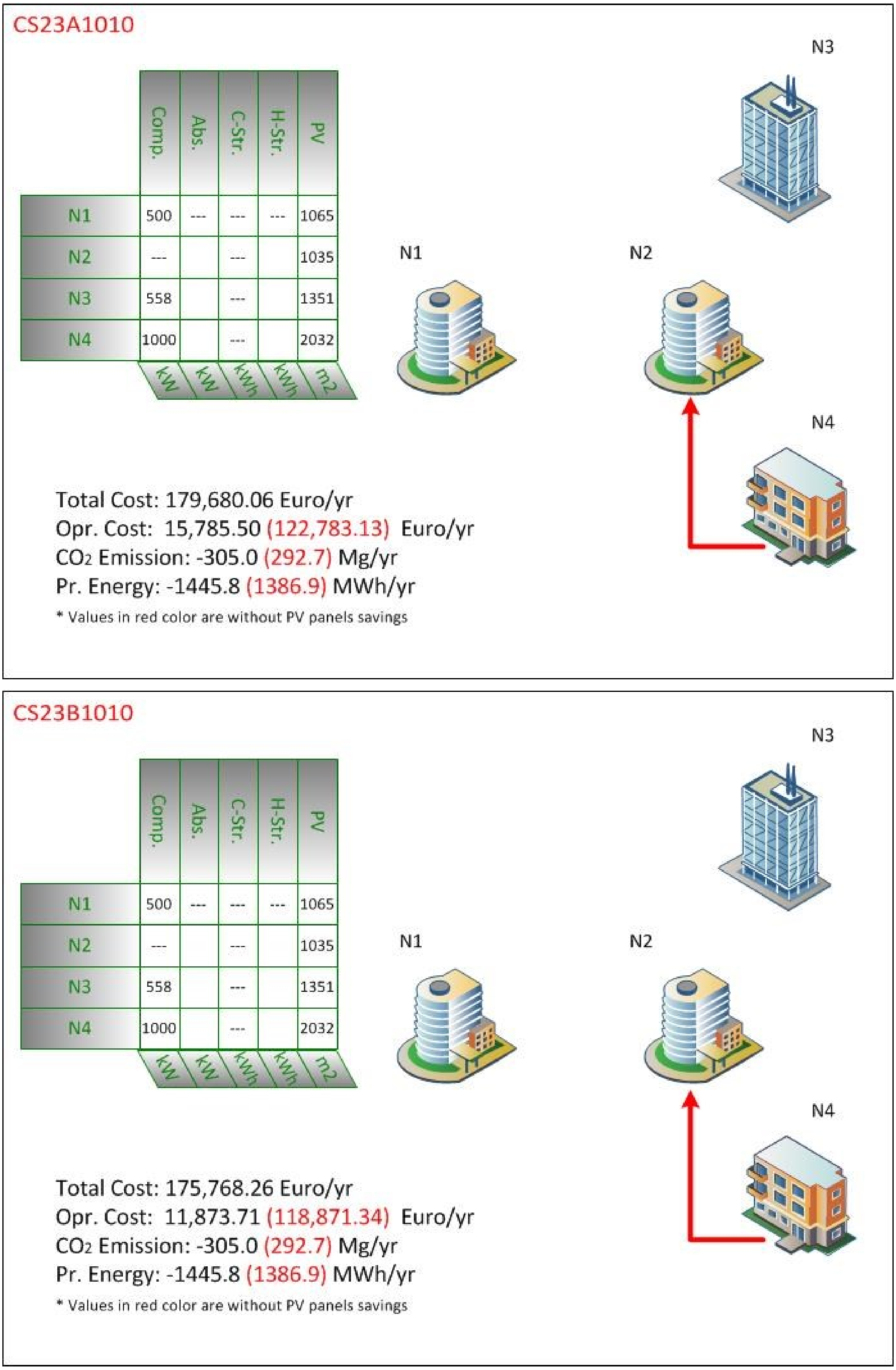


Figure 5.5: Annual cost optimization reference scenario for case study 2 with electricity both tariffs A and B.

Similarly, installing chillers with capacities over 1000 kW would offer even higher COP and thus by choosing bigger chillers, the model can use further savings in operational costs to install and operate a network connecting a couple of building whose cooling load demand is met by one production plant. That was the case of connecting buildings N2 and N4. The chiller installed at building N4 was of 1000 kW capacity which is in fact an oversized chiller since the peak loads of buildings N2 and N4 do not occur at the same time as shown in Figure 5.3. The savings in operational cost resulting from installing a chiller with high COP were invested to install piping network connecting the two buildings and thus supplying building N2 with the required cooling energy. By observing the decisions made in both case studies 1 and 2, it was concluded that for residential buildings that have long operational hours it might be more cost effective to install oversized chillers if the higher capacities of these chillers would offer a significant increase in the value of COP. It is important here to mention that the optimization model developed in this work does not count COP down fall during partial load operation. Therefore, this conclusion might not be valid for the more realistic cases when COP values vary with partial loads.

The distance between the two buildings connected with a pipeline, N2-N4, is the shortest in comparison to other buildings. However, the question of which buildings to connect within the network is related not only to the distances between the different buildings but also to the cooling load profiles of these buildings because transporting high rates of energy requires bigger pipelines which means higher investment cost. For example when two buildings have cooling load profiles that are similar to each other, i.e. have their non-load and full load periods at the same time and also have their peak load and the same hour, it will be required to install big pipelines to assure high energy transportation capacity which is needed at peak load hours. The option of installing storage tanks and benefit from off-load hours is a possible solution. However that is also highly dependent on the investment costs of such storage tank. To further investigate this issue a comparison between four scenarios, with four possible pipeline networks, was carried out:

CS23A1010: Connection N4→N2 only, which is the reference scenario outcome presented in Figure 5.5.

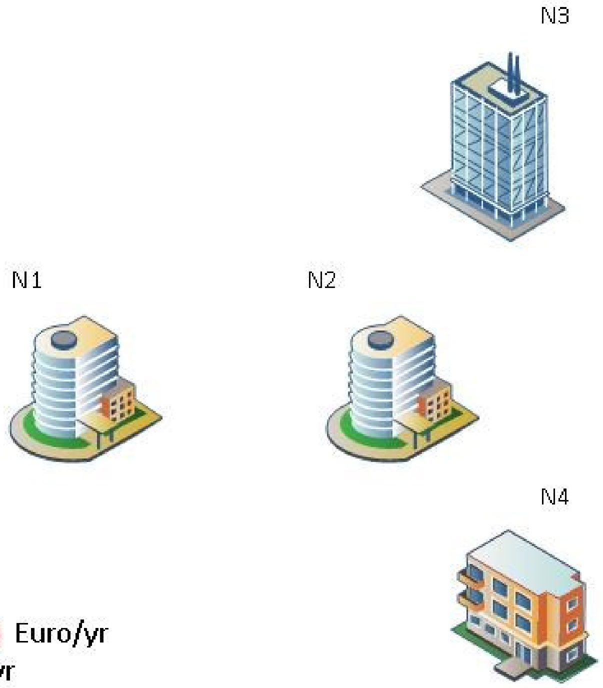
CS23A1011: No network connection: Where line N4→N2 was forced to be removed and thus N2 was equipped with its own cooling system. See Figure 5.6.

CS23A1012: Connection N3→N2 only: Where line N4→N2 was forced to be removed and N3 was connected to N2 instead. See Figure 5.7.

CS23A2010: Centralized DCS: all buildings where connected in one pipeline network as shown in Figure 5.8.

CS23A1011

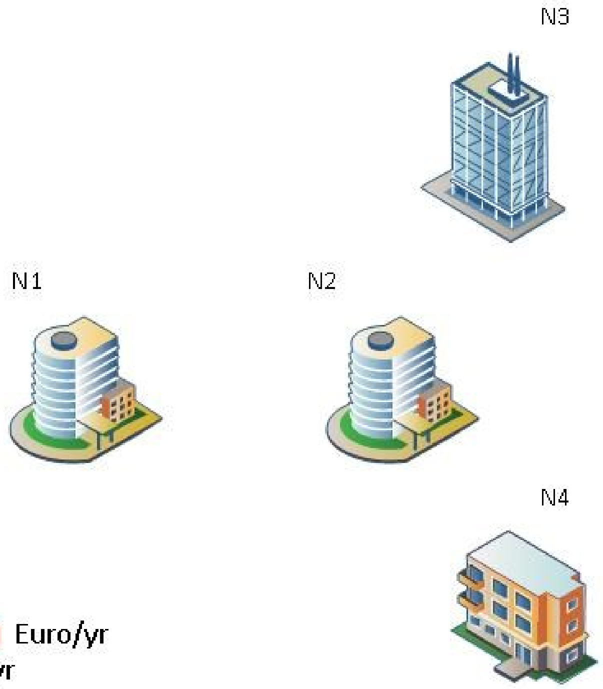
	Comp.	Abs.	C-Str.	H-Str.	PV
N1	500	---	---	---	1065
N2	500		---		1035
N3	558		---		1351
N4	1000		---		2032
	kW	kW	kWh	kWh	m2



Total Cost: 180,384.14 Euro/yr
Opr. Cost: 17,460.42 (123,029.07) Euro/yr
CO_2 Emission: -298.3 (299.4) Mg/yr
Pr. Energy: -1414.1 (1418.6) MWh/yr
* Values in red color are without PV panels savings

CS23B1011

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	500	---	---	---	1065
N2	500		---		1035
N3	558		---		1351
N4	1000		---		2032
	kW	kW	kWh	kWh	m2



Total Cost: 176,472.35 Euro/yr
Opr. Cost: 13,548.63 (119,117.28) Euro/yr
CO_2 Emission: -298.3 (299.4) Mg/yr
Pr. Energy: -1414.1 (1418.6) MWh/yr
* Values in red color are without PV panels savings

Figure 5.6: No DC network scenario for case study 2 with electricity tariffs A and B.

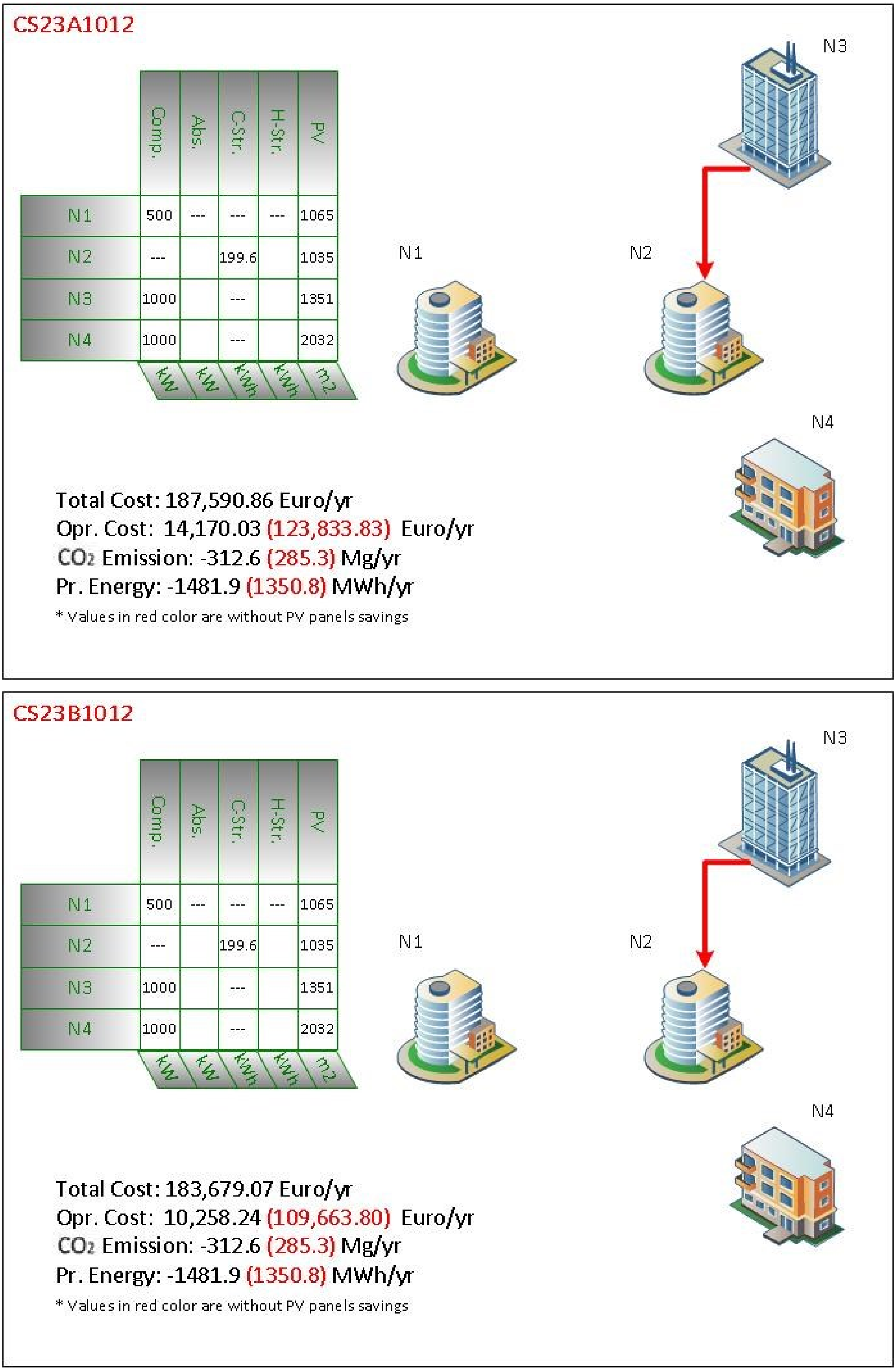
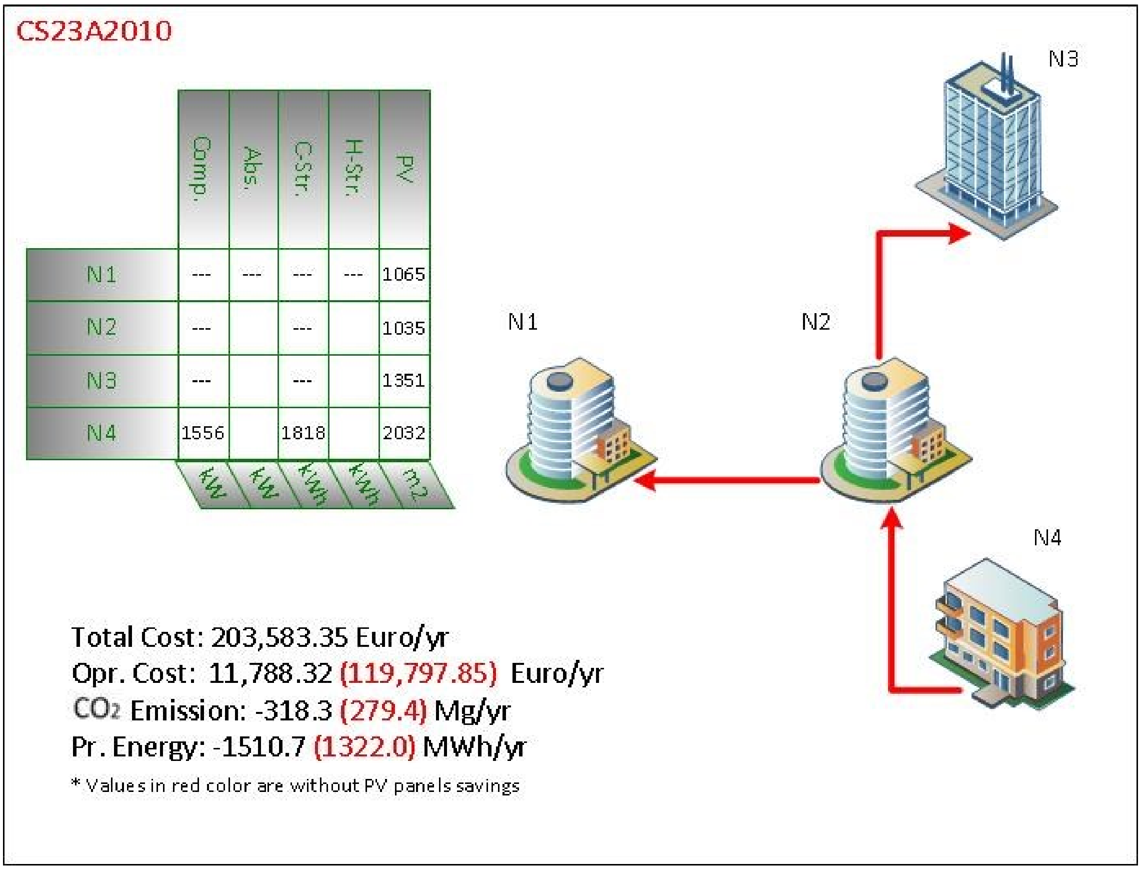


Figure 5.7: A test scenario for case study 2 by implementing N3→N2 pipeline instead on N4→N2, with electricity tariffs A and B.



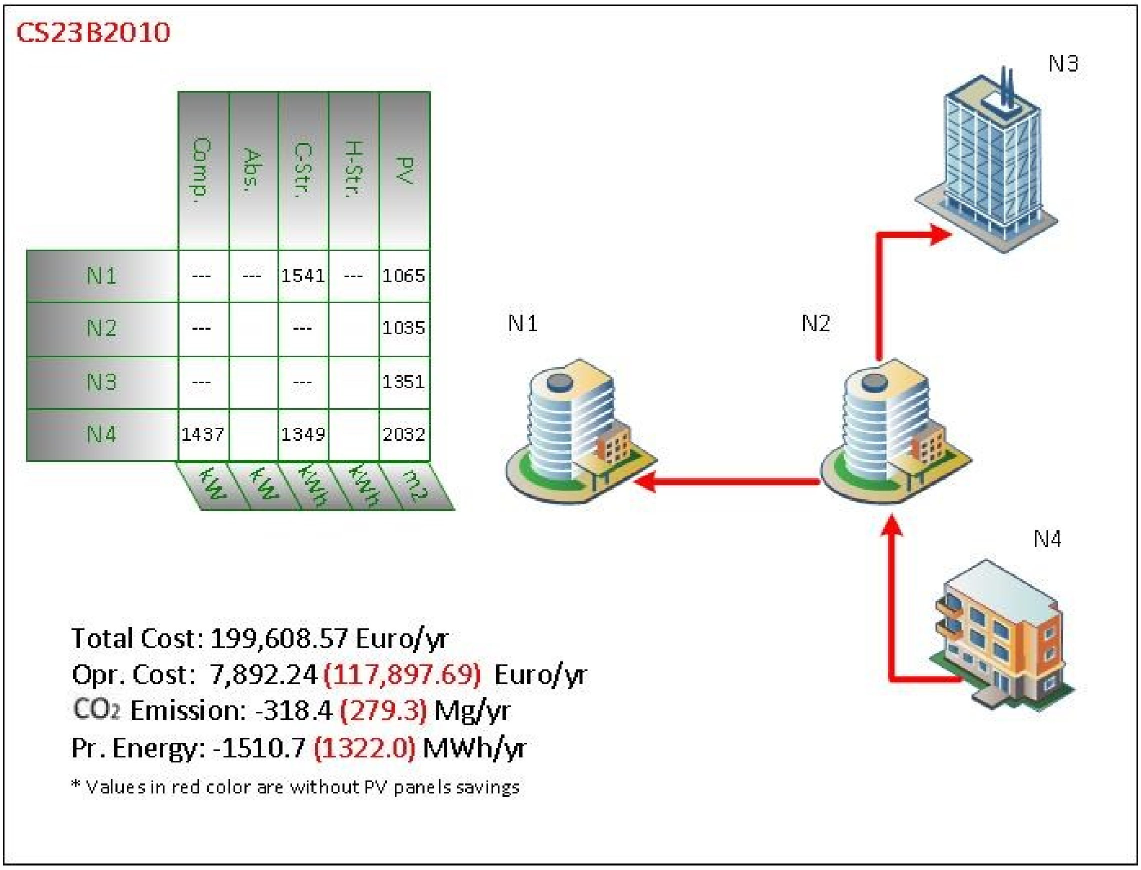


Figure 5.8: Centralized DC network scenario for case study 2 with electricity tariffs A and B.

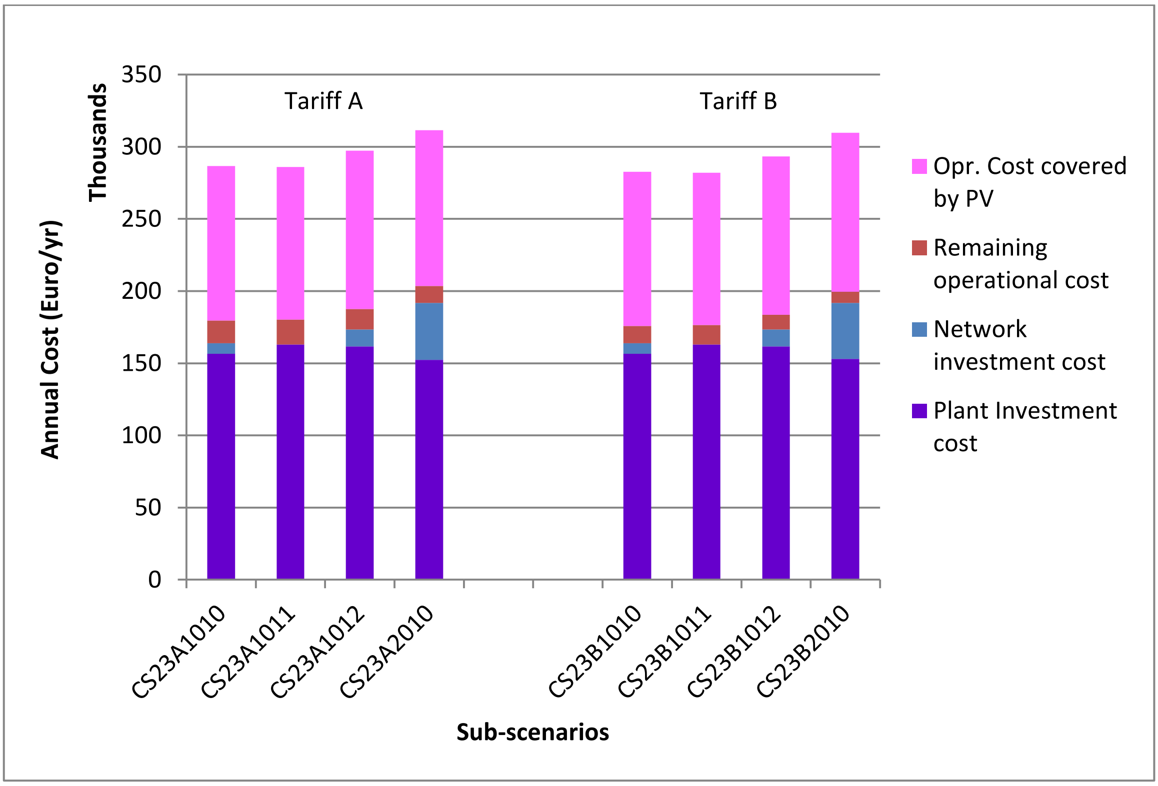


Figure 5.9: Total annual costs of several sub-scenarios with different DC networks. Note: PV savings (pink) are to be subtracted from the total annual cost, i.e. comparison is to be made at the red color.

In general, it was noticed that installing DC network would notably reduce the operational cost of the cooling system, however it increases the investment cost due to the added DC pipelines and storage tanks, if any. Therefore the model tries to find out the best option by balancing between the two major cost categories, investment and operation, and thus the reference scenario came out to be with a single pipeline connecting N2 to N4. This pipeline has reduced the operation cost, in comparison to the No-Network scenario, with an amount that exceeds its investment cost. Not to forget the reduction in plant investment cost due to eliminating the chiller at N2. Installing further pipelines, or another pipeline, would cause the network investment cost to increase to a point where it exceeds the savings in operational costs which makes such investment not cost effective. This was the same case with installing a full DC network connecting all buildings where the system had a higher total cost, in comparison to the other three sub-scenarios, despite having a lower operational cost. A certain point of interest was the location chosen to be the central energy production plant. Building N4 was chosen by the model to serve as production plant instead building N2 which has a central position in the investigated district. More focus is paid for this issue in the following segment.

5.3.2 Solar energy integration policy

The investigations within case study 1 have strongly showed that PV panels have a significant impact on the obtained systems and their DC networks. Where the obtained cooling systems were having significantly different layout from the systems obtained for the same scenarios with no PV panels allowed. One of the very obvious impacts was the location of the chilled water production plant, especially within centralized DCS. The same impact has been observed within case study 2 as well. Building N2 which has a centralized location was expected to serve as the central production plant, however the model chose building N4. A couple of testing and validating sub-scenarios were carried out to analyze this phenomenon.

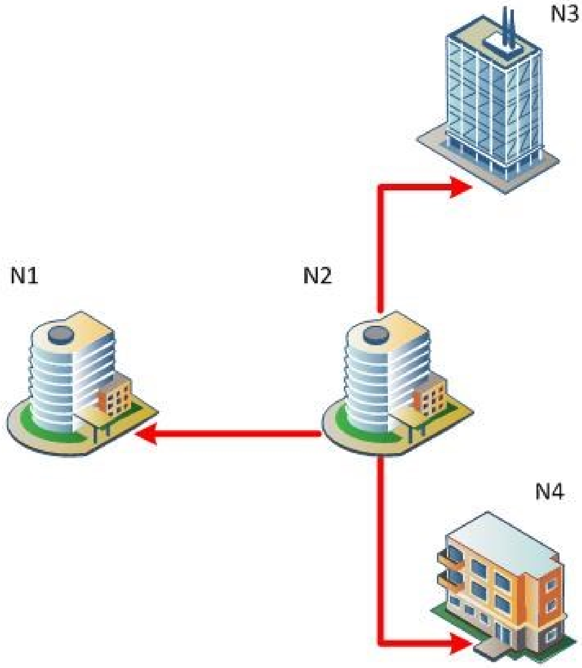
Figure 5.10 shows the obtained system when no PV panels are allowed to be installed. The results of this scenario presented building N2 as the central production plant. However this system has a much higher total annual cost due to the lost PV energy savings. The testing and validating sub-scenarios, in addition to the comparison between the two central DC systems, have led to the conclusion that choosing building N4 within CS23A2010, i.e. Figure 5.8, was mainly due to the PV panels' energy integration policy adopted in the optimization model. Therefore, a new yet slightly different integration policy was introduced:

CS23A2010: Old PV integration policy, see Figure 5.8, where energy produced by PV panels is either to be locally consumed, i.e. used to operate the chillers if the chillers were ON at the time of production, or to be sold to the national electricity grid. However, only the energy produced at the same building where the chiller is installed can be used for local consumption. Energy produced at other buildings had to be sold to the grid. And since that the electricity selling price to the grid (0.16 €/kWh) is lower than the purchase price of electricity from the grid (0.24 €/kWh), any further selling of PV panels' energy to the grid will result in income loses.

CS23A2020: New PV integration policy, see Figure 5.11, where energy produced by PV panels is also either to be locally consumed when the cooling chillers are ON at the time of production or to be sold to the national electricity grid when the chillers are OFF. The difference is that electricity produced by PV panels at any building can be used to operate any chiller within the DC system even if they were installed in other buildings.

CS23A1019

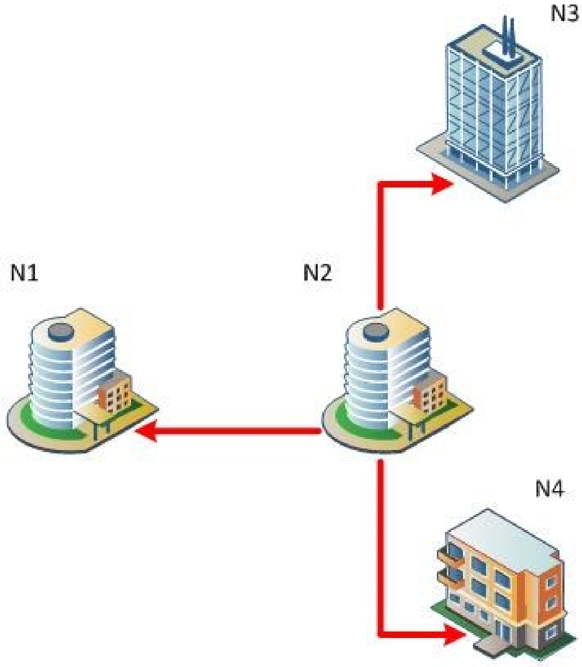
	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	510	---	---
N2	1707		---		---
N3	---		---		---
N4	---		---		---
	kW	kW	kWh	kWh	m2



Total Cost: 269,795.08 Euro/yr
Opr. Cost: 189,532.82 Euro/yr
CO_2 Emission: 279.1 Mg/yr
Pr. Energy: 1321.3 MWh/yr
* No PV panels were allowed to be installed

CS23B1019

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	2073	---	---
N2	1047		2257		---
N3	---		2070		---
N4	---		---		---
	kW	kW	kWh	kWh	m2

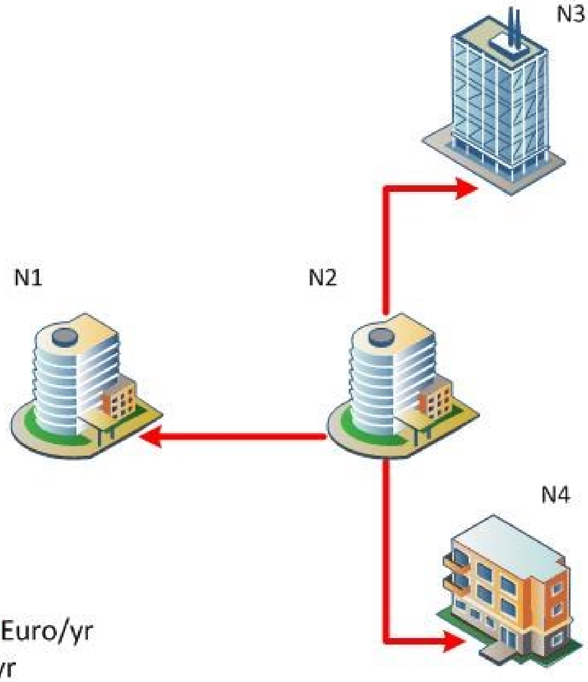


Total Cost: 258,113.71 Euro/yr
Opr. Cost: 175,698.47 Euro/yr
CO_2 Emission: 279.1 Mg/yr
Pr. Energy: 1321.3 MWh/yr
* No PV panels were allowed to be installed

Figure 5.10: Centralized DC network scenario, with no PV panels, for case study 2 with electricity tariffs A and B.

CS23A2020

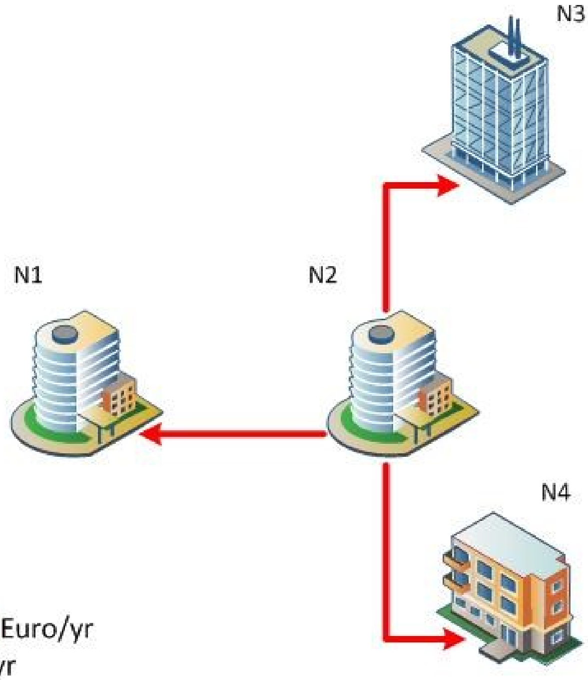
	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	---	---	---	---	1065
N2	1463		2655		1035
N3	---		---		1351
N4	---		---		2032



Total Cost: 199,962.03 Euro/yr
Opr. Cost: 9,109.08 (111,969.49) Euro/yr
CO_2: Emission: -318.5 (279.2) Mg/yr
Pr. Energy: -1511.3 (1321.4) MWh/yr
* Values in red color are without PV panels savings

CS23B2020

	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	---	---	---	---	1065
N2	1633		1126		1035
N3	---		---		1351
N4	---		---		2032



Total Cost: 197,207.00 Euro/yr
Opr. Cost: 7,164.41 (114,517.44) Euro/yr
CO_2: Emission: -318.5 (279.4) Mg/yr
Pr. Energy: -1511.3 (1321.4) MWh/yr
* Values in red color are without PV panels savings

Figure 5.11: Centralized DC network scenario, with new PV panel integration policy, for case study 2 with electricity tariffs A and B.

Similar to what was observed within case study 1, the results of the scenarios with no PV panels allowed, i.e. Figure 5.10, have showed that the obtained systems without utilizing solar energy have much less investment cost in comparison to those with PV panels installed. The savings in operational cost that PV panels offer were the main reason giving the lead to the DC systems with integrated PV panels. Namely, the locally consumed PV energy within the DC system which lowers the amount of electricity purchased from the grid and also the PV income from selling the extra electricity to the grid. The latter is presented in Figure 5.12 in pink color.

As shown in Figure 5.11, the DC systems with new policy to integrate PV panels had the central located building N2 as their central cooling energy production plant which has led to the conclusion that choosing N4 in the previous systems was mainly due to the old PV integration policy. However, despite the fundamental changes in the system layout, it was very clear that both investment and operational costs were close to each other with a slight advantage for the DC systems with new PV integration policy. The reductions in total annual cost were 1.7% and 1.2% for both electricity tariffs A and B, respectively, as presented in Figure 5.12. However, it is decided that from this point on the new PV integration policy will be permanently adopted with further investigations within this work.

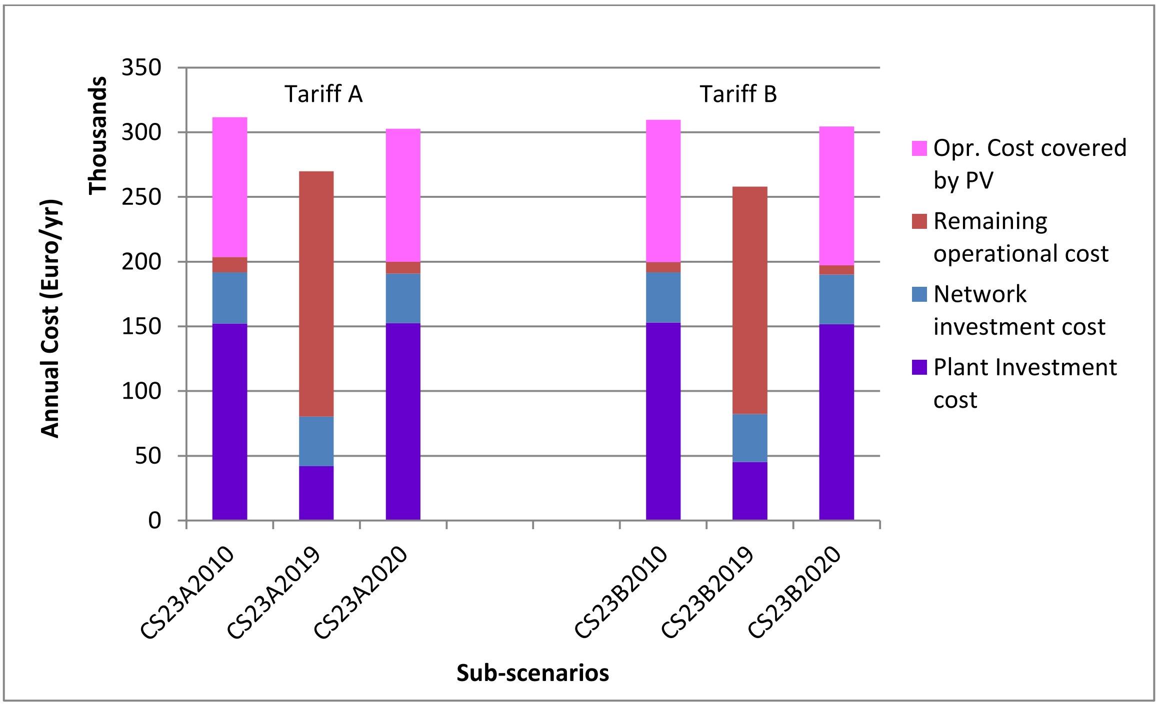


Figure 5.12: Total annual costs of Centralized DC network scenarios with: old, no and new PV panels integration policies. Note: PV savings (pink) are to be subtracted from the total annual cost, i.e. comparison is to be made at the red color.

5.4 CO_2 Emissions Optimization Objective

As a second stage of investigating case study 2, a single objective optimization investigation was carried out with minimizing CO_2 emissions being the main objective function. This single objective optimization is to be combined with total annual cost optimization within multi-objective optimization stage. The CO_2 emissions objective function developed at earlier stage of this work focus majorly on optimizing operational patterns of the DC systems and selects the best cooling technology and equipment's to be installed in the system based on the lowest CO_2 emissions possible during the system operation. Design CO_2 emissions were implemented symbolically in the model as explained previously in this work.

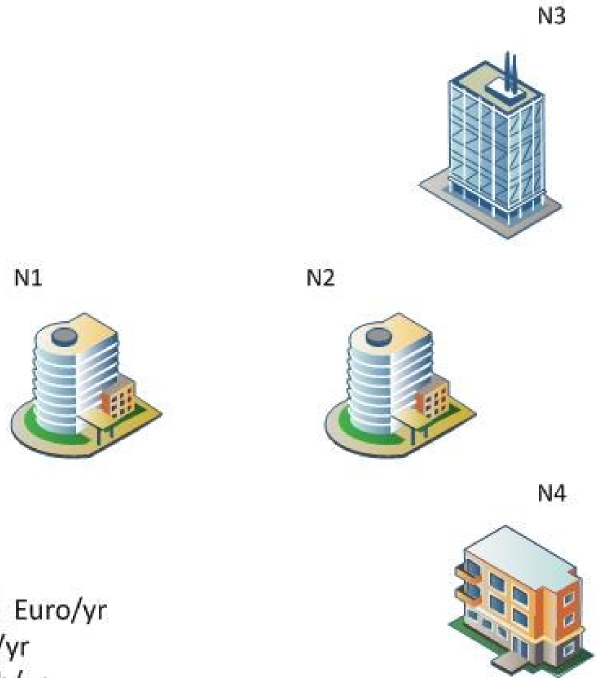
The same set of assumptions adapted to in the total annual cost optimization was adopted at this stage also to obtain a reference scenario. This include that COP are considered constant in regards to the partial load and outdoor temperature variation, however COPs were considered variable in regards to the chiller size. Three values of compression chiller COPs were introduced according to the chiller capacity as shown in Figure 5.4. Hence, the higher chiller capacity chosen by the model the higher COP implemented which would lead to less CO_2 emissions. All buildings were assumed to have an entire floor or basement as free space to install the cooling system equipment. Waste heat availability was not considered and no other operation conditions such as load shifting were applied. The obtained reference system is to be compared to other systems such as centralized DC later in the investigation. The values of total annual cost and CO_2 emissions obtained at this stage are crucial for the multi-optimization stage. Both old and new PV panels' integration policies were investigated.

After obtaining the reference scenario for both electricity tariffs A and B, comparison with the no PV panels systems was performed. Then the investigation was expanded to centralized DC systems in the same approach, i.e. old and new PV integration policy and no-PV DC systems:

CS25A/B1010: Old PV integration policy for de-centralized DC system. See Figure 5.13.
CS25A/B1019: No PV panels allowed in de-centralized DC system. See Figure 5.14.
CS25A/B1020: New PV integration policy for de-centralized DC system. See Figure 5.15.
CS25A/B2010: Old PV integration policy for centralized DC system. See Figure 5.16.
CS25A/B2019: No PV panels allowed in de-centralized DC system. See Figure 5.17.
CS25A/B2020: New PV integration policy for de-centralized DC system. See Figure 5.18.

CS25A1010

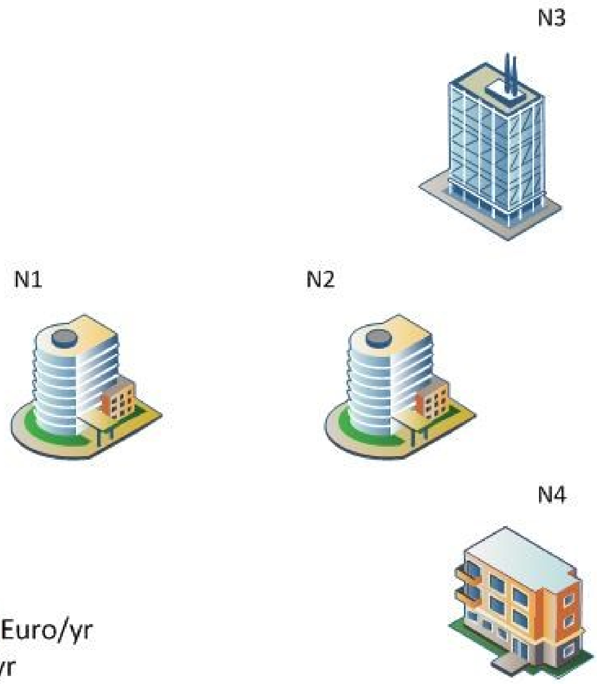
	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	1000	---	---	---	1065
N2	1000		---		1035
N3	1000		---		1351
N4	1000		---		2032



Total Cost: 186,992.52 Euro/yr
Opr. Cost: 11,206.9 (121,601.84) Euro/yr
CO_2 Emission: -319.7 (278.0) Mg/yr
Pr. Energy: -1515.4 (1317.3) MWh/yr
* Values in red color are without PV panels savings

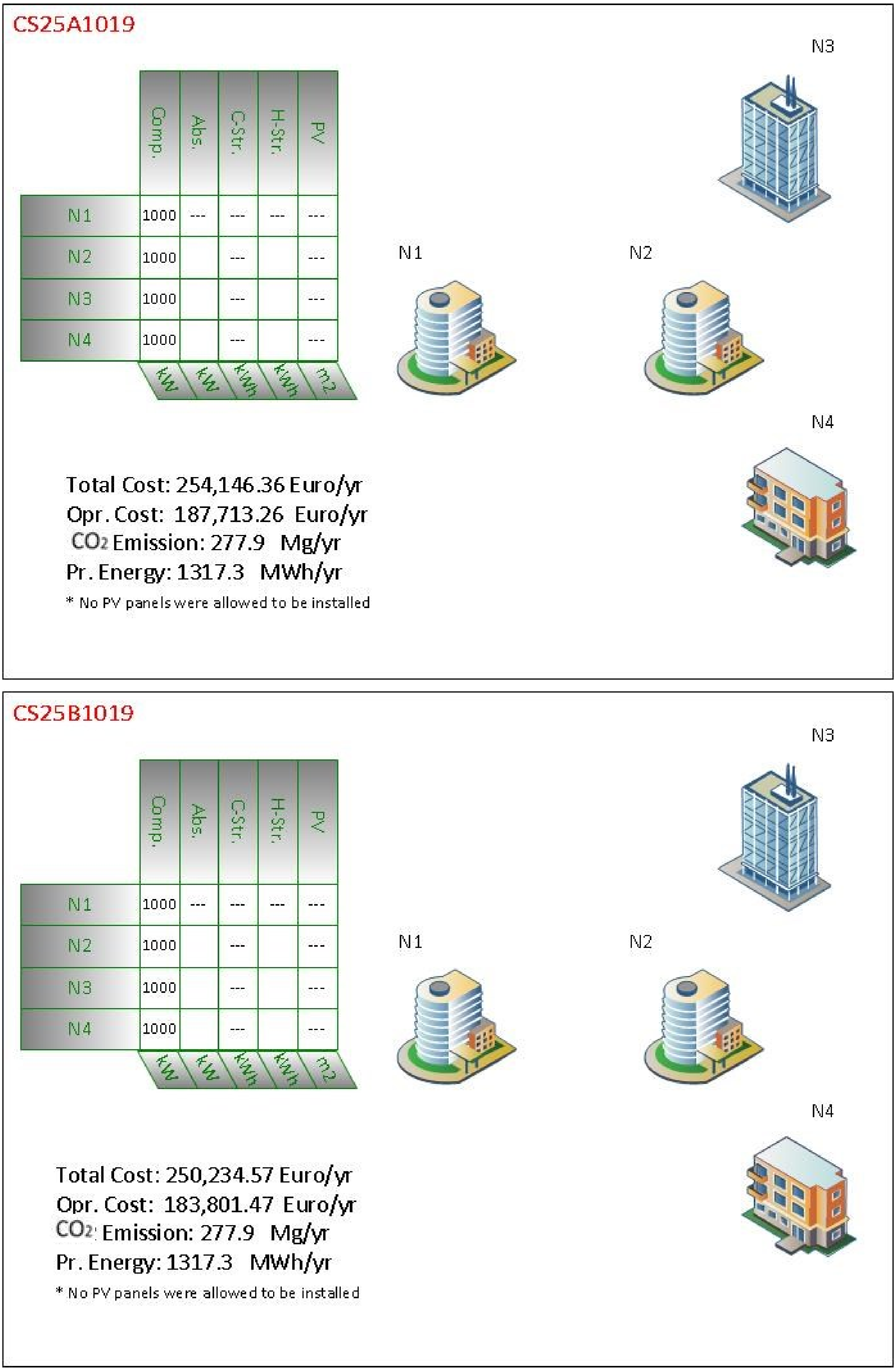
CS25B1010

	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	1000	---	---	---	1065
N2	1000		---		1035
N3	1000		---		1351
N4	1000		---		2032



Total Cost: 183,080.73 Euro/yr
Opr. Cost: 7,295.11 (117,690.05) Euro/yr
CO_2 Emission: -319.7 (278.0) Mg/yr
Pr. Energy: -1515.4 (1317.3) MWh/yr
* Values in red color are without PV panels savings

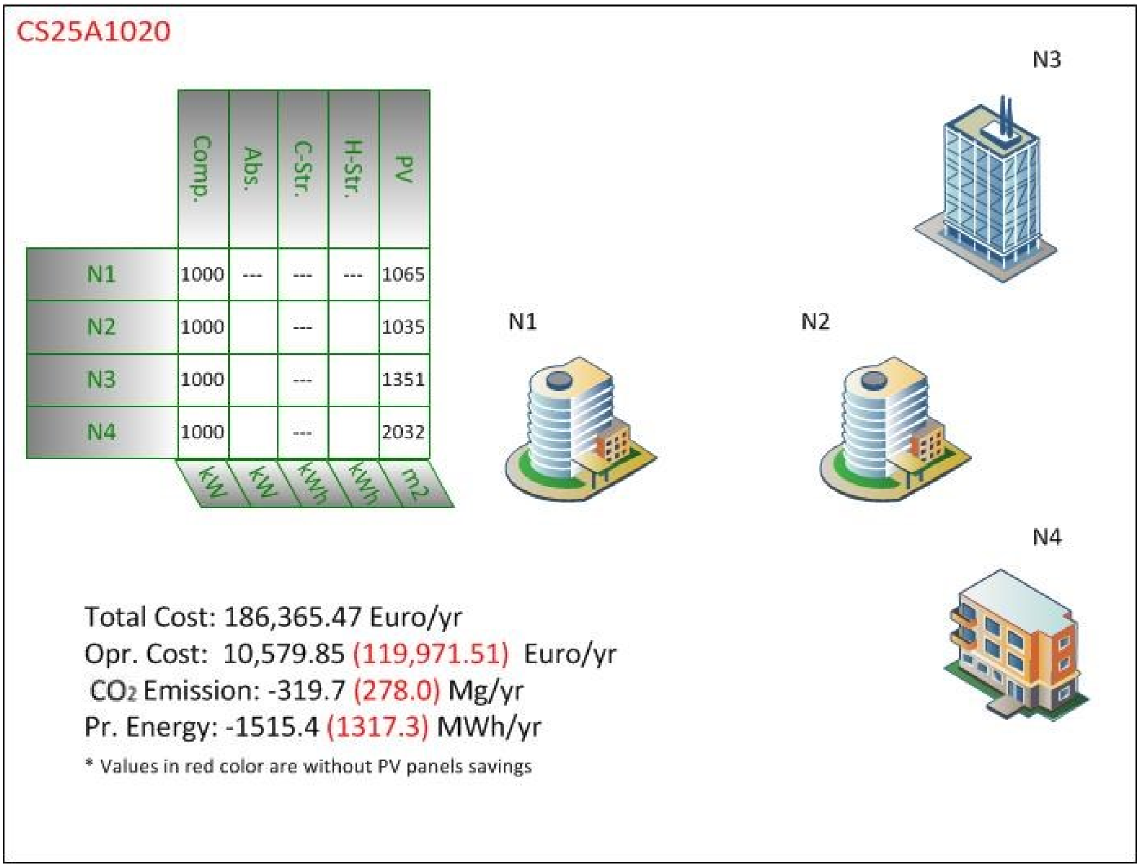
Figure 5.13: Total annual CO_2 emissions optimization reference scenario for case study 2 with electricity tariffs A and B.



	Comp.	Abs.	C-Str.	H-Str.	PV
N1	1000	---	---	---	---
N2	1000		---		---
N3	1000		---		---
N4	1000		---		---
	kW	kW	kWh	kWh	m2

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	1000	---	---	---	---
N2	1000		---		---
N3	1000		---		---
N4	1000		---		---
	kW	kW	kWh	kWh	m2

Figure 5.14: De-centralized DC network scenario at CO_2 emission optimization stage with no PV panels allowed to be installed for case study 2 with electricity tariffs A and B.



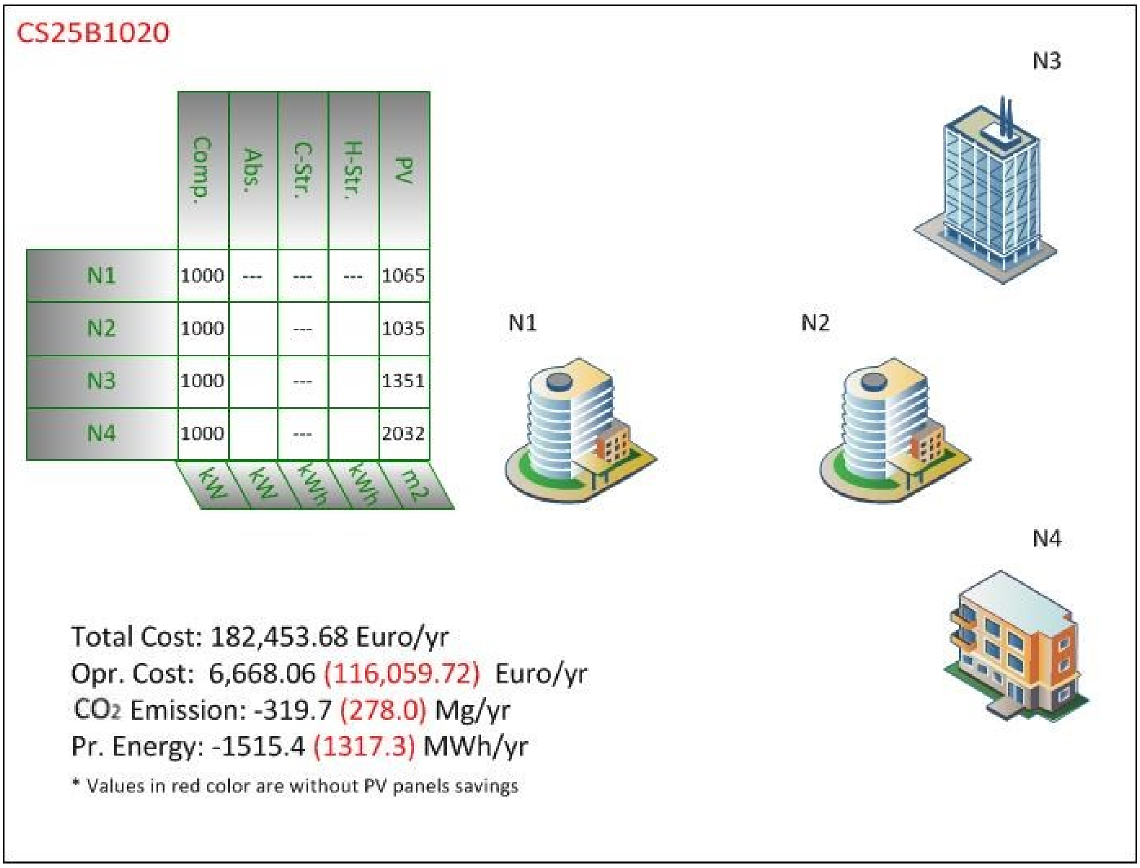


Figure 5.15: De-centralized DC network scenario at CO_2 emission optimization stage with new PV panel integration policy for case study 2 with electricity tariffs A and B.

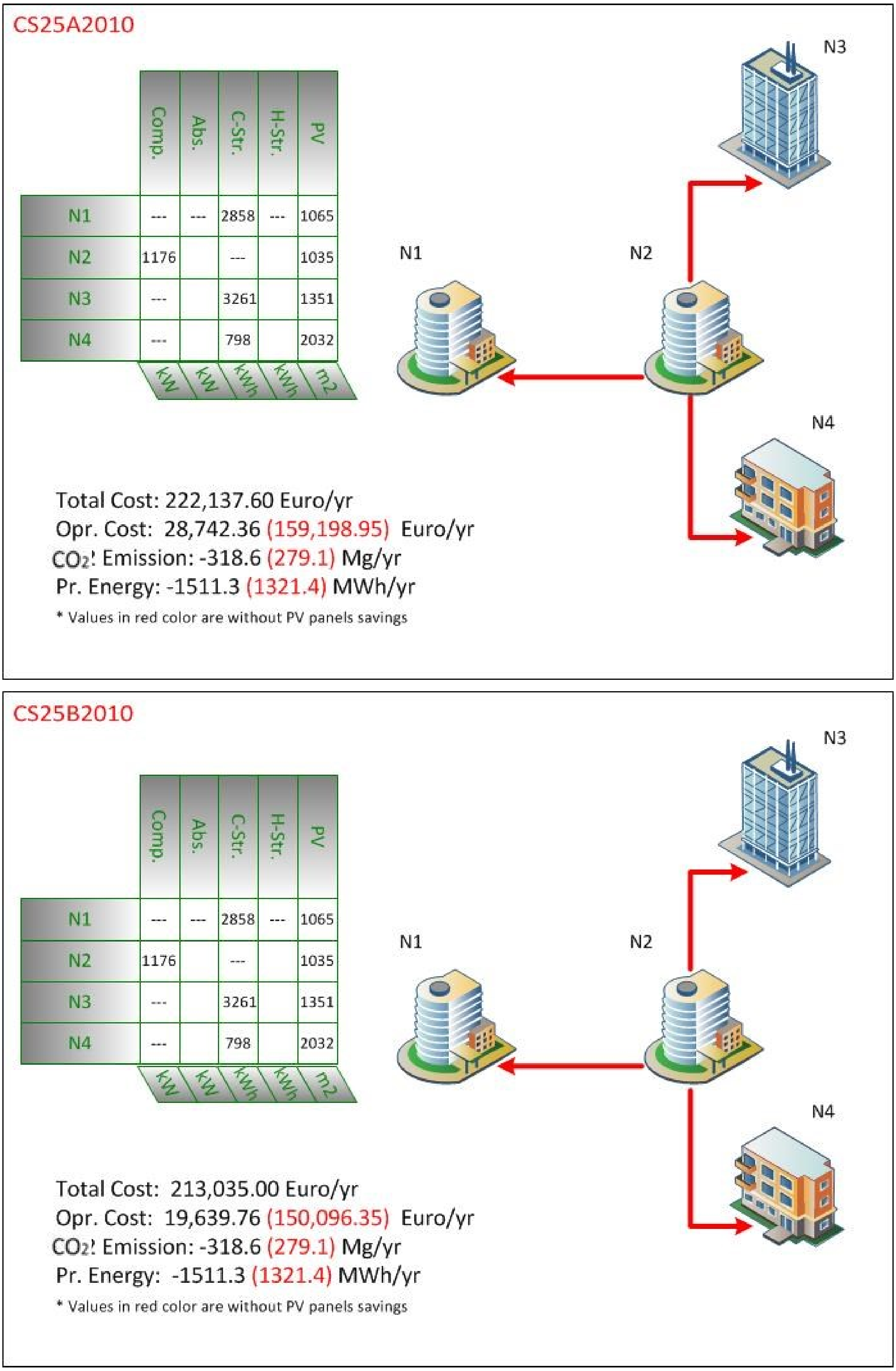
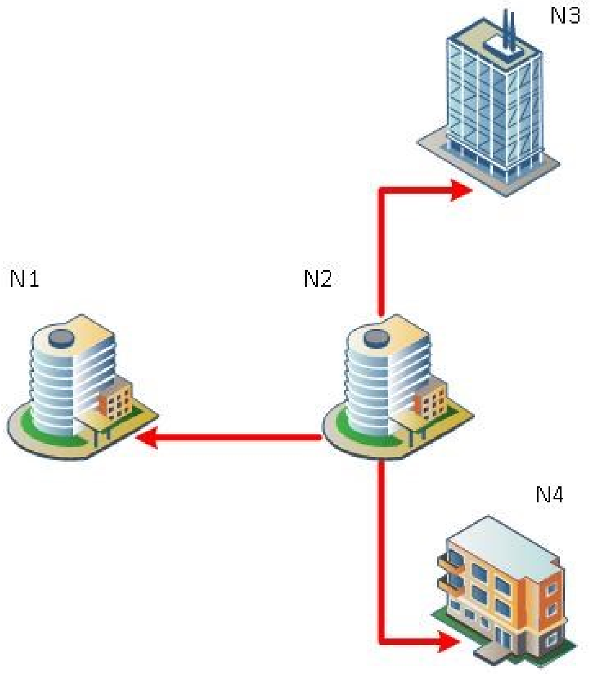


Figure 5.16: Centralized DC network scenario at CO_2 emission optimization stage for case study 2 with electricity tariffs A and B.

CS25A2019

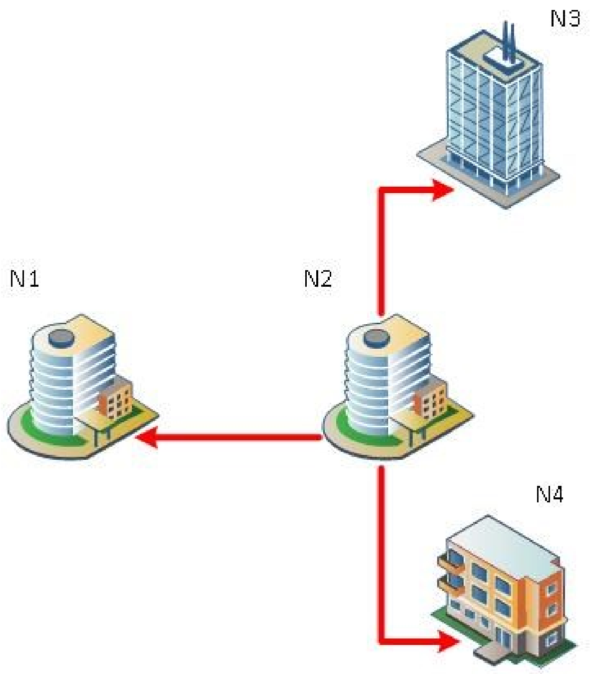
	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	2858	---	---
N2	1176		---		---
N3	---		3261		---
N4	---		798		---
	kW	kW	kWh	kWh	m2



Total Cost: 275,445.84 Euro/yr
Opr. Cost: 191,403.14 Euro/yr
CO_2 Emission: 279.1 Mg/yr
Pr. Energy: 1321.3 MWh/yr
*No PV panels were allowed to be installed

CS25B2019

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	2858	---	---
N2	1176		---		---
N3	---		3261		---
N4	---		798		---
	kW	kW	kWh	kWh	m2



Total Cost: 266,288.07 Euro/yr
Opr. Cost: 182,245.37 Euro/yr
CO_2 Emission: 279.1 Mg/yr
Pr. Energy: 1321.3 MWh/yr
*No PV panels were allowed to be installed

Figure 5.17: Centralized DC network scenario at CO_2 emission optimization stage with no PV panels allowed to be installed for case study 2 with electricity tariffs A and B.

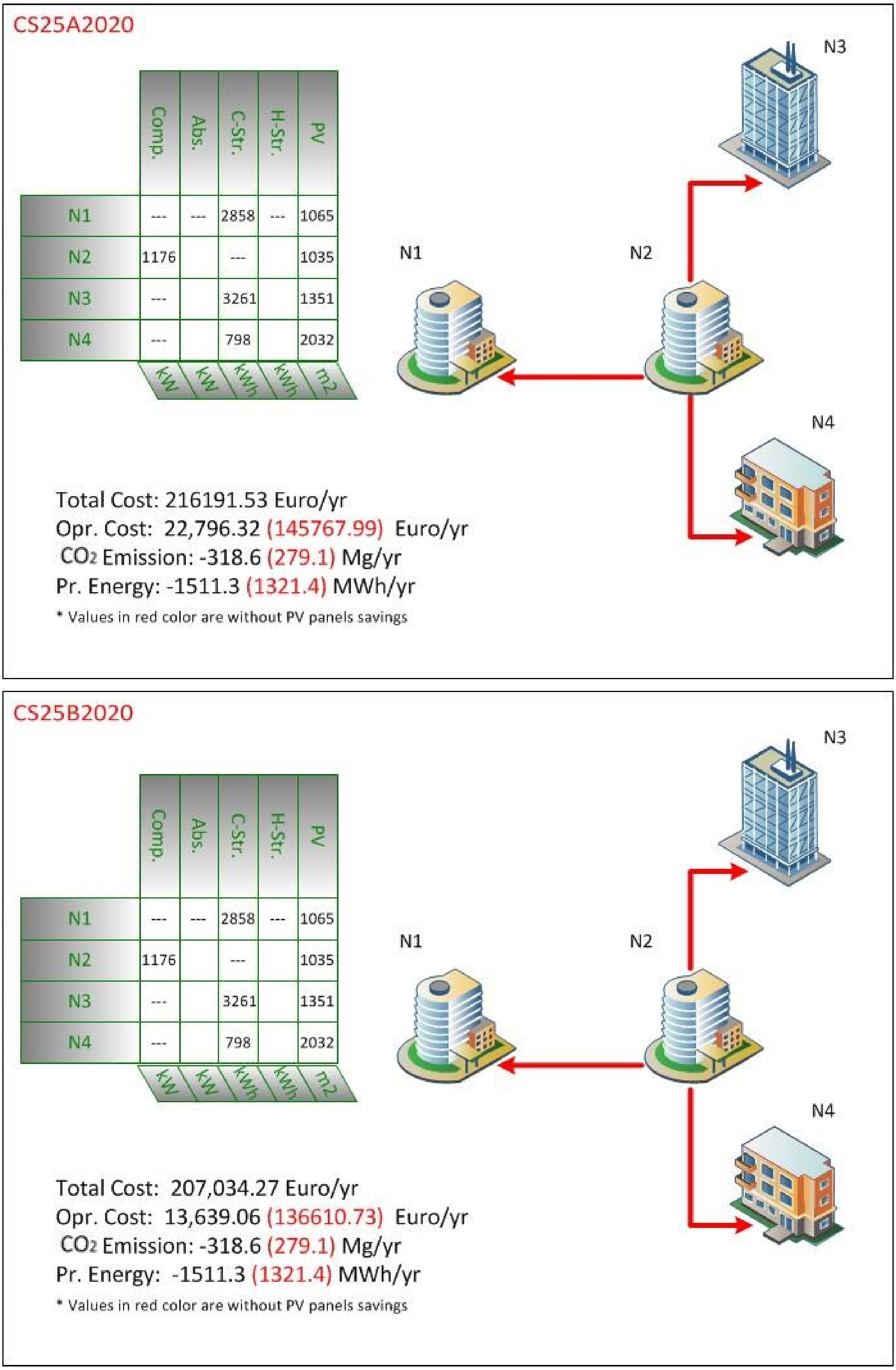


Figure 5.18: Centralized DC network scenario at CO_2 emission optimization stage with new PV panel integration policy for case study 2 with electricity tariffs A and B.

The results obtained for the investigated sub-scenarios have showed that:

- Changing the electricity tariff had notable impact only on the total annual cost of the systems but the design layouts of the systems and the CO_2 emission values were unaffected and for both De-centralized and centralized DC systems as shown in Figures 5.13 to 5.18. This is because cost of energy consumed is not considered in the CO_2 objective which eliminates the effect of changing tariffs. However, such change in electricity prices would naturally affect the total cost of the system. Therefore, the CO_2 investigation will focus only on electricity tariff A from this point on.

- Changing the PV integration policy also did not have any impact on the design layout for neither de-centralized nor centralized DC systems. The amount of CO_2 emitted was almost unaffected within the de-centralized DC systems, as shown in Figures 5.13 and 5.15, because there was no DC network installed which eliminate the advantage of changing the integration policy. However there was a very slight impact on the CO_2 emissions within the centralized DC systems where changing the integrating policy can allow for more local energy consumption resulting in less electricity purchase from the grid and thus less CO_2 emission. However this impact was a matter of some kilograms of CO_2 per year therefore it is not clearly demonstrated in Figures 5.16 and 5.18.

- Utilizing PV panels, with either integration policy, had a great impact on the total annual CO_2 emissions in comparison to the no-PV panel sub-scenarios. However, the new policy did not affect the design layout of the system, i.e. chillers and other equipment sizes remained unaffected as well as the DC network, which opens the possibility to optimize the cooling system in separation from the PV panels being integrated into it. The amount of CO_2 emissions of the sub-scenarios with integrated PV panels had negative values, as shown in Figure 5.19. These negative values are a result of CO_2 savings due to the use of PV panels where these savings had higher values than the amount of CO_2 emitted from the system. It was noticed that the CO_2 savings had the same value, 597.7 Mg/yr, in most of the scenarios where it is mostly dependent on the installed PV panels area.

- In General, it was concluded that CO_2 optimization in de-centralized systems push towards maximizing the capacity of chillers, where the cost is not considered here, for the sake of increasing the COP value and thus reducing the amount of primary energy needed. Whereas, in centralized systems, once the chiller capacity that guarantee the highest possible COP is exceeded, the model starts to install oversized storage tanks, which are not used to their full capacity, and use them to meet peak load demands since that the installed central chiller can meet around 60% of the total peak load only. This attitude is expected to have a significant impact on the systems obtained at the multi-objective optimization where CO_2 objective function will be considered a long side the cost function.

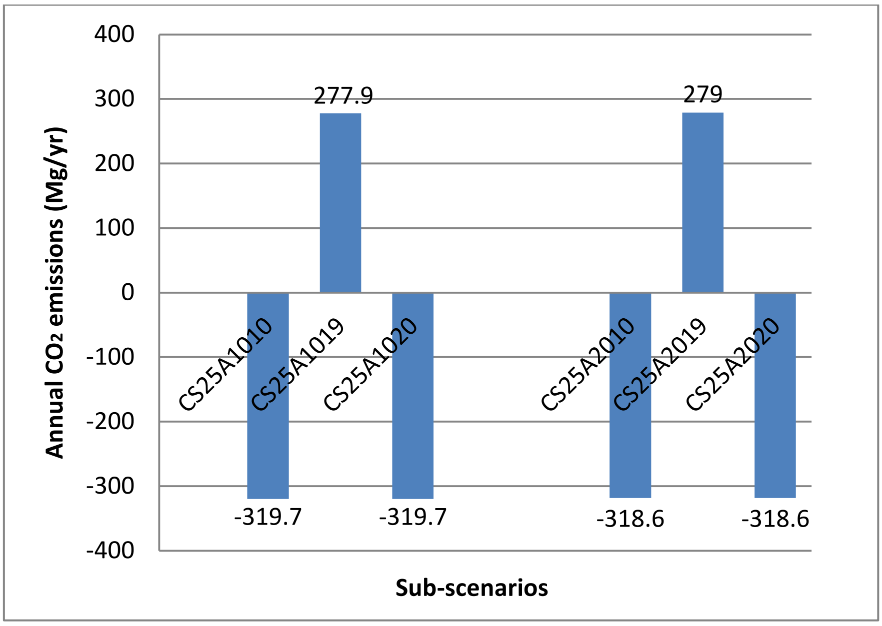


Figure 5.19: Total annual CO_2 emissions of de-centralized and centralized sub-scenarios at the CO_2 optimization stage.

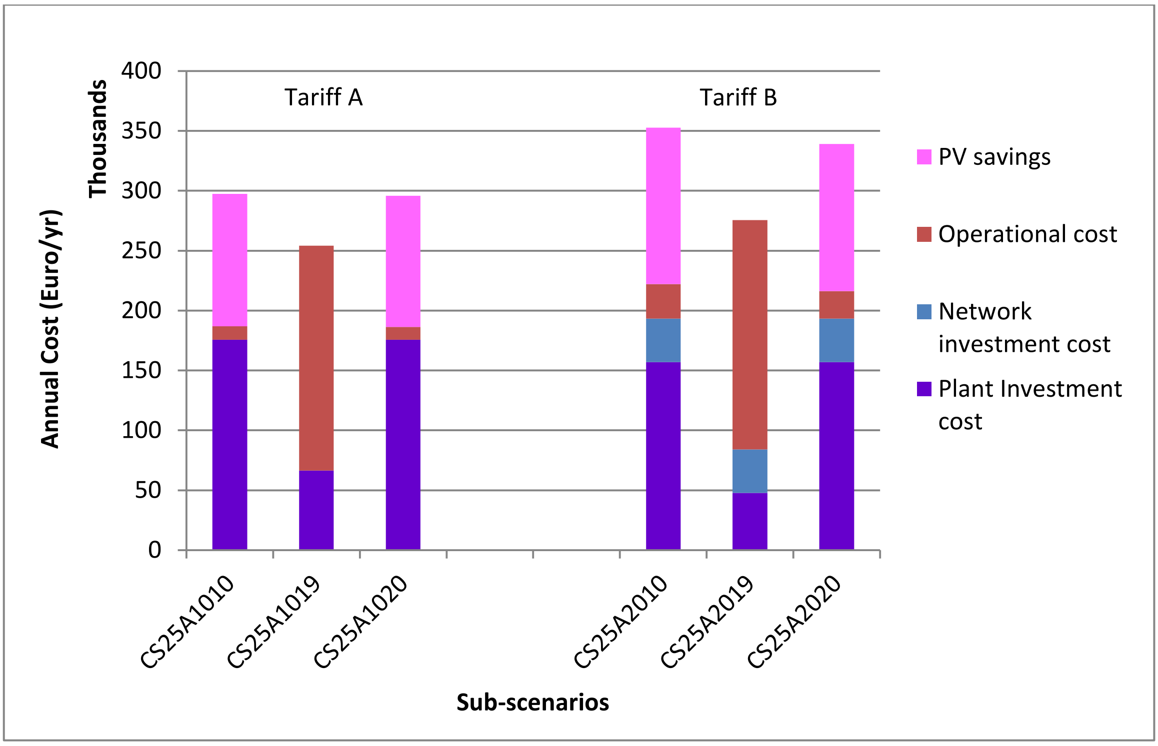


Figure 5.20: Total annual costs of de-centralized and centralized sub-scenarios at the CO_2 optimization stage. Note: PV savings (pink) are to be subtracted from the total annual cost, i.e. comparison is to be made at the red color.

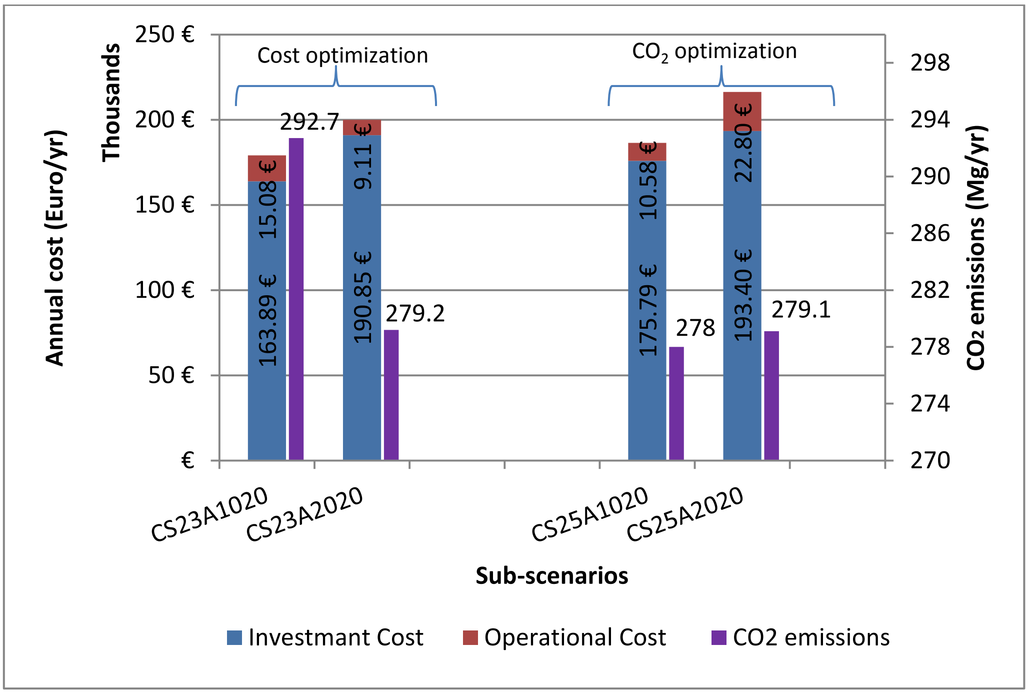


Figure 5.21: Investment and operational costs and CO_2 of de-centralized and centralized DCS obtained at the total annual cost and CO_2 single objective optimization stages. Note: values of the CO_2 do not include PV savings.

- Comparing the obtained annual costs for both single objective optimizations, presented in Figure 5.21, indicate a slight difference to results obtained at case study 1 where the centralized DC systems has 11.7% increase in total cost to the de-centralized system at cost optimization scenario and 16% at the CO_2 emissions optimization scenario. Such increase in total annual cost is relatively high and it is up to the decision maker to decide whether to invest in a centralized system or not.

- On the other hand comparing the annual CO_2 emission results for the two single objective scenarios has showed a similar pattern to the one observed at case study 1 where deciding for centralized DC system has lowered the total annual CO_2 emissions by 4.6% within the cost optimization objective function, yet caused an increase of only 0.4% within the CO_2 emission optimization objective function. Again, CO_2 emissions level for the centralized DC systems under the two objective functions were almost the same and very close to that obtained at de-centralized systems under CO_2 emission optimization. This validates the previous conclusion that investing in centralized DC systems will automatically save CO_2 emissions even when it is not counted for.

- The reduction in CO_2 emissions achieved by switching the objective function from minimizing total cost to minimizing CO_2 emissions, i.e. from CS23A1020 to CS25A1020, was 5%. Similar to case study 1, optimizing case study 2 under reducing CO_2 emissions objective does not achieve a significant impact in comparison to that obtained at cost objective since cost optimizing process already includes reducing operational cost by lowering the amount of primary energy consumed and thus already having achieved enhanced CO_2 emission results.

In the next section, multi objective optimization combining both annual cost and CO_2 emissions for this case study will be carried out. A simplified version of Pareto frontier will be obtained and the reliability of DC systems within hot climate regions will be investigated.

5.5 Multi-Objective Optimization: Cost and CO_2 Emissions

The scope of this work is expanded to include multi objective optimizations combining both total annual cost and CO_2 emissions objectives. The purpose of this stage is to investigate and analyze the impact of including environmental objectives in the decision making process as an addition to the traditional cost criteria. At this stage of the investigation the same assumptions adopted in both cost and CO_2 emission optimizations were adopted as well. Most importantly, COPs were considered constant in regards to the partial load and outdoor temperature variation, however variable in regards to the chiller size. Only the new PV panels' integration policy was considered at this stage. Investigations were performed for de-centralized and centralized DC systems for both electricity tariffs A and B.

5.5.1 De-Centralized DC systems

As explained in Chapter 3, the combination of the two objectives has been performed by adopting the Normalized Weighted Sum method where the two contradicting objective functions were turned into a one normalized objective function by means of normalizing weights, see eq. (3.88). These weights were calculated by difference between each objectives magnitude when the other objective is minimized (also known as Nadir value Z^N) and each objectives minimum value when optimized alone (Utopia value Z^U):

$$Z_{Multi} = W_C \,.Z_C + W_{CO2}\,.Z_{CO2} \qquad \text{Eq. (3.88)}$$

$$W_C = U_C \cdot \frac{1}{Z_C^N - Z_C^U}$$

$$W_{CO2} = U_{CO2} \cdot \frac{1}{Z_{CO2}^N - Z_{CO2}^U}$$

Where U_C and U_{CO2} are importance weights assigned by the decision maker according to the importance of each objective in the decision making process. Table 5.3 shows the Nadir and Utopia value obtained at each single objective optimization.

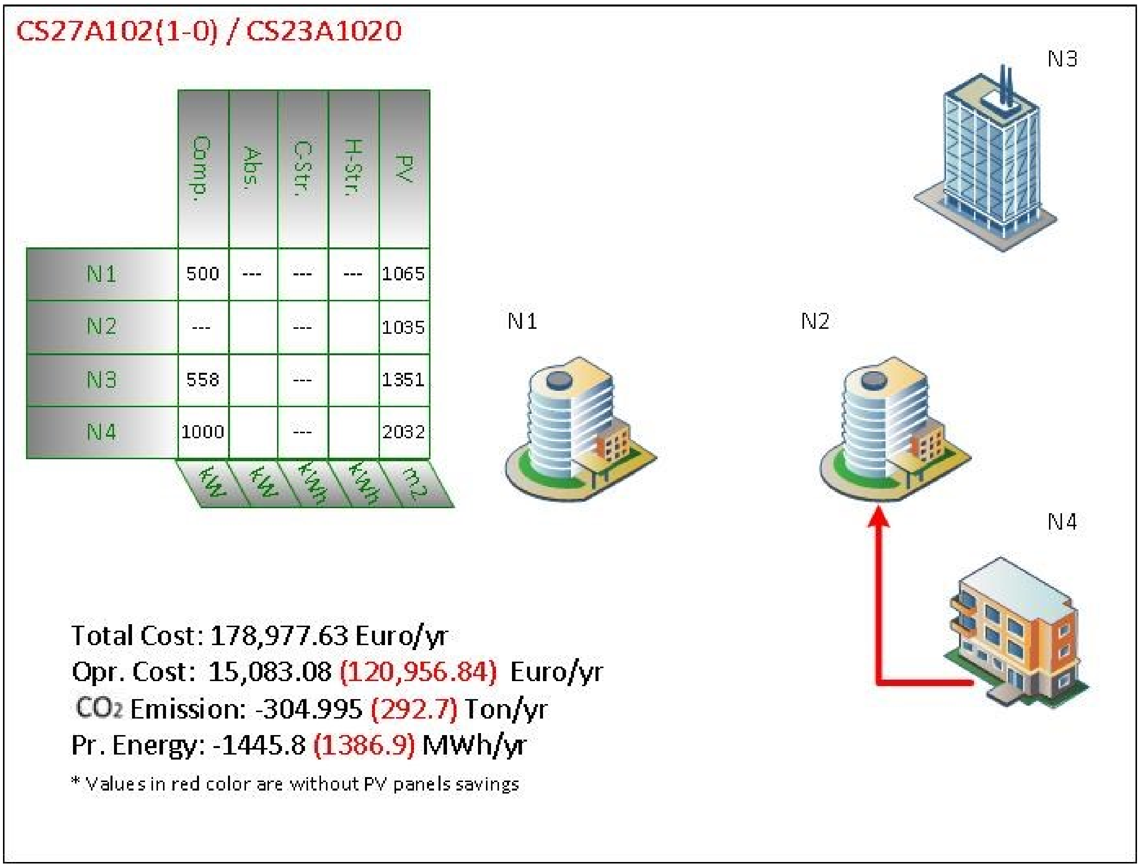
Table 5.3: Nadir and Utopia values obtained at each single objective optimization for the de-centralized DC systems.

Single objective optimization		Total annual cost (Euro/yr)	Total annual CO_2 emission (Ton/yr)
Total annual cost objective	CS23A1020	Z_C^U = 178977.63	Z_{CO2}^N = -304.995
	CS23B1020	Z_C^U = 175065.84	Z_{CO2}^N = -304.995
CO_2 emission objective	CS25A1020	Z_C^N = 186365.47	Z_{CO2}^U = -319.731
	CS25B1020	Z_C^N = 182453.68	Z_{CO2}^U = -319.731

Observing the obtained DC systems at the single objective optimizations and their Utopia and Nadir values can give us a sufficient overview of where a multi objective optimization solution may lay where each of the single objective optimization scenarios represents the far limit to which one can reach in regards to that particular objective. Any obtained system under multi-objective optimization would be somewhere between these two far limits. These two far limits along with a certain number of multi objective optimization scenarios can give a clear imagination of Pareto Frontier. The Utopia and Nadir values, presented in Table 5.3, also tell a lot about possible enhancement. For example, the value of CO_2 emissions at the total annual cost optimization, i.e. CO_2 Nadir value, for both electricity tariffs was (-304.995 Ton/year), while the CO_2 Utopia value, when CO_2 is the objective to be optimized, was (-319.731 Ton/year). The difference between the two values, 14.7 ton/year, represents the maximum possible enhancement in CO_2 emissions which can only be achieved when the optimization is completely shifted from optimizing merely annual cost to optimizing CO_2 emissions only. Similarly, the differences in the Utopia and Nadir values for the annual cost at each electricity tariff represent the maximum possible enhancement in annual cost that can only be achieved when the optimization is completely shifted from optimizing merely CO_2 emissions to optimizing annual cost only. In order to generate the Pareto Frontier, several values for the importance weights, i.e. U_C and $U_{CO2,}$ were adopted. These values are very important to analyze the impact of considering each objective and its impact on the outcomes of the other objective in in the decision making process. The values of these weights considered in this work were:

CS27A/B102(0-1): Cost 0-1 CO_2 (i.e. Single objective, CO_2 only: CS25A/B1020), Figure 5.15.
CS27A/B102(1-0): Cost 1-0 CO_2 (i.e. Single objective, Cost only: CS23A/B1020), Figure 5.22.
CS27A/B102(1-1): Cost 1-1 CO_2 (i.e. Multi objective with equal importance), Figure 5.23.
CS27A/B102(1-2): Cost 1-2 CO_2 (i.e. Multi objective with environmental focus), Figure 5.24.
CS27A/B102(2-1): Cost 2-1 CO_2 (i.e. Multi objective with economic focus), Figure 5.25.
CS27A/B102(2-3): Cost 2-3 CO_2, Figure 5.26.
CS27A/B102(3-2): Cost 3-2 CO_2, Figure 5.27.
CS27A/B102(1-5): Cost 1-5 CO_2, Figure 5.28.
CS27A/B102(5-1): Cost 5-1 CO_2, Figure 5.29.
CS27A/B102(1-9): Cost 1-9 CO_2, Figure 5.30.
CS27A/B102(9-1): Cost 9-1 CO_2, Figure 5.31.

Figures 5.23 to 5.31 show the obtained solutions for de-centralized DC systems with the adopted importance weights. Observing these DC systems confirms the expectations that a multi objective optimization solution will be somewhere between the single objective optimization scenarios. The obtained DC system when optimizing CO_2 emissions, i.e. Figure 5.15, consist of separated over-sized individual systems at each building, whereas the obtained system at the annual cost optimization, Figure 5.22, contains a small de-centralized DC network connecting buildings N2 and N4. All the obtained system under multi-objective optimization were somewhere between these two options where de-centralized DC connecting the two buildings was preserved but the capacities of the installed chillers were varying from one multi objective scenario to another. When CO_2 emissions have higher importance values then chiller capacities tend to be over-sized to the value of 1000 kW which provides the highest COP. On the other hand, when annual cost had significant higher importance weight than that of CO_2 emissions, i.e. Figures 5.29 and 5.31, chiller capacities were obtained at the same values of the cost single objective scenario, i.e. Figure 5.15. However, when annual cost had slightly higher importance weight than that of CO_2 emissions, i.e. Figures 5.25 and 5.27, chiller at building N3 was over-sized. This is due to the effect of considering the CO_2 emissions objective which resulted in better, i.e. lower, CO_2 emissions for the obtained system.



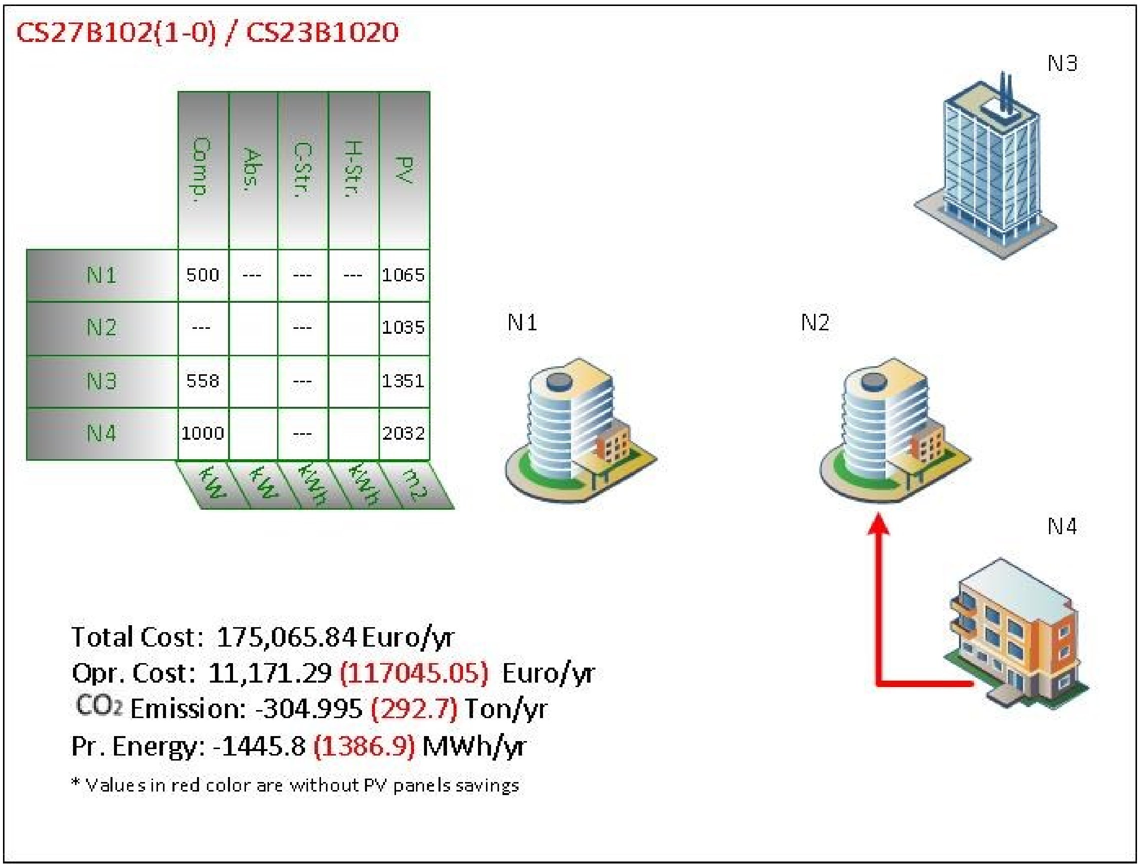


Figure 5.22: De-centralized DC network scenario at single objective (cost) optimization stage with new PV panels integration policy for case study 2 with electricity tariffs A and B.

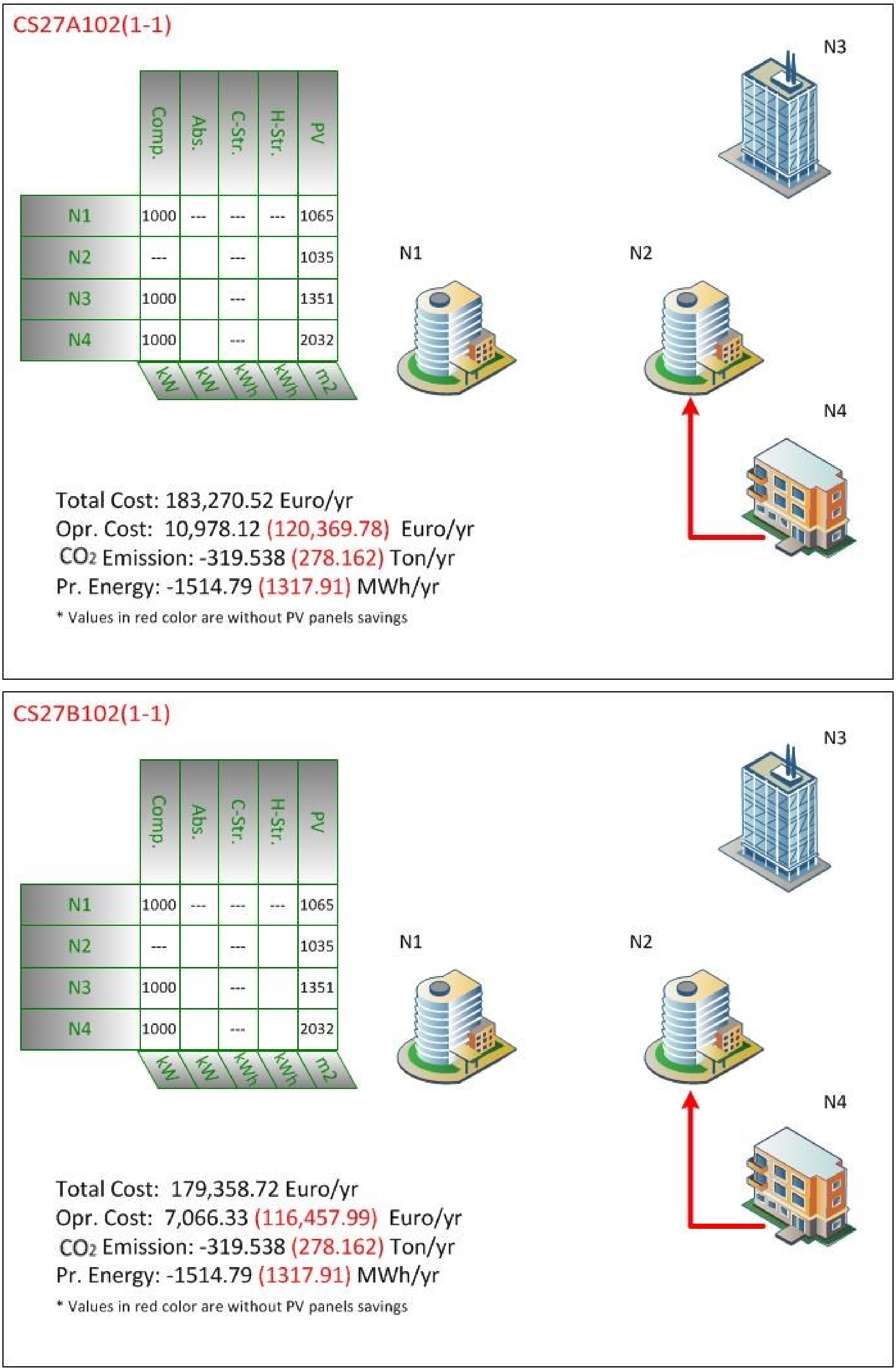


Figure 5.23: De-centralized DC network scenario at Multi objective (cost 1-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

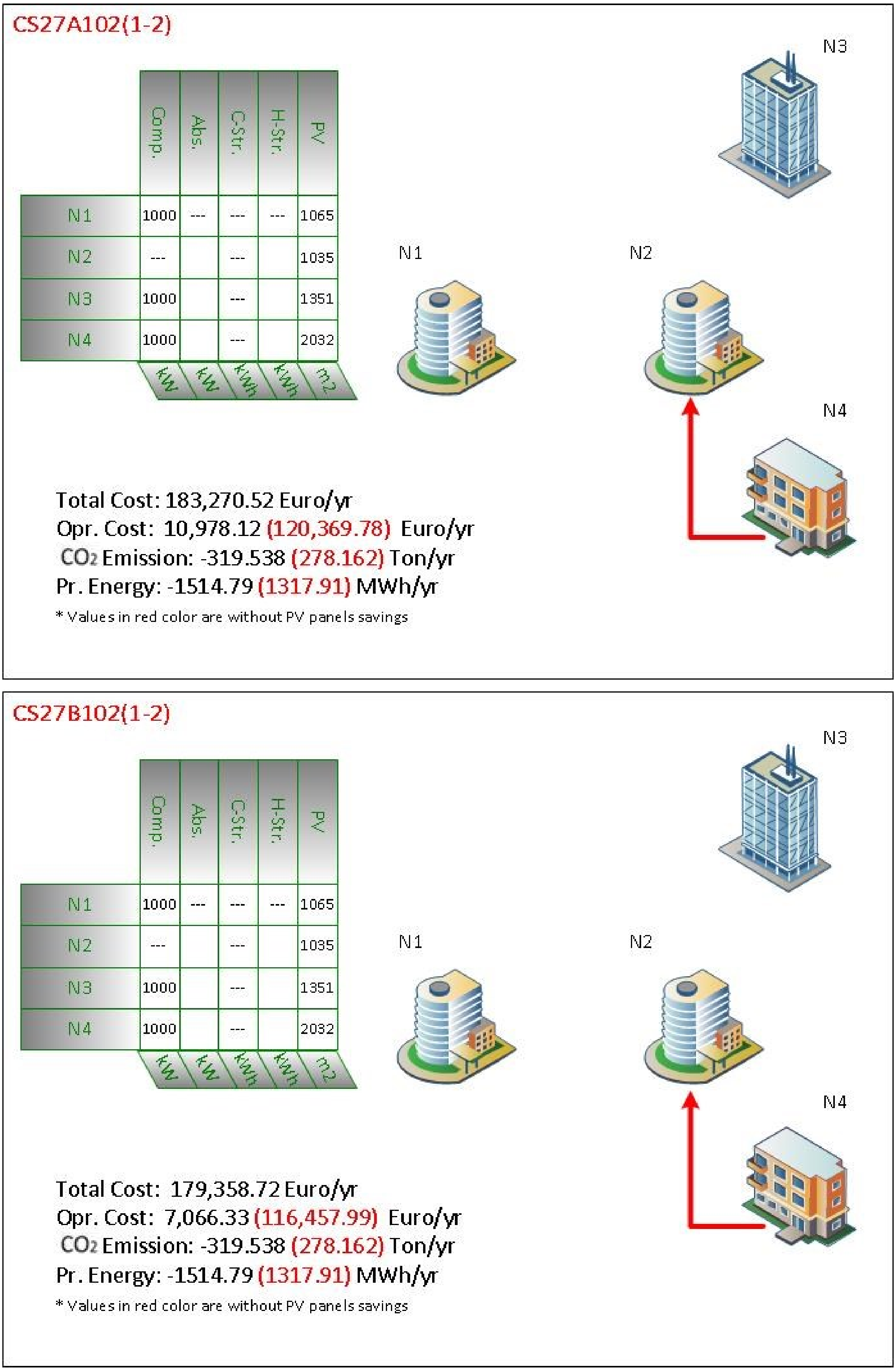
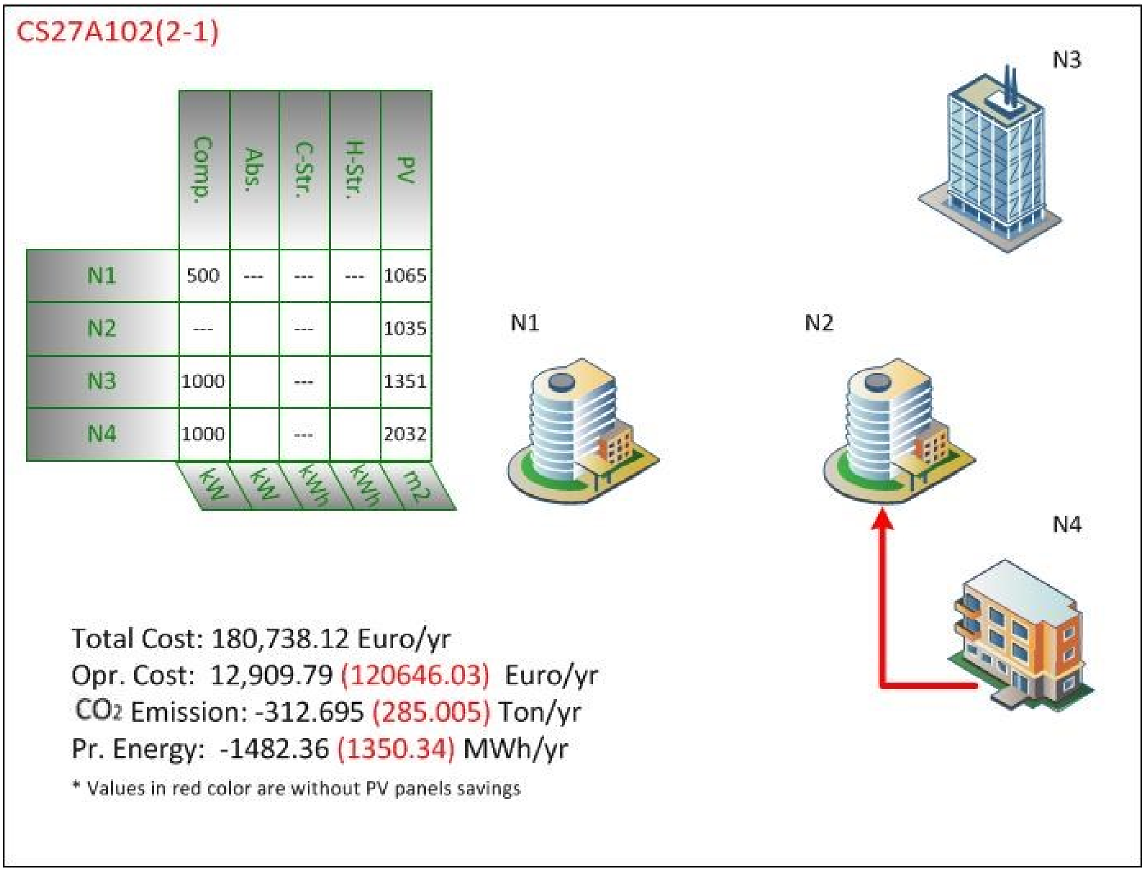
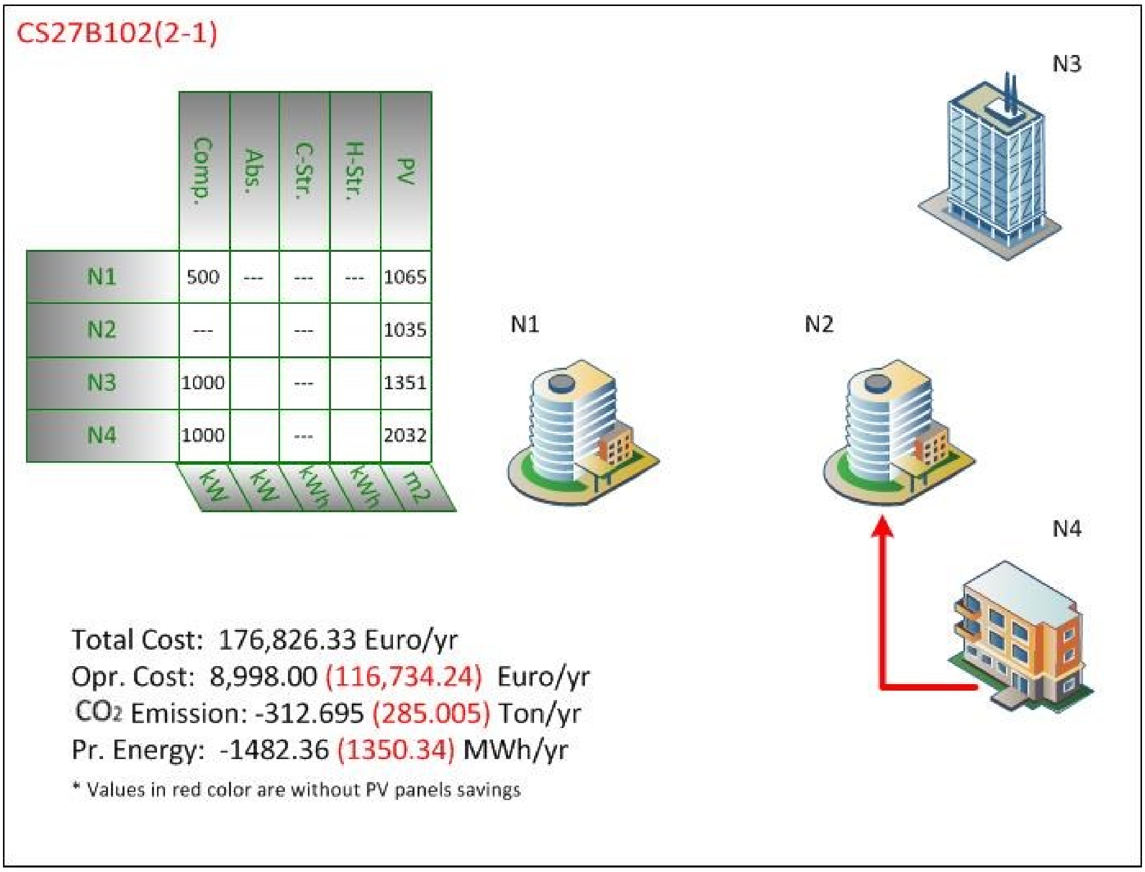


Figure 5.24: De-centralized DC network scenario at Multi objective (cost 1-2 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



	Comp.	Abs.	C-Str.	H-Str.	PV
N1	500	---	---	---	1065
N2	---		---		1035
N3	1000		---		1351
N4	1000		---		2032
	kW	kW	kWh	kWh	m2



	Comp.	Abs.	C-Str.	H-Str.	PV
N1	500	---	---	---	1065
N2	---		---		1035
N3	1000		---		1351
N4	1000		---		2032
	kW	kW	kWh	kWh	m2

Figure 5.25: De-centralized DC network scenario at Multi objective (cost 2-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

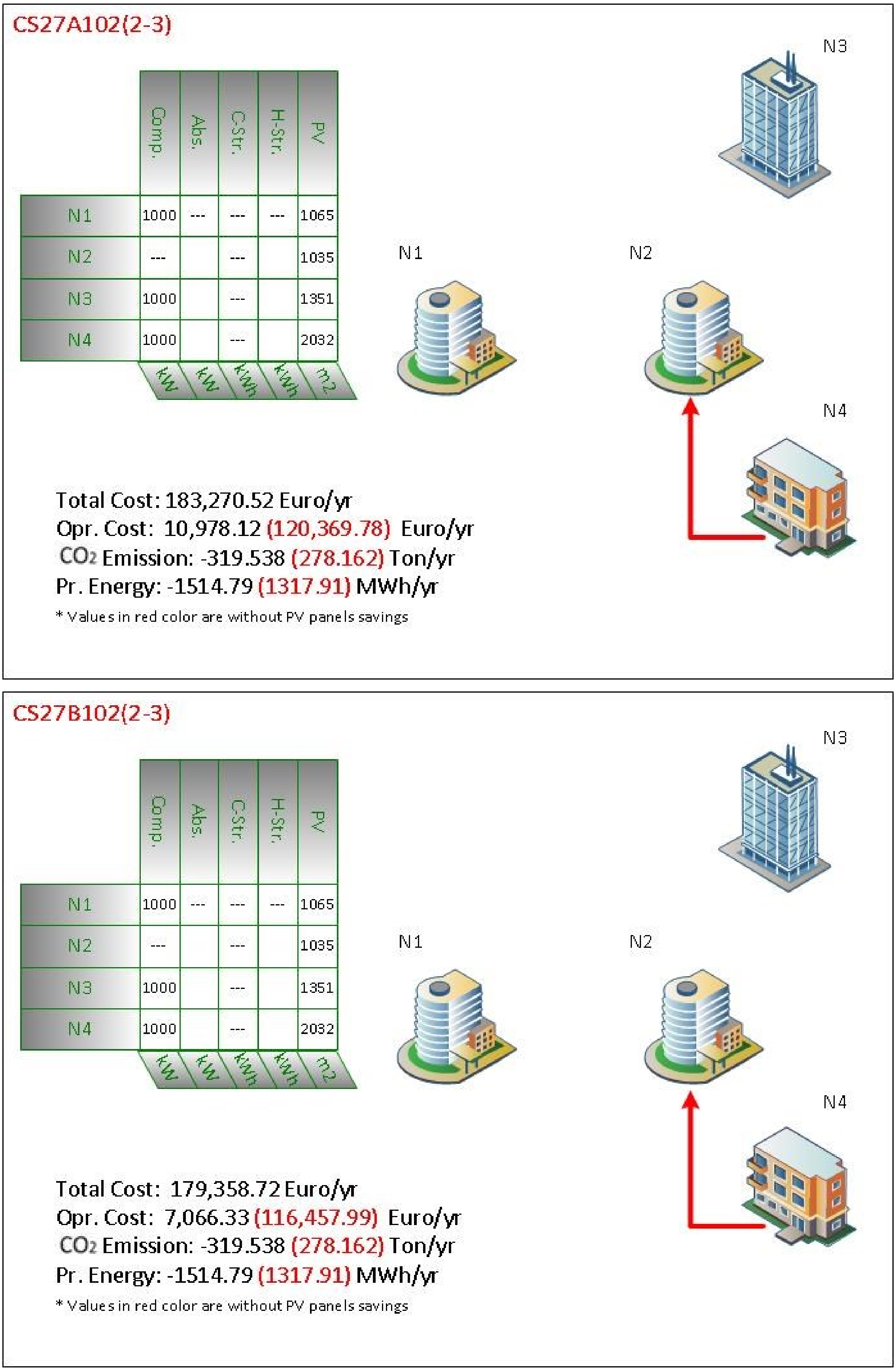
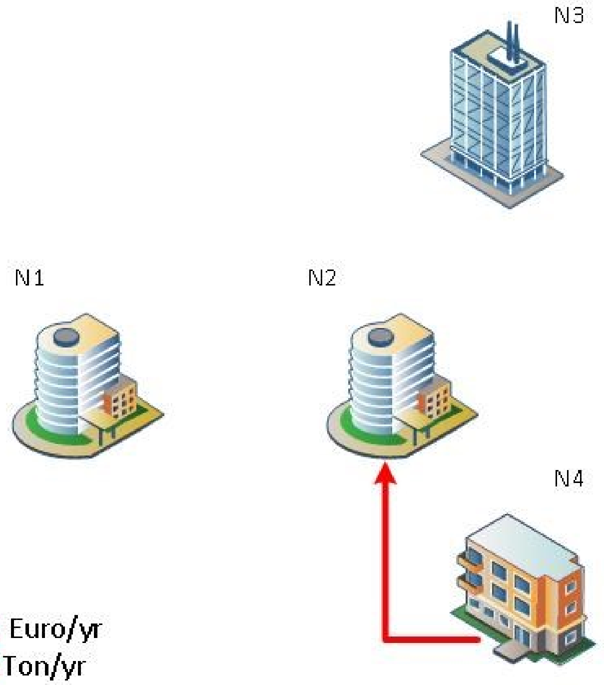


Figure 5.26: De-centralized DC network scenario at Multi objective (cost 2-3 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

CS27A102(3-2)

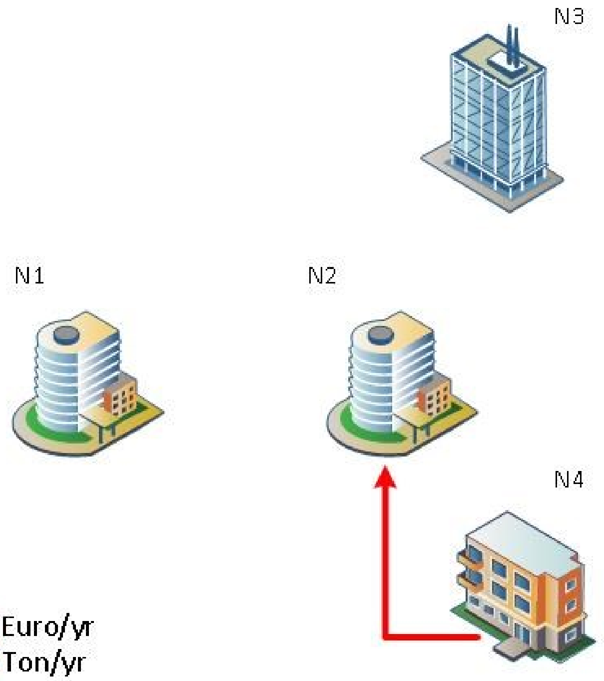
	Comp.	Abs.	C-Str.	H-Str.	PV
N1	500	---	---	---	1065
N2	---		---		1035
N3	1000		---		1351
N4	1000		---		2032
	kW	kW	kWh	kWh	m2



Total Cost: 180,738.12 Euro/yr
Opr. Cost: 12,909.79 (120646.03) Euro/yr
CO_2 Emission: -312.695 (285.005) Ton/yr
Pr. Energy: -1482.36 (1350.34) MWh/yr
* Values in red color are without PV panels savings

CS27B102(3-2)

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	500	---	---	---	1065
N2	---		---		1035
N3	1000		---		1351
N4	1000		---		2032
	kW	kW	kWh	kWh	m2



Total Cost: 176,826.33 Euro/yr
Opr. Cost: 8,998.00 (116,734.24) Euro/yr
CO_2 Emission: -312.695 (285.005) Ton/yr
Pr. Energy: -1482.36 (1350.34) MWh/yr
* Values in red color are without PV panels savings

Figure 5.27: De-centralized DC network scenario at Multi objective (cost 3-2 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

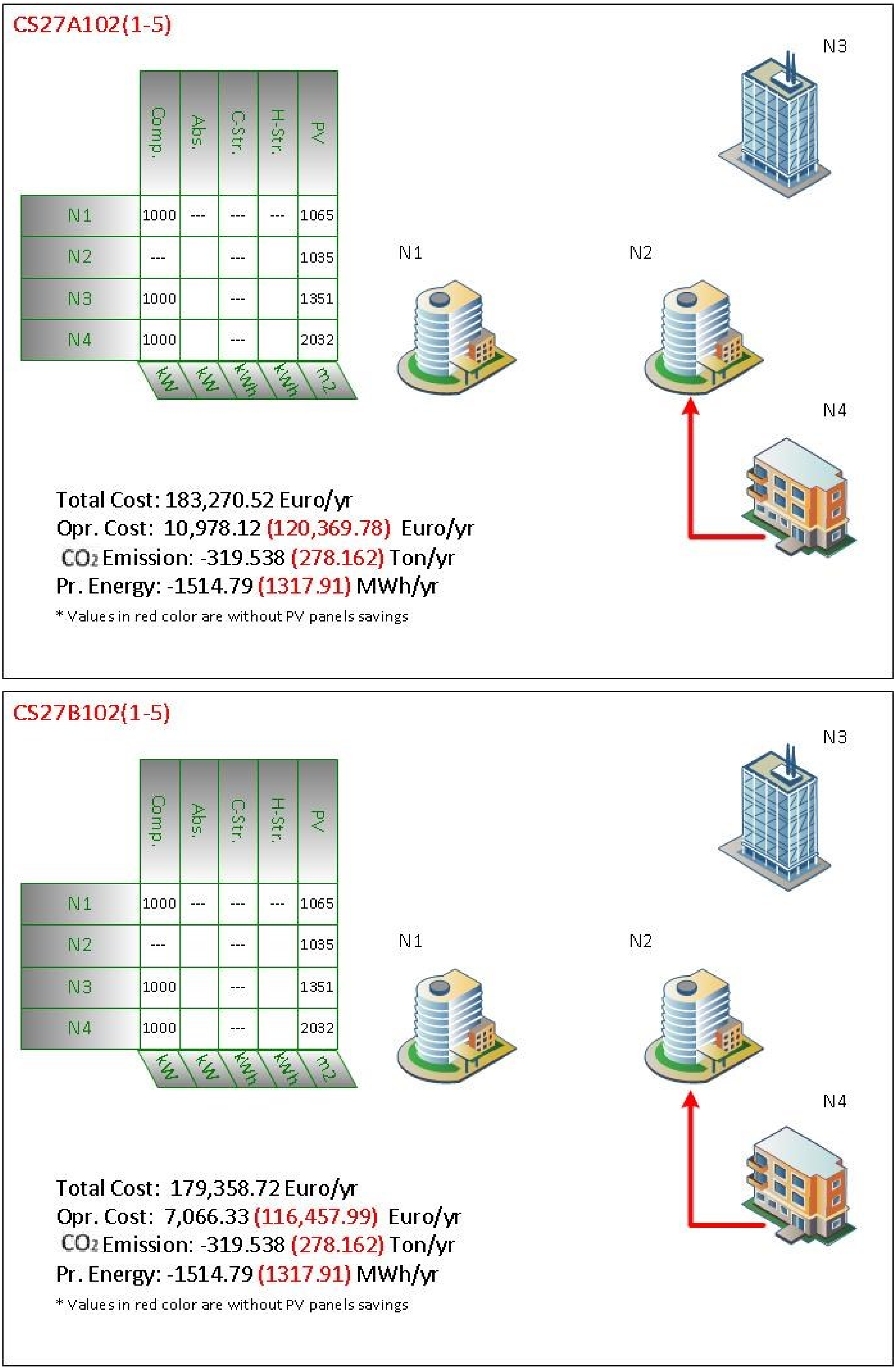
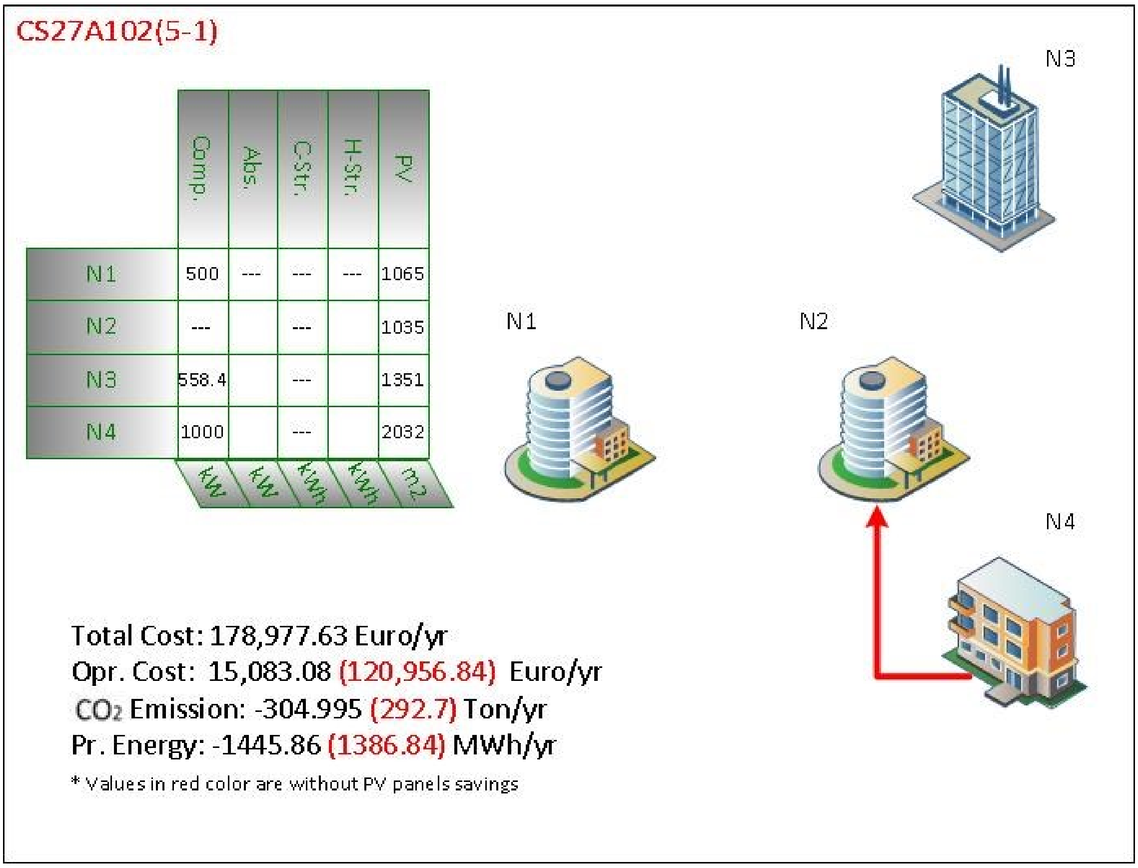


Figure 5.28: De-centralized DC network scenario at Multi objective (cost 1-5 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



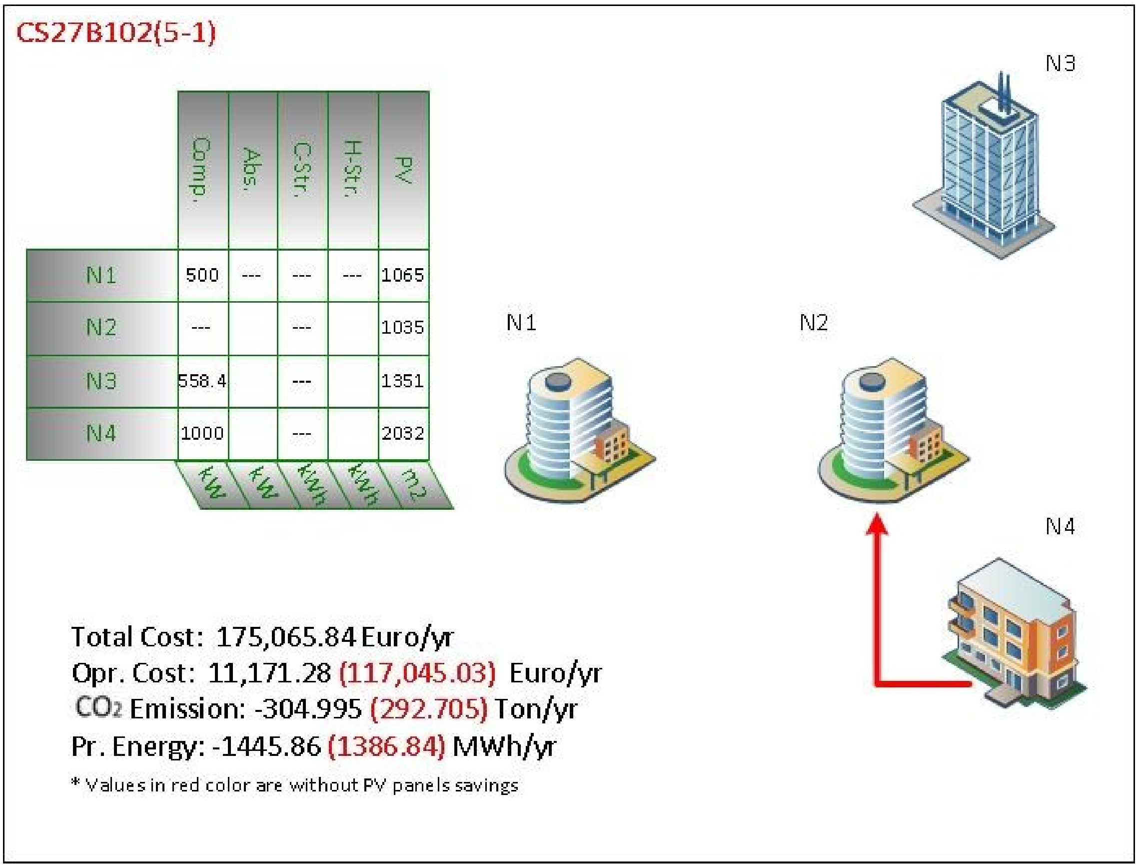
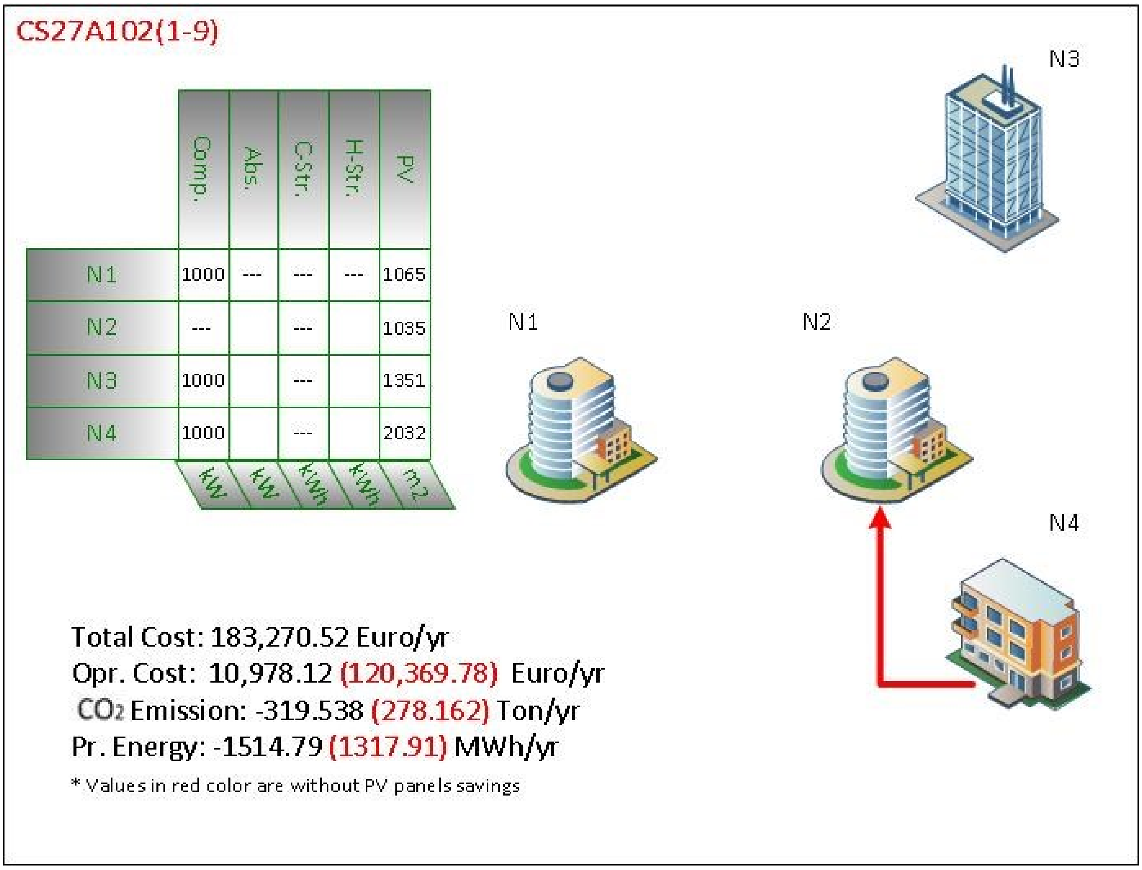
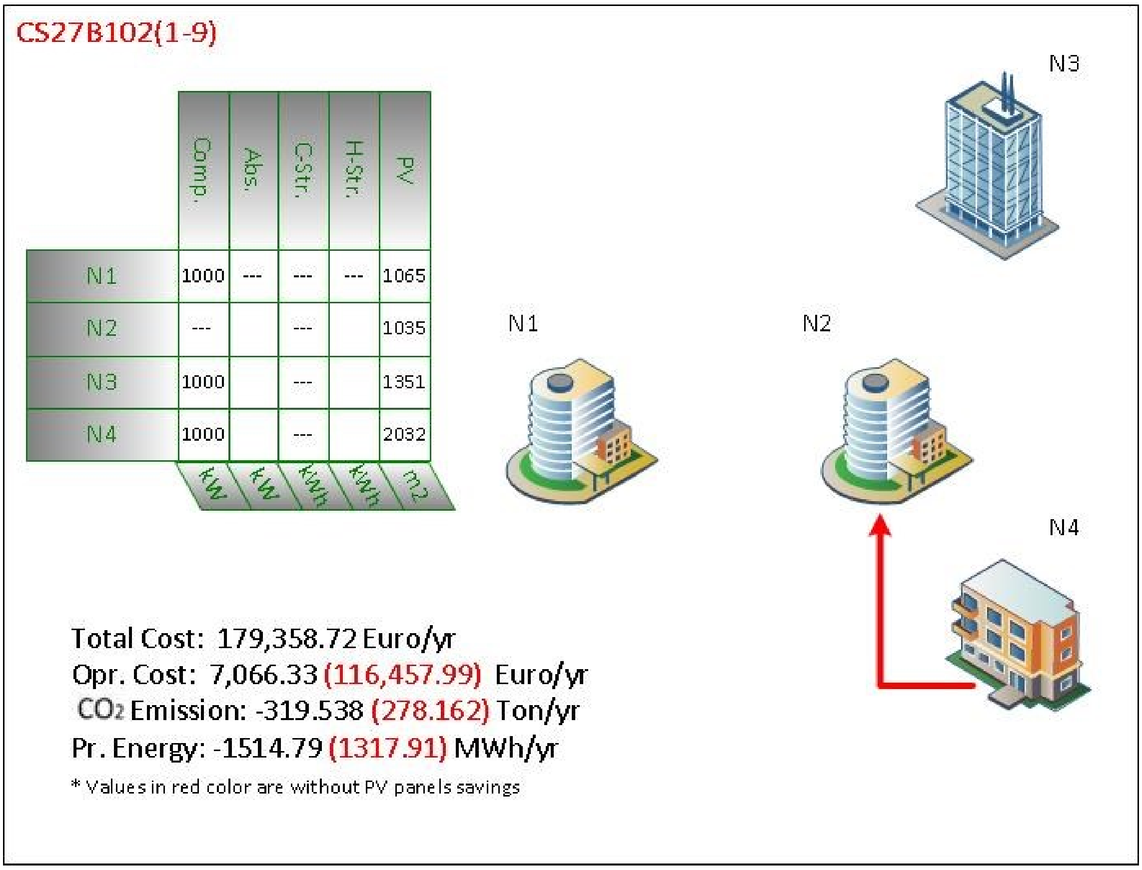


Figure 5.29: De-centralized DC network scenario at Multi objective (cost 5-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	1000	---	---	---	1065
N2	---		---		1035
N3	1000		---		1351
N4	1000		---		2032



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	1000	---	---	---	1065
N2	---		---		1035
N3	1000		---		1351
N4	1000		---		2032

Figure 5.30: De-centralized DC network scenario at Multi objective (cost 1-9 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

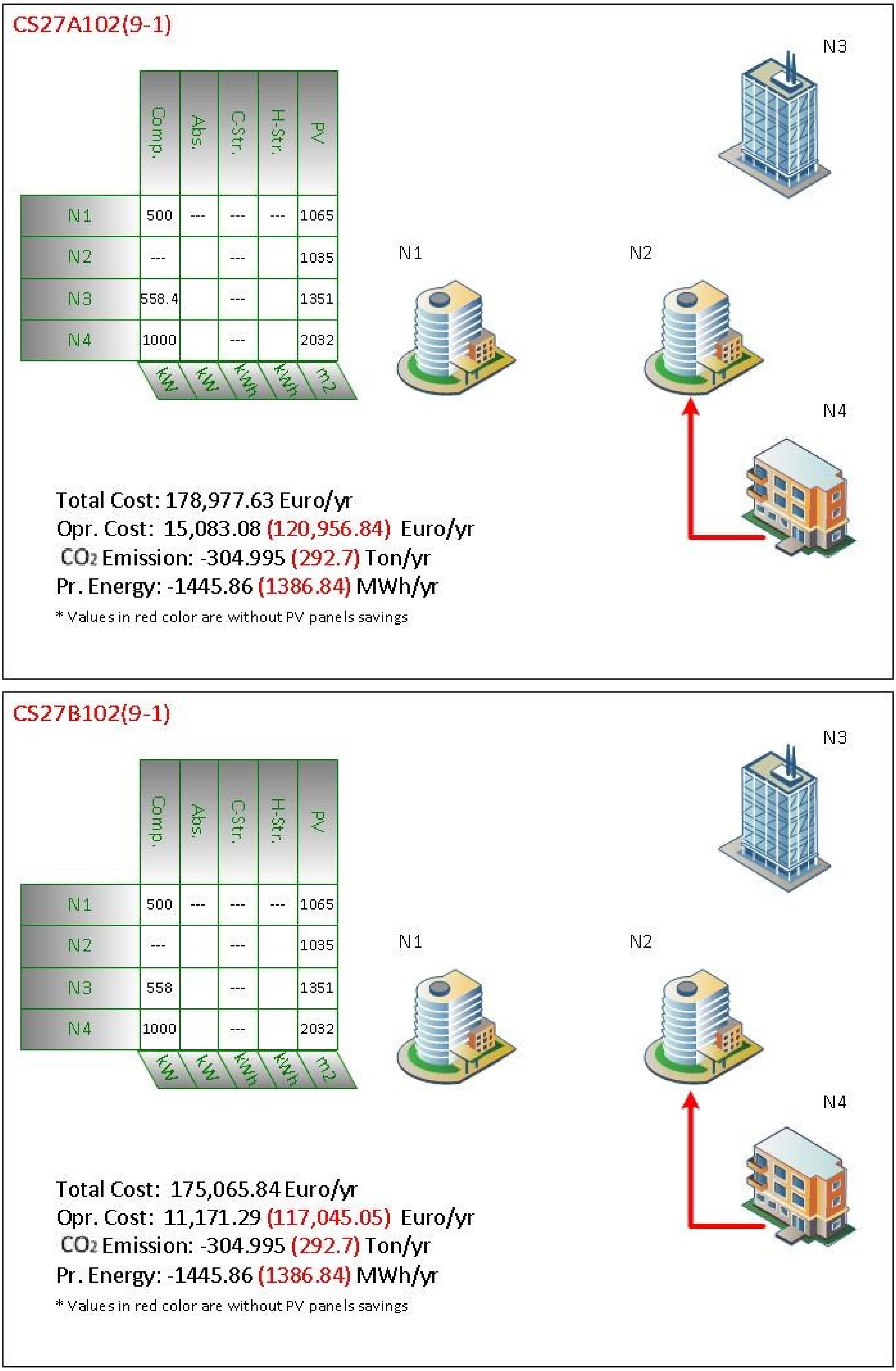


Figure 5.31: De-centralized DC network scenario at Multi objective (cost 9-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

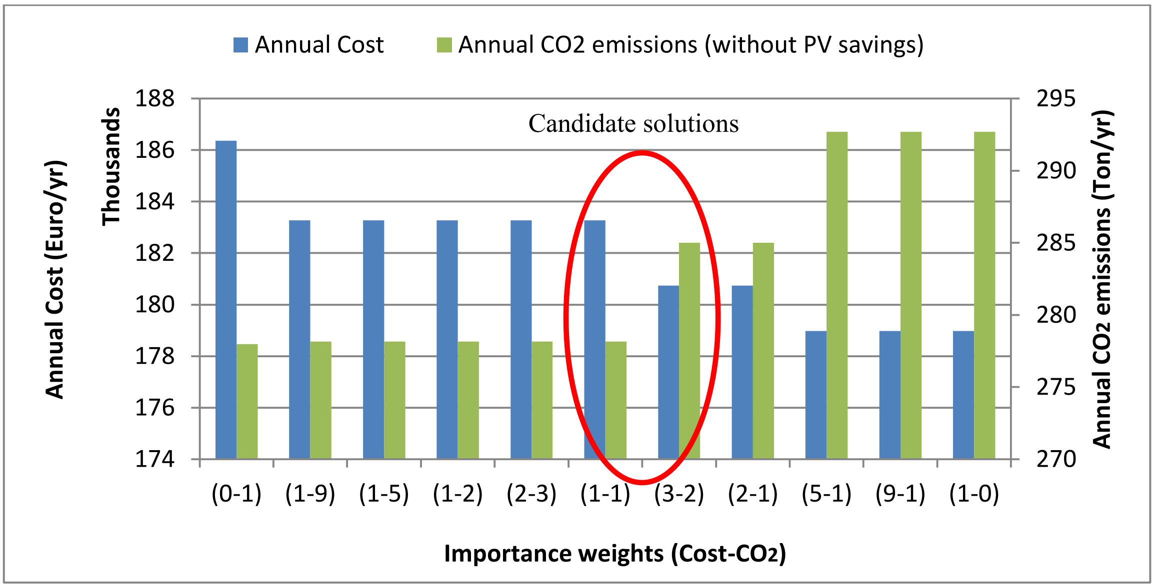


Figure 5.32: Annual cost and CO_2 emissions for the multi objectives de-centralized DC scenarios at different importance weights for case study 2 with electricity tariff A.

Figure 5.32 shows the total annual costs and CO_2 emissions of the various multi objectives scenarios. Pareto Frontier can be obtained by adopting CO_2 emissions as X-axis and annual cost as Y-axis as presented in Figure 5.33. Pareto Frontier represents the group of non-dominated multi objective solutions, i.e. no enhancement to one of the objectives is possible without harming the other objectives. It is possible to obtain solutions to the right-upper side of the frontier which are known as dominated solutions. A dominated solution is not considered as Pareto solution since that improving at least one of its objectives without harming the other objectives is still possible. However, it is realistically not possible to obtain a solution at the left-lower side of Pareto Frontier which is considered as idealistic region.

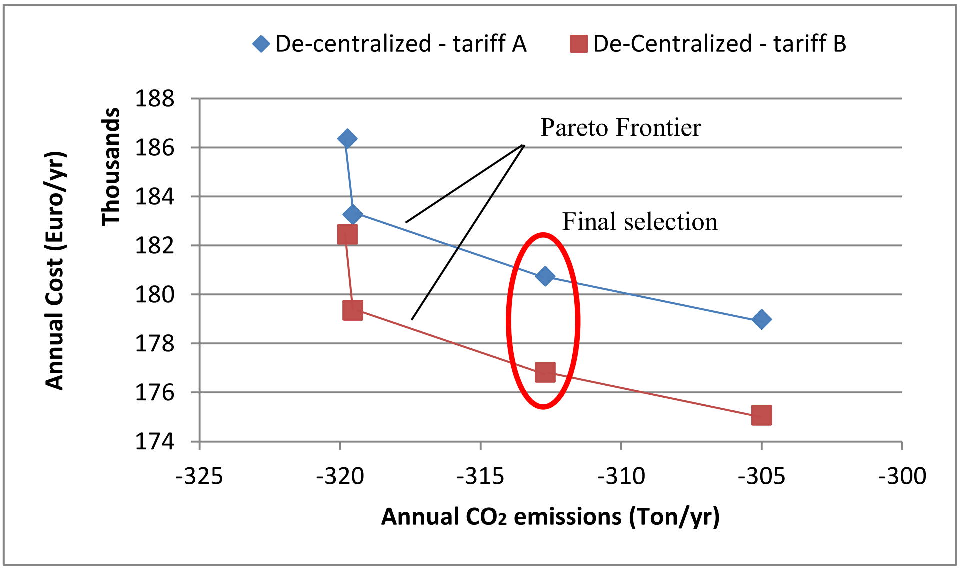


Figure 5.33: Pareto Frontier for De-centralized DC systems at various cost and CO_2 importance weights.

Based on the results demonstrated in Figures 5.32 and 5.33, two multi objective solutions stand out as reasonable solutions. The first one is the multi objective solution with importance weights (1-1) where it has achieved almost the same Utopia value for CO_2 emissions obtained at the single objective optimization scenario. This scenario has reduced the Nadir-Utopia gap for the cost objective by around 30-40% of the gap value. The second candidate solution is the multi objective solution with importance weights (3-2), which is the same solution with (2-1) weights. This solution has reduced the Nadir-Utopia gap for the total cost and CO_2 emissions objectives by around 75% and 50%, respectively. Thus the second candidate solution, i.e. solution (3-2), emerges as the preferred solution. However, since that the total annual cost Nadir-Utopia gap represents only 4% increase to the Utopia values, i.e. lowest total cost achievable, and the CO_2 emission Nadir-Utopia gap represents about 4.5 % increase to the CO_2 emission Utopia values, deciding for the first candidate solution, i.e. solution (1-1), would be a reasonable choice as well.

5.5.2 Centralized DC systems

Since the obtained DC systems at multi objective optimizations were always somewhere between the two single objective scenarios, this indicated that full centralized DC systems are out of the Pareto Frontier. Therefore, an investigation was carried out to obtain a set of centralized DC systems through multi objective optimization. In order to achieve that the Utopia and Nadir, presented in Table 5.4, were obtained from the single objective optimization scenarios, where:

CS27A/B202(0-1): Cost 0-1 CO_2 (i.e. Single objective, CO_2 only: CS25A/B2020), Figure 5.18.
CS27A/B202(1-0): Cost 1-0 CO_2 (i.e. Single objective, Cost only: CS23A/B2020), Figure 5.11.

Table 5.4: Nadir and Utopia values obtained at each single objective optimization for the centralized DC systems.

Single objective optimization		Total annual cost (Euro/yr)	Total annual CO_2 emission (Ton/yr)
Total annual cost objective	CS23A2020	Z_C^U = 199,962.03	Z_{CO2}^N = -318.548
	CS23B2020	Z_C^U = 197,207.00	Z_{CO2}^N = -318.549
CO_2 emission objective	CS25A2020	Z_C^N = 216,191.53	Z_{CO2}^U = -318.621
	CS25B2020	Z_C^N = 207,034.27	Z_{CO2}^U = -318.621

By observing the centralized DC systems obtained at the single objective scenarios it was noticed that the difference between Utopia and Nadir values is relatively smaller than that of the de-centralized DC systems. Figure 5.34 shows the annual cost and CO_2 emissions values of these single objective solutions in relative to the de-centralized Pareto Frontier. As mentioned previously, all multi objective scenarios will be somewhere between the two single objective solutions. Such small differences between Utopia and Nadir values, especially for CO_2 emission objective, indicate that a Pareto Frontier analysis is not needed since the multi objective solutions will not achieve big enhancements. In such cases single objective scenario with importance weights of (1 – 0) is sufficient and recommended due to the very small enhancement potential in the CO_2 emissions when switching the objectives. However, to validate this particular recommendation, the same importance weights adopted within the de-centralized DC scenarios were adopted to obtain the Pareto Frontier for the centralized DC systems as well:

CS27A/B202(1-1): Cost 1-1 CO_2 (i.e. Multi objective with equal importance), Figure 5.35.
CS27A/B202(1-2): Cost 1-2 CO_2 (i.e. Multi objective with environmental concern), Figure 5.36.
CS27A/B202(2-1): Cost 2-1 CO_2 (i.e. Multi objective with economic focus), Figure 5.37.
CS27A/B202(2-3): Cost 2-3 CO_2 , Figure 5.38.
CS27A/B202(3-2): Cost 3-2 CO_2 , Figure 5.39.
CS27A/B202(1-5): Cost 1-5 CO_2 , Figure 5.40.
CS27A/B202(5-1): Cost 5-1 CO_2 , Figure 5.41.
CS27A/B202(1-9): Cost 1-9 CO_2 , Figure 5.42.
CS27A/B202(9-1): Cost 9-1 CO_2 , Figure 5.43.

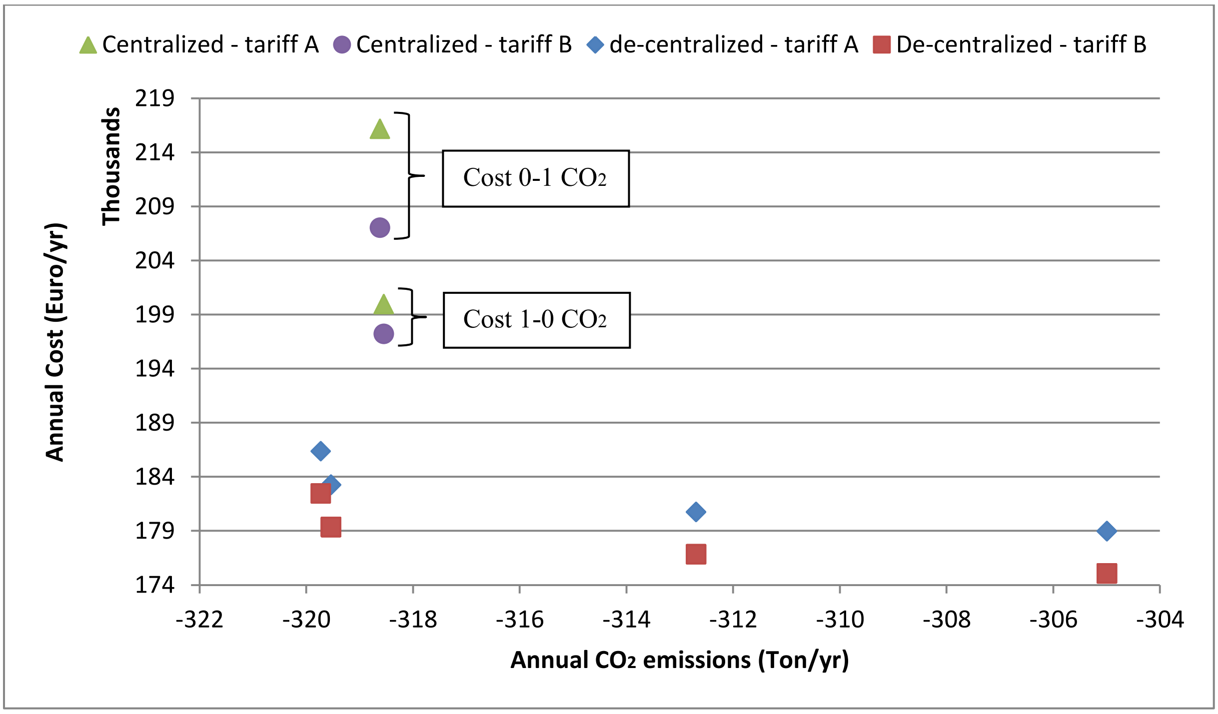


Figure 5.34: Pareto Frontier for De-centralized DC systems at various cost and CO_2 importance weights along with the centralized DC systems obtained at single objective scenarios.

Figures 5.35 to 5.43 show the obtained centralized DC systems for various importance weights adopted in this work. The optimization process was forced to select one central cooling energy plant. Therefore very limited changes occur on the DC network. A clearer impact can be observed on the location and sizes of cold storage tanks attached to the network. The annual cost of single objective reference scenario, i.e. Figure 5.11, had a central storage tank at the same location of the central chiller. On the other hand, the annual CO_2 emission of single objective reference scenario, i.e. Figure 5.16, had three cold storage tanks distributed at the various ends of the network with no storage installed at the central cooling energy production plant. Therefore, it was expected that higher importance weights for CO_2 emissions objective will push in the direction of distributing the storage tanks while higher importance weights will push in the direction of installing a central storage tank. However, no specific pattern of the chosen sizes or location was detected.

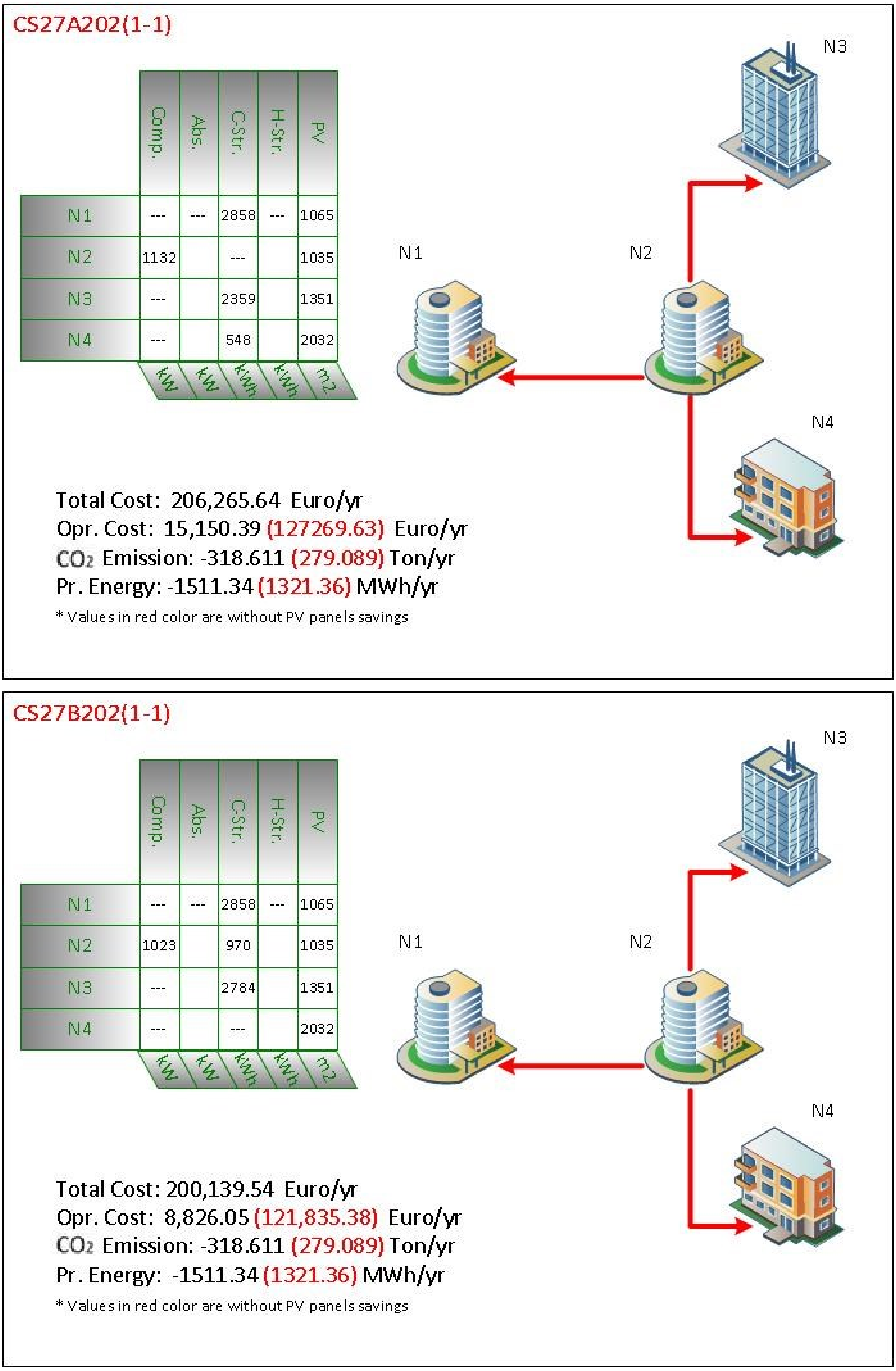


Figure 5.35: Centralized DC network scenario at Multi objective (cost 1-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

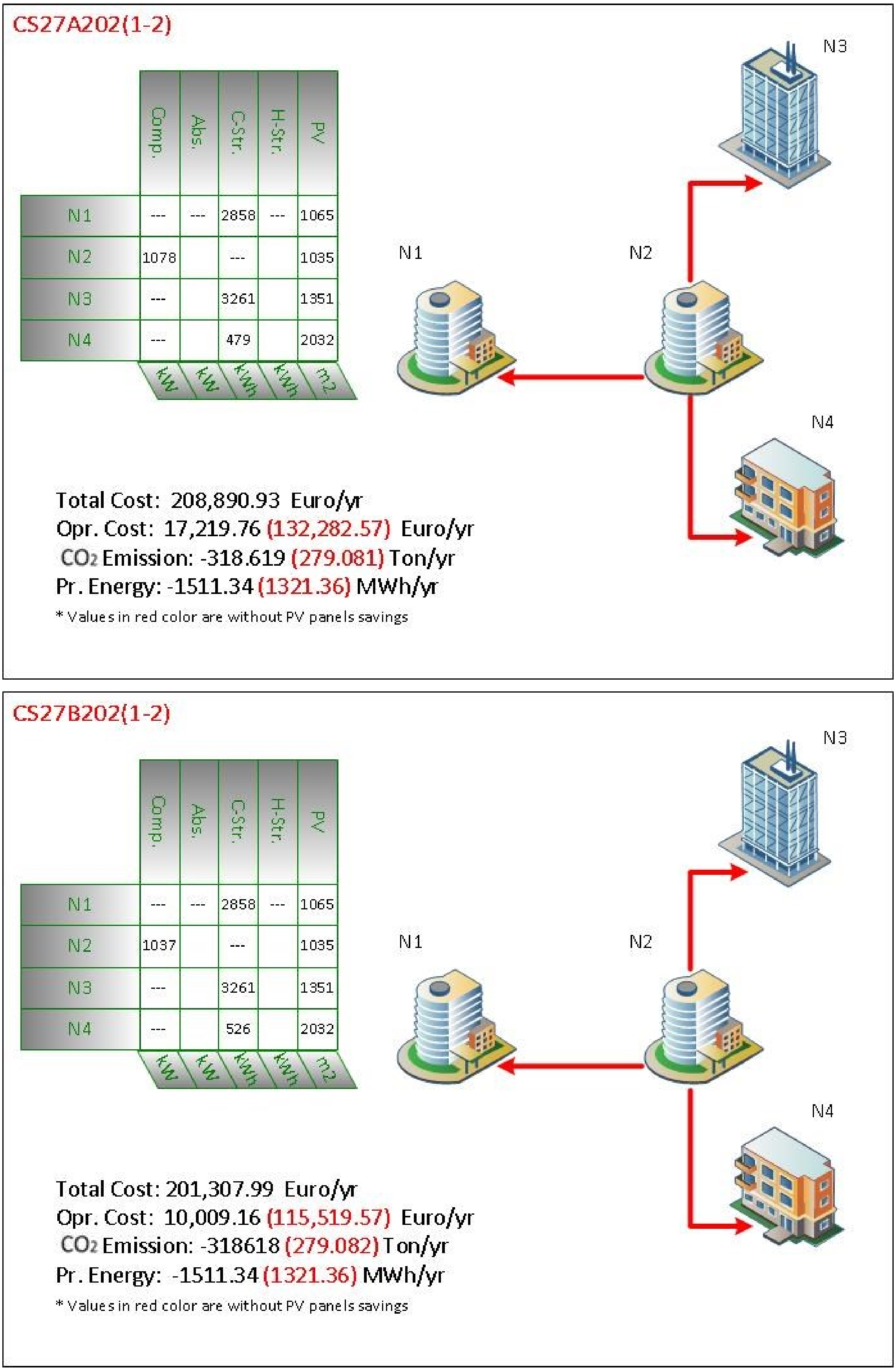
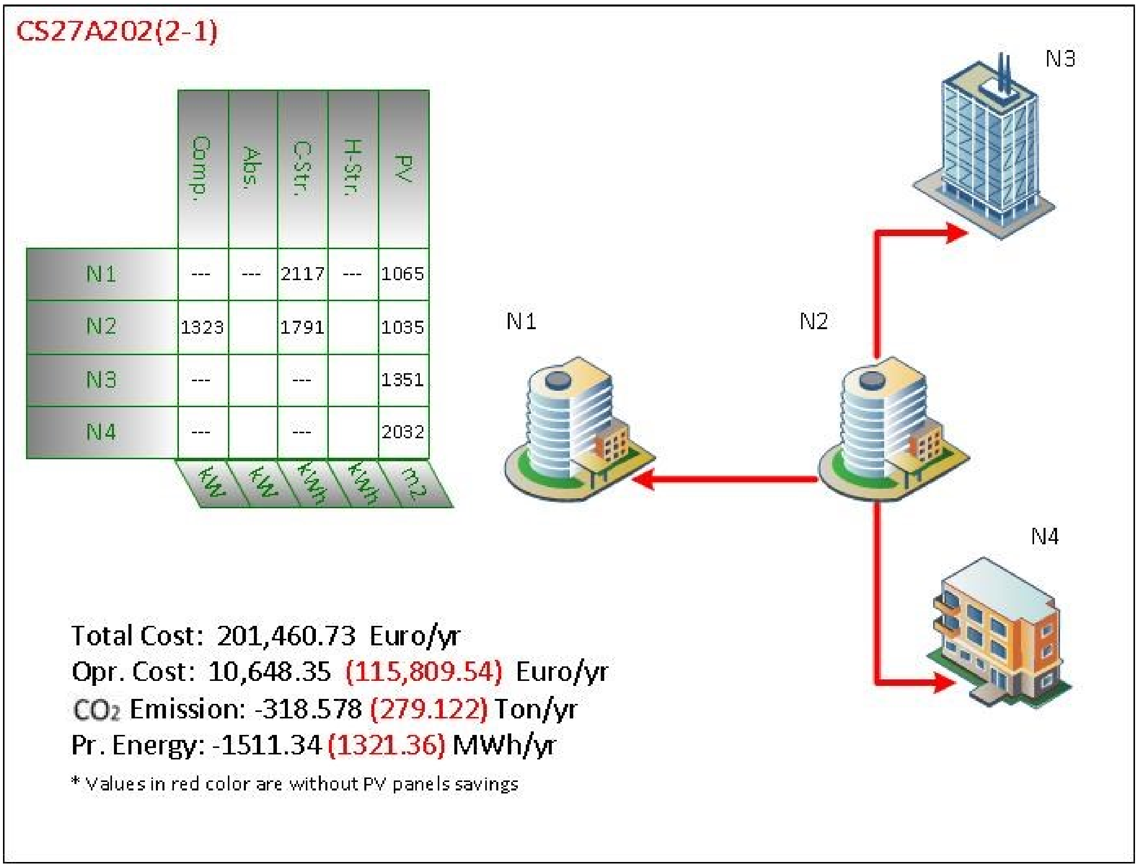
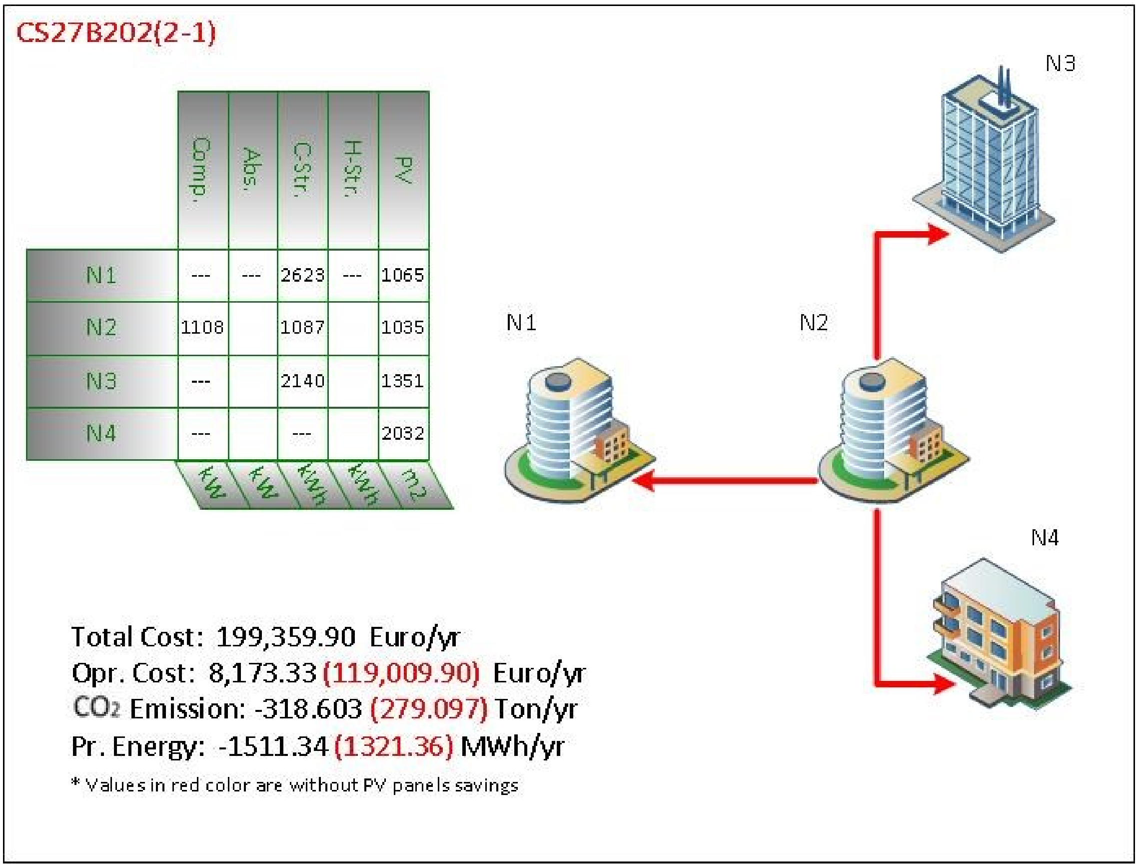


Figure 5.36: Centralized DC network scenario at Multi objective (cost 1-2 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	---	---	2117	---	1065
N2	1323		1791		1035
N3	---		---		1351
N4	---		---		2032



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	---	---	2623	---	1065
N2	1108		1087		1035
N3	---		2140		1351
N4	---		---		2032

Figure 5.37: Centralized DC network scenario at Multi objective (cost 2-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

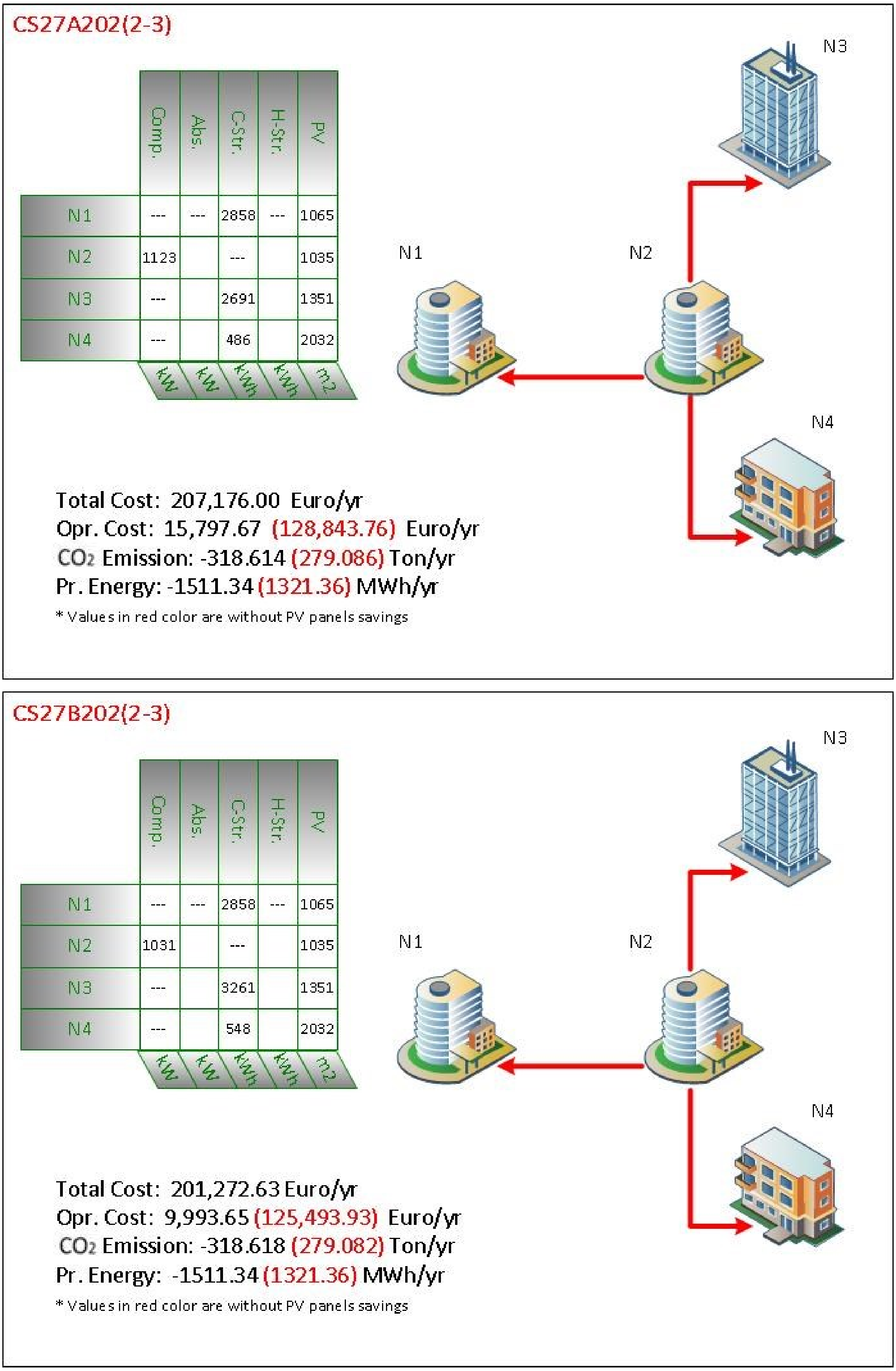
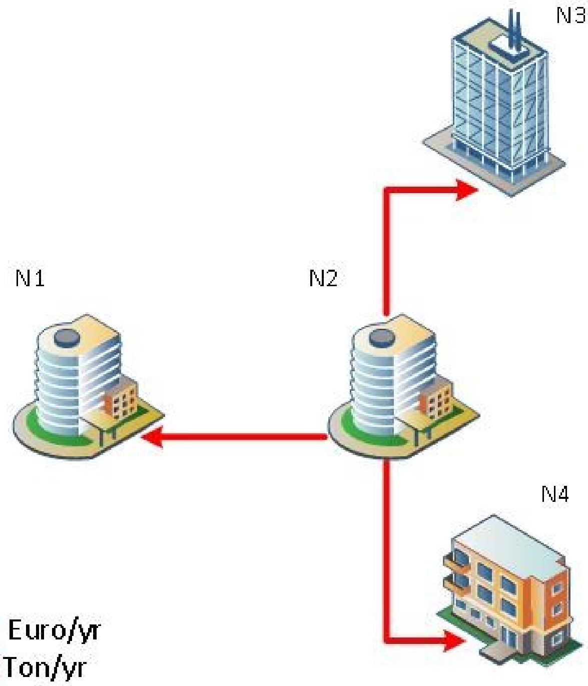


Figure 5.38: Centralized DC network scenario at Multi objective (cost 2-3 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

CS27A202(3-2)

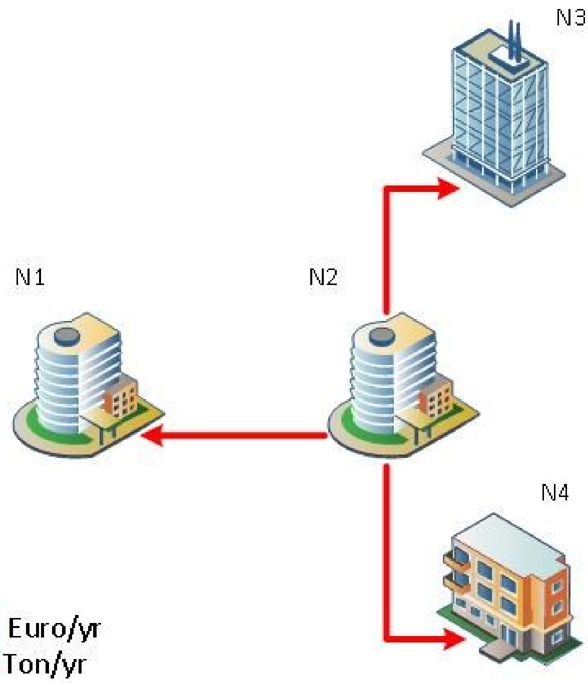
	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	---	---	2385	---	1065
N2	1173		1103		1035
N3	---		1777		1351
N4	---		---		2032



Total Cost: 203,747.97 Euro/yr
Opr. Cost: 12,600.38 (120,789.8) Euro/yr
CO_2 Emission: -318.597 (279.103) Ton/yr
Pr. Energy: -1511.34 (1321.36) MWh/yr
* Values in red color are without PV panels savings

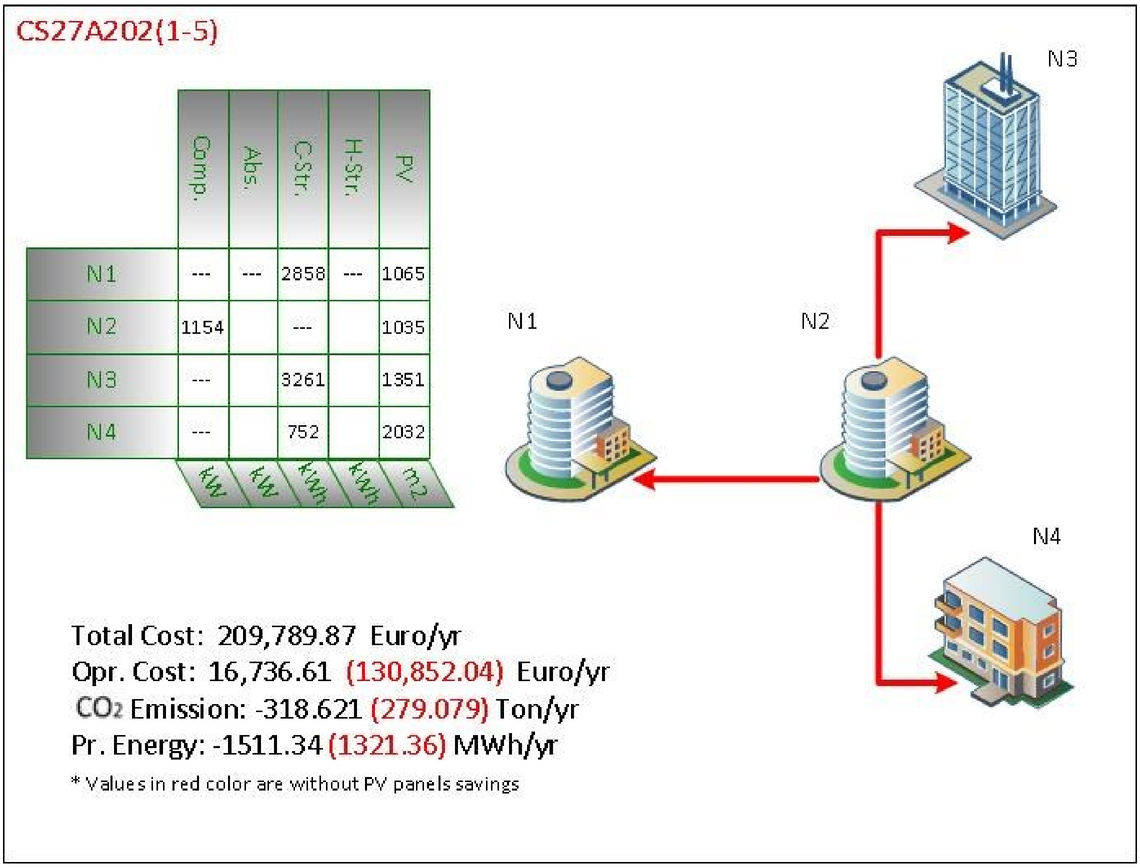
CS27B202(3-2)

	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	---	---	2657	---	1065
N2	1051		1087		1035
N3	---		2613		1351
N4	---		---		2032



Total Cost: 199,691.14 Euro/yr
Opr. Cost: 8,383.14 (120,242.04) Euro/yr
CO_2 Emission: -318.607 (279.093) Ton/yr
Pr. Energy: -1511.34 (1321.36) MWh/yr
* Values in red color are without PV panels savings

Figure 5.39: Centralized DC network scenario at Multi objective (cost 3-2 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



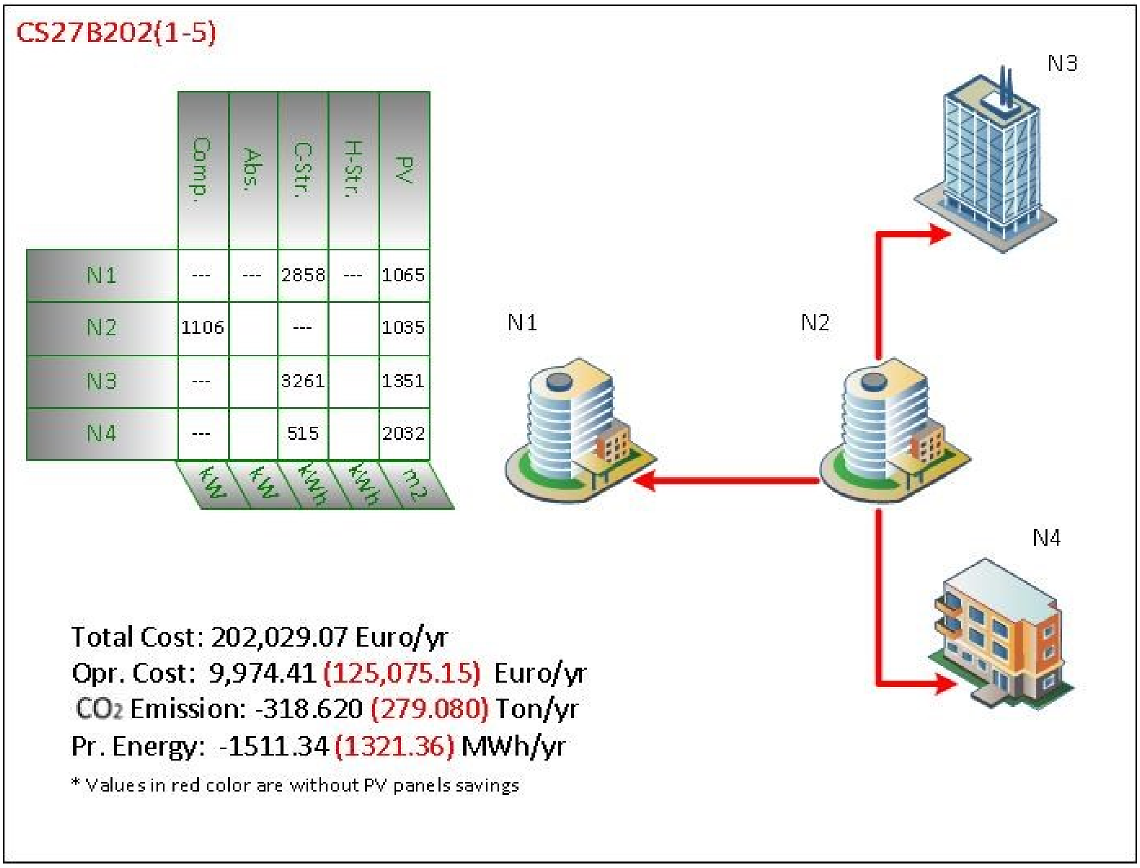
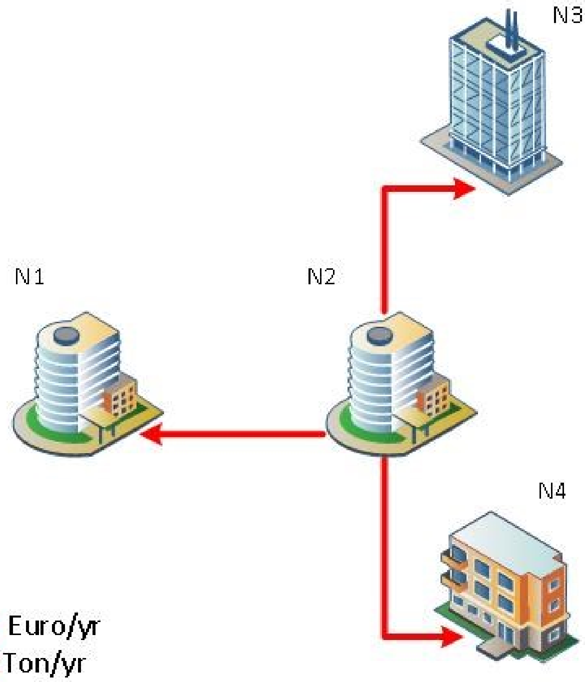


Figure 5.40: Centralized DC network scenario at Multi objective (cost 1-5 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

CS27A202(5-1)

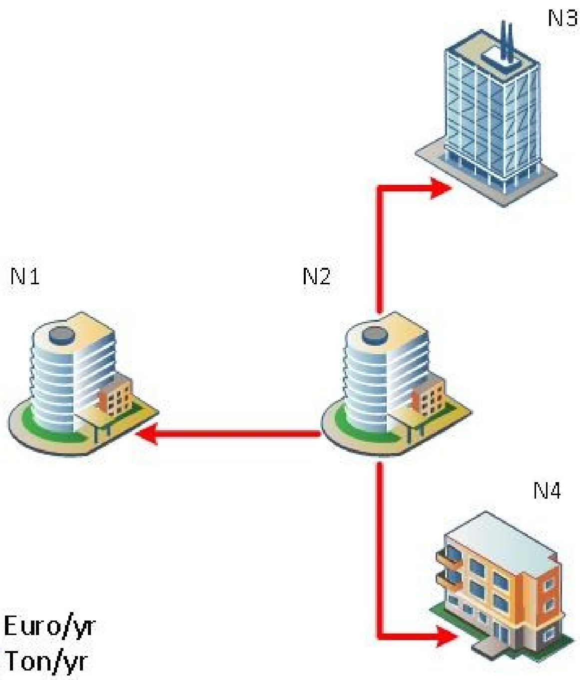
	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	1316	---	1065
N2	1360		2260		1035
N3	---		---		1351
N4	---		---		2032
	kW	kW	kWh	kWh	m2



Total Cost: 200,673.64 Euro/yr
Opr. Cost: 9,651.67 (113,309.34) Euro/yr
CO_2 Emission: -318.567 (279.133) Ton/yr
Pr. Energy: -1511.34 (1321.36) MWh/yr
* Values in red color are without PV panels savings

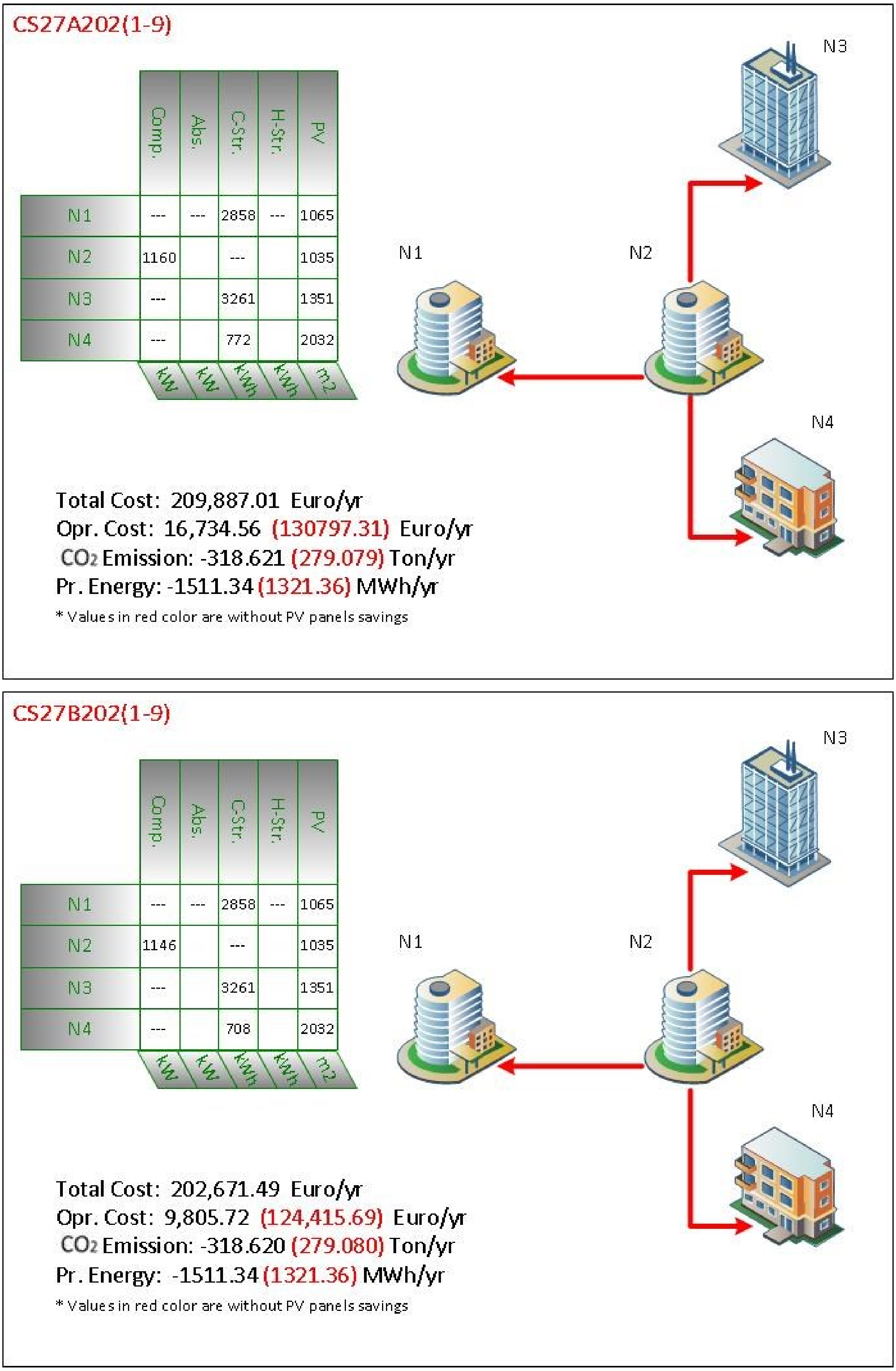
CS27B202(5-1)

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	2001	---	1065
N2	1410		1126		1035
N3	---		---		1351
N4	---		---		2032
	kW	kW	kWh	kWh	m2



Total Cost: 197,943.12 Euro/yr
Opr. Cost: 7,488.53 (115,374.57) Euro/yr
CO_2 Emission: -318.577 (279.123) Ton/yr
Pr. Energy: -1511.34 (1321.36) MWh/yr
* Values in red color are without PV panels savings

Figure 5.41: Centralized DC network scenario at Multi objective (cost 5-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



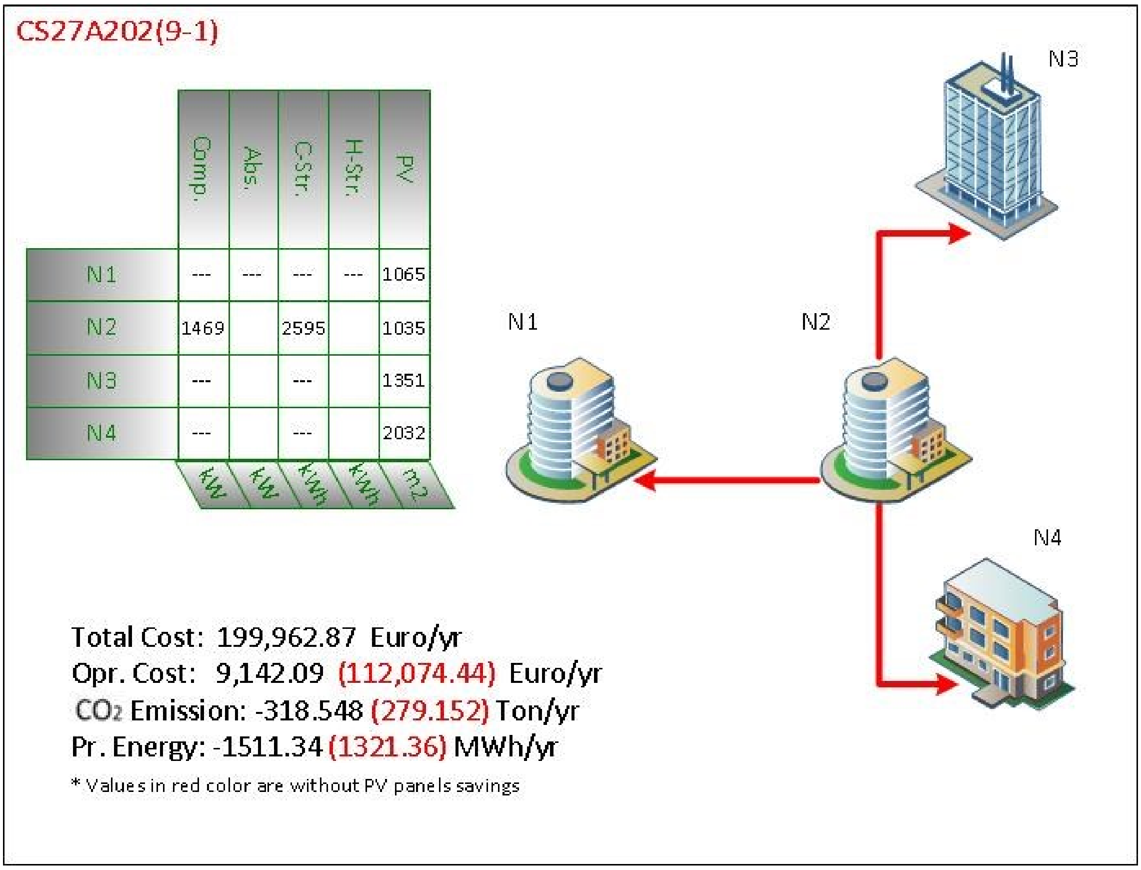
CS27A202(1-9)

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	2858	---	1065
N2	1160		---		1035
N3	---		3261		1351
N4	---		772		2032
	kW	kW	kWh	kWh	m2

CS27B202(1-9)

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	---	---	2858	---	1065
N2	1146		---		1035
N3	---		3261		1351
N4	---		708		2032
	kW	kW	kWh	kWh	m2

Figure 5.42: Centralized DC network scenario at Multi objective (cost 1-9 CO_2) optimization stage for case study 2 with electricity tariffs A and B.



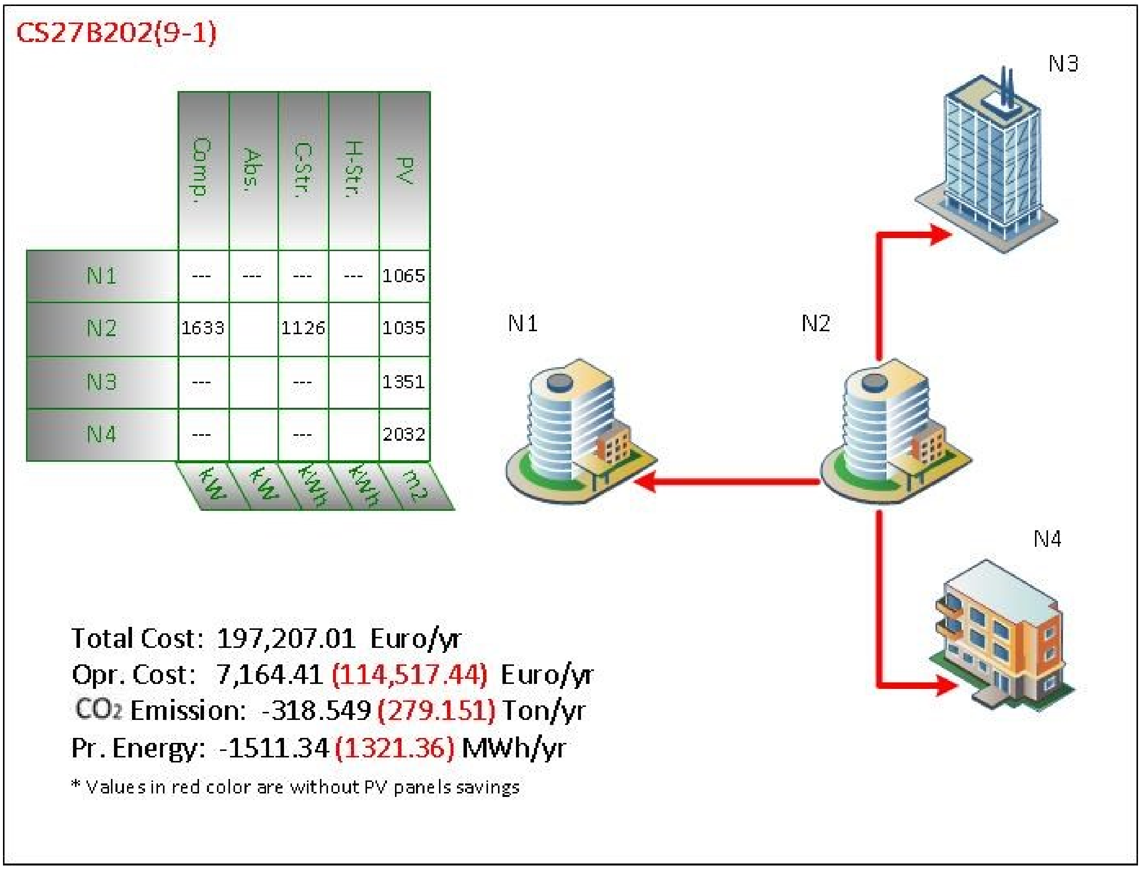


Figure 5.43: Centralized DC network scenario at Multi objective (cost 9-1 CO_2) optimization stage for case study 2 with electricity tariffs A and B.

The values of the total annual costs and CO_2 emissions of the obtained centralized DC systems are presented in Figure 5.44. As it can be clearly observed from these values, improving, i.e. reducing, one of the objectives is not possible without harming, i.e. increasing, the other objective. This is a sign that Pareto Fortier can easily be visualized by projecting the values of obtained objective on the "CO_2 emissions – Cost" diagram. Since that all the multi objective solutions, and their objective values, lay down between the Utopia and Nadir values of the two single objective reference scenarios and since the later values were too close to each other in relative to the de-centralized DC system as shown in Figure 5.34, a separated Pareto Frontier diagram was created for the centralized DC scenarios as presented in Figure 5.45 where the far two edges of the frontier represent the single objective scenarios.

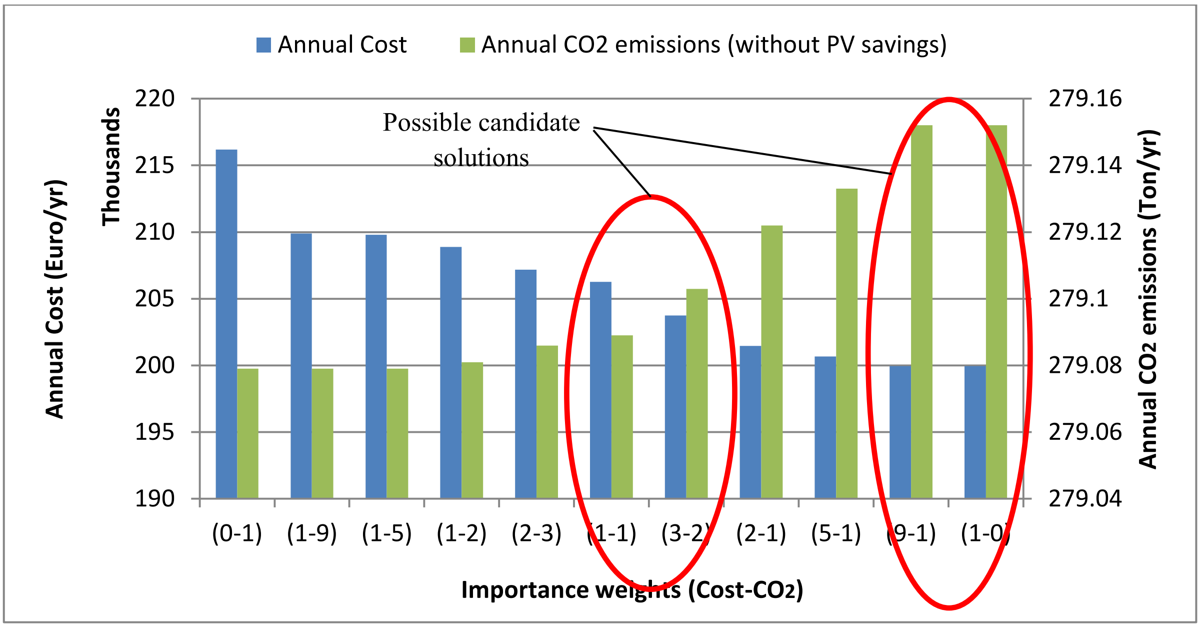


Figure 5.44: Annual cost and CO_2 emissions for the multi objectives centralized DC scenarios at different importance weights for case study 2 with electricity tariff A.

It was observed that the differences between the objective values for the obtained systems are reletively small especially for the CO_2 emissions in comparison to the de-centralized DC systems. That means paying so much attention to CO_2, by putting a high importance weight for it, will cause a significant increase in the total annual cost for a very little enhancement in the amount of CO_2 emitted annually. This observation was made at the very early stage when obtaining the Utopia and Nadir values of the signle objective scenarios and based on these values a recommendation was made to select the single objective scenario with importance weights of (1 – 0), i.e. only cost, due to the very small Nadir-Utopia gap in the CO_2 emissions objective. Such low gap between the two values, i.e. Utopia and Nadir for one or both of the objectives, should make the decision maker re-think about the worthness, in terms of time and effort, of going into obtaining several multi objective scenarios and generating Pareto Frontier. However, this selection is merely concerned with the particular situation of case study 2. Other case studies might have higher gap between their Utopia and Nadir values which leaves the door open for the decision maker to carry out a multi objective investigation.

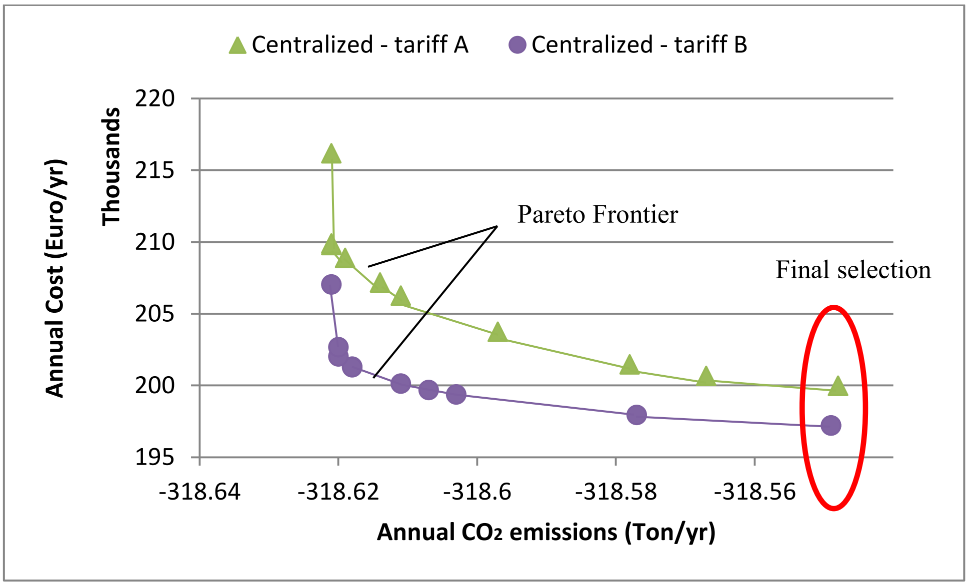


Figure 5.45: Pareto Frontier for Centralized DC systems at various cost and CO_2 importance weights

Based on this, it is recommended for decision makers who want to take more than one objective into their consideration when designing a DC system to first obtain the Utopia and Nadir values of each single objective separately. The difference between these two values, for each objective function, will give them a solid imagination about how much enhancement is achievable at each objective separately and how much damage such enhancement on one objective can cause on the other objective. Then the decision making process should go through these possibilities:

I. If the gap between the Utopia and Nadir values for one objective is too small, i.e. few Euros or CO_2 grams, while the difference between these values for the other objective is relatively big, then it is recommended to focus only on the objective high (Z^N-Z^U) value by either adopting the single objective scenario or adopting a multi objective scenario with a high importance weight for that particular objective.

II. If the (Z^N-Z^U) gap was too small for both or all objectives, then it is recommended to obtain one multi objective scenario with importance weight of 1 for all objectives. This will guarantee that consideration has been paid to all objectives without wasting unnecessarily time and effort on multi objective investigations.

III. If the (Z^N-Z^U) gap was high for both or all objectives, then more attention and effort should be paid through carrying out extensive multi objective investigations where shifting from one solution to another can achieve significant improvement of one objective but in the same time can cause significant damage to the other objectives. In this case, decision maker should be very careful in adopting importance weights that fit the projects goals and preferences.

5.5.3 Operational Constraints: Outdoor Temperature Effect

This work has a major focus on design and operation of DC systems in hot climate regions. As explained previously in details in Chapter 4 of this thesis, see sections 4.3.5.4 and 4.3.8.2, one of the major problems that face operating cooling systems in general in hot climate regions is the variation in Chiller COP value during day and night due to change in outdoor temperature as shown in Figure 4.46.

This is a special phenomenon which occurs in hot climates that has a major impact on the cooling system performance where the high ambient temperature has a negative impact on the COP values of the compression chillers. This is because most of the chillers in the market are manufactured to work with around 30-35°C outdoor temperature. The high ambient temperatures in hot climate regions can reach up to 55 °C. Figures 4.44 and 4.45 present sample profiles of ambient temperature for the cities of Basra and Baghdad, respectively.

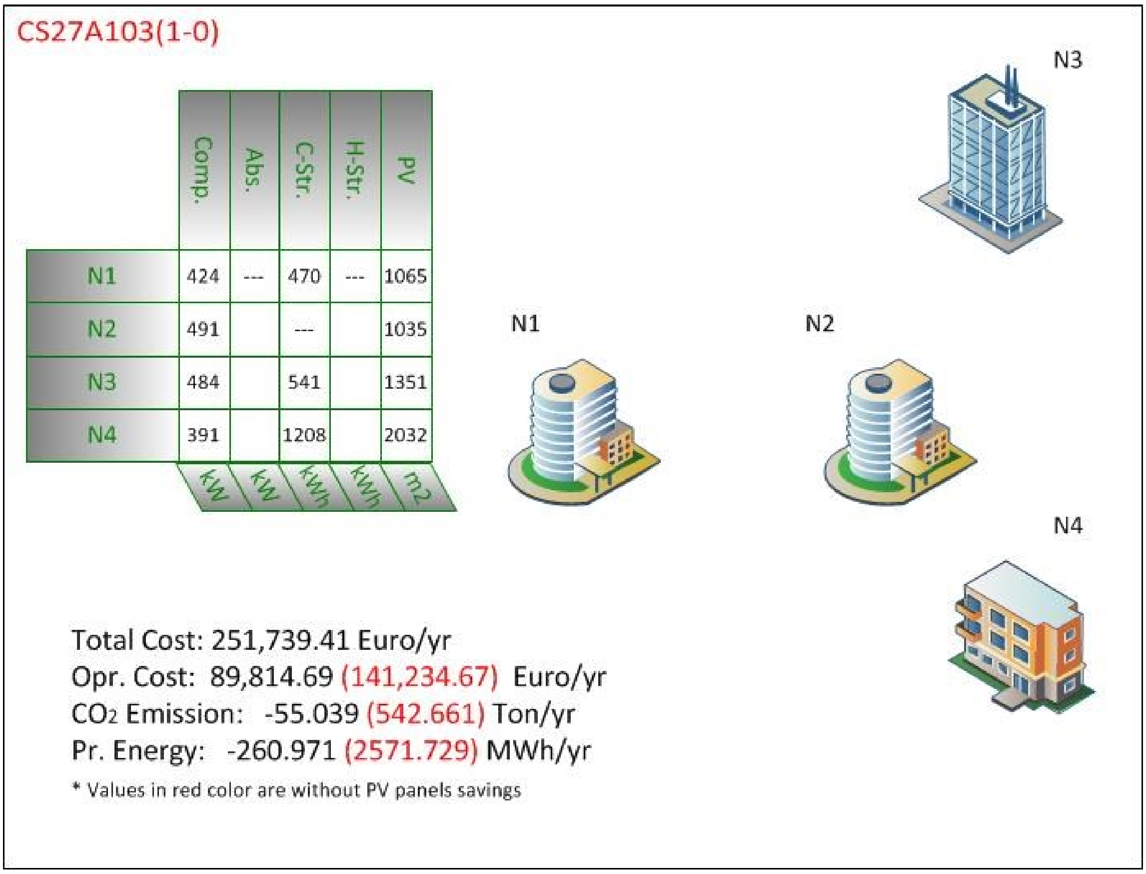
Optimized solutions were obtained for case study 2 while taking the operational constraint, i.e. impact of high outdoor temperatures on chiller COP, into consideration. That is a full optimization of the case study within the applied operational constraint. This investigation was carried out within the multi objective optimization scope of this work using the decision making approach obtained in the previous section.

1. De-centralized DC systems:

CS27A/B103(1-0): Cost 1-0 CO_2 (i.e. Single objective, Cost only), Figure 5.46.
CS27A/B103(0-1): Cost 0-1 CO_2 (i.e. Single objective, CO_2 only), Figure 5.47.
CS27A/B103(1-1): Cost 1-1 CO_2 (i.e. Multi objective with equal importance), Figure 5.48.

2. Centralized DC systems:

CS27A/B203(1-0): Cost 1-0 CO_2 (i.e. Single objective, Cost only), Figure 5.49.
CS27A/B203(0-1): Cost 0-1 CO_2 (i.e. Single objective, CO_2 only), Figure 5.50.
CS27A/B203(1-1): Cost 1-1 CO_2 (i.e. Multi objective with equal importance), Figure 5.51.



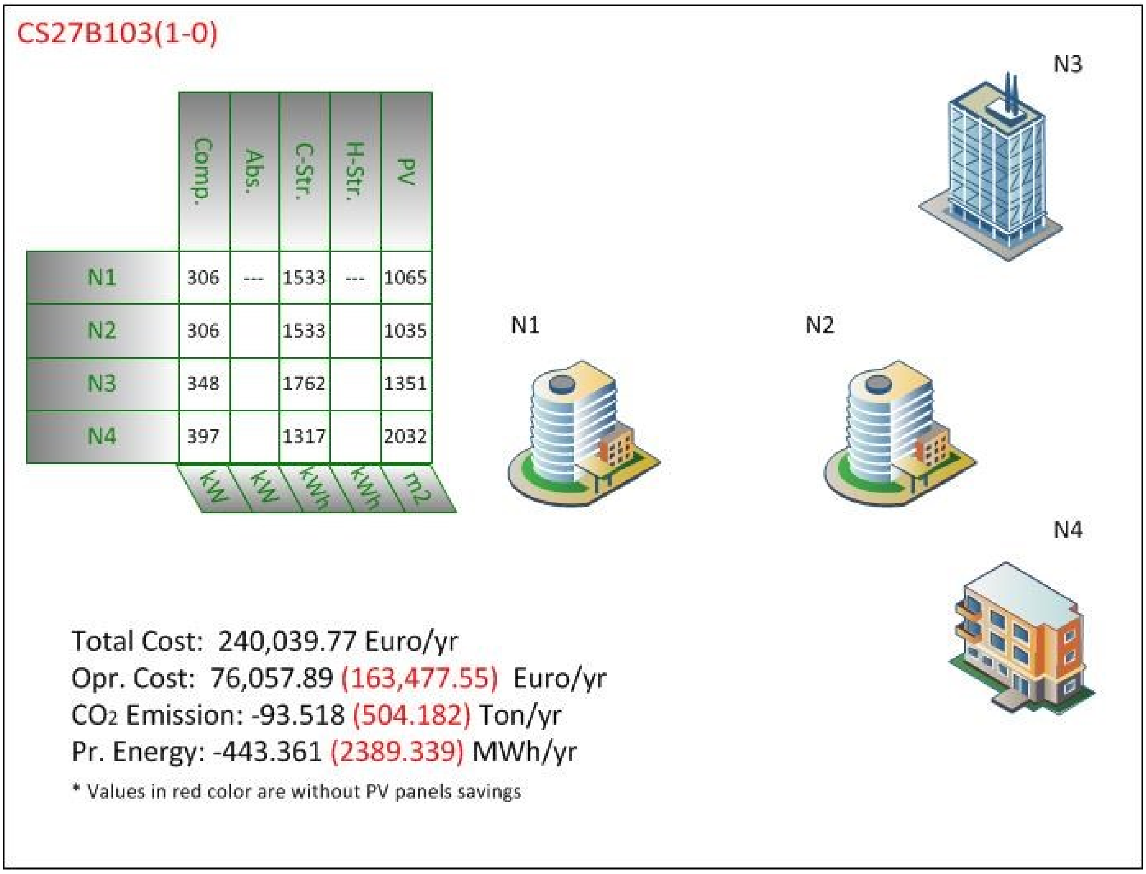
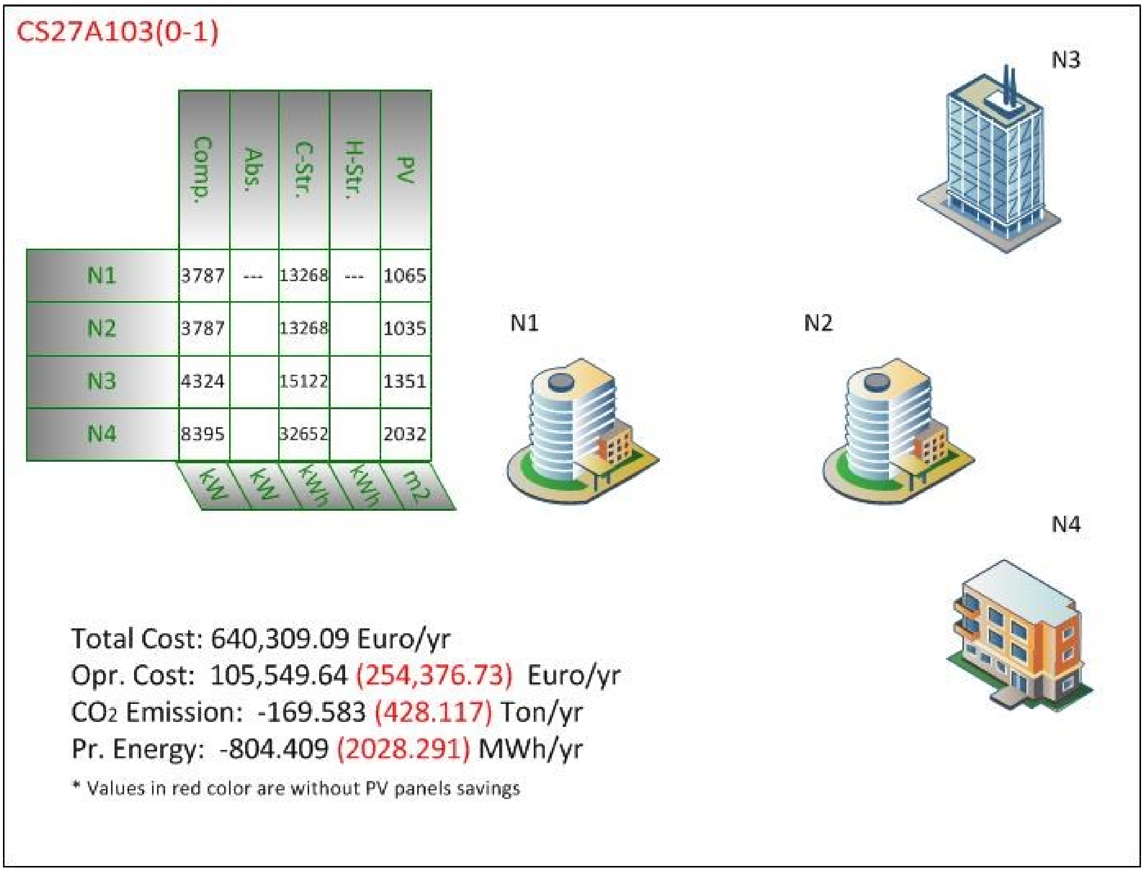
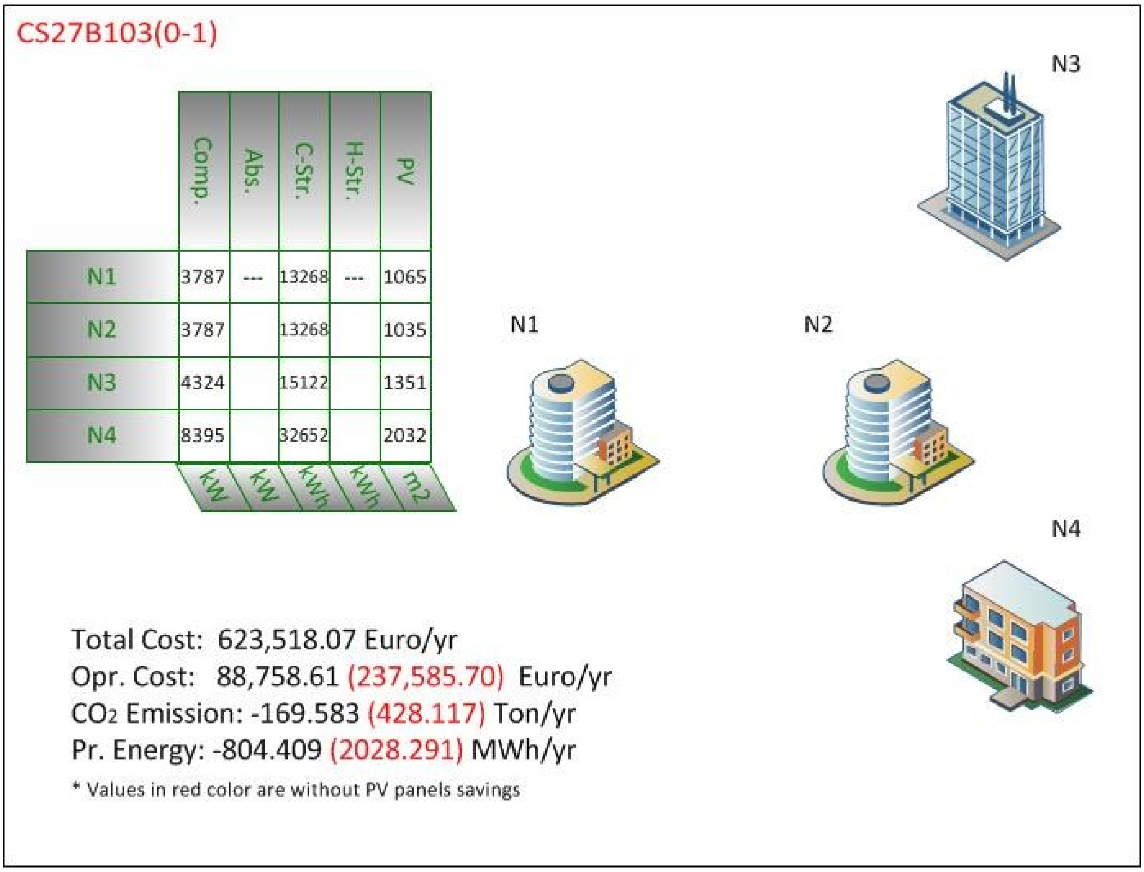


Figure 5.46: De-centralized DC network scenario at single cost objective optimization stage with Outdoor Temperature Effect constraint for case study 2 with electricity tariffs A and B.



	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	3787	---	13268	---	1065
N2	3787		13268		1035
N3	4324		15122		1351
N4	8395		32652		2032

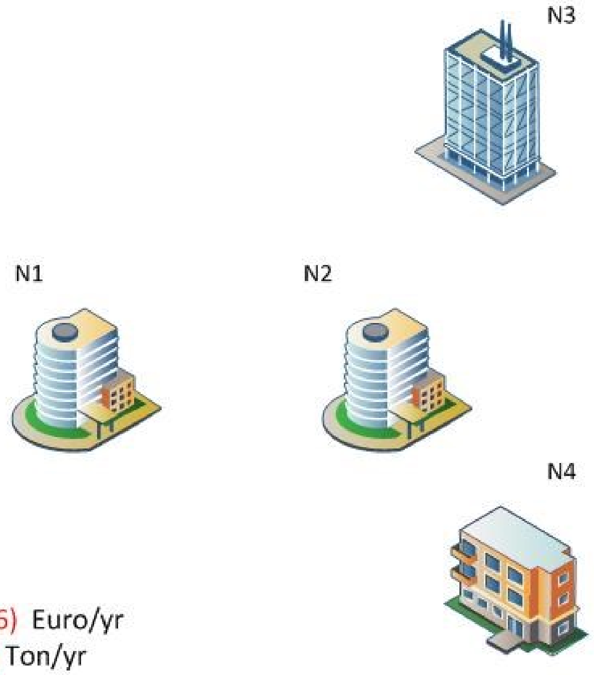


	Comp. (kW)	Abs. (kW)	C-Str. (kWh)	H-Str. (kWh)	PV (m2)
N1	3787	---	13268	---	1065
N2	3787		13268		1035
N3	4324		15122		1351
N4	8395		32652		2032

Figure 5.47: De-centralized DC network scenario at single CO_2 objective optimization stage with Outdoor Temperature Effect constraint for case study 2 with electricity tariffs A and B.

CS27A103(1-1)

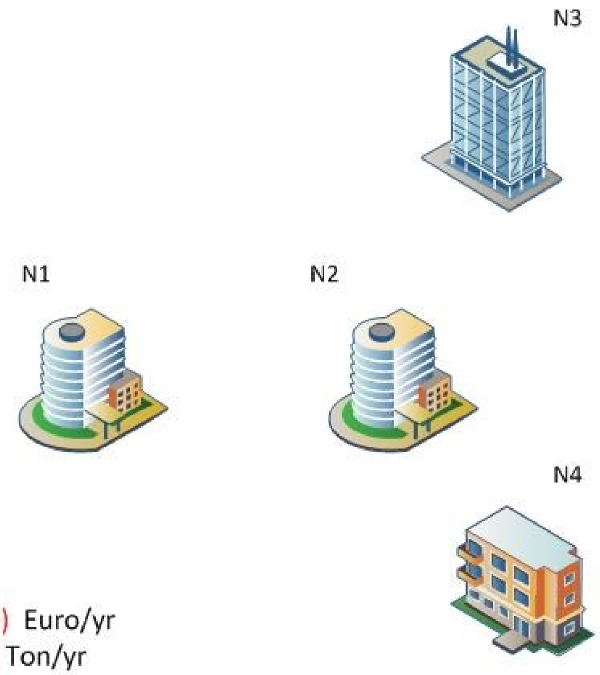
	Comp.	Abs.	C-Str.	H-Str.	PV
N1	699	---	3334	---	1065
N2	589		3334		1035
N3	683		3811		1351
N4	1455		5518		2032
	kW	kW	kWh	kWh	m2



Total Cost: 314,636.05 Euro/yr
Opr. Cost: 105,834.37 (246,776.86) Euro/yr
CO_2 Emission: -155.708 (441.992) Ton/yr
Pr. Energy: -738.168 (2094.532) MWh/yr
* Values in red color are without PV panels savings

CS27B103(1-1)

	Comp.	Abs.	C-Str.	H-Str.	PV
N1	833	---	3334	---	1065
N2	833		3334		1035
N3	1000		3887		1351
N4	1600		5870		2032
	kW	kW	kWh	kWh	m2



Total Cost: 299,165.37 Euro/yr
Opr. Cost: 78,912.21 (224,529.75) Euro/yr
CO_2 Emission: -158.942 (438.758) Ton/yr
Pr. Energy: -753.511(2079.189) MWh/yr
* Values in red color are without PV panels savings

Figure 5.48: De-centralized DC network scenario at Multi objective (cost 1-1 CO_2) optimization stage with Outdoor Temperature Effect constraint for case study 2 with electricity tariffs A and B.

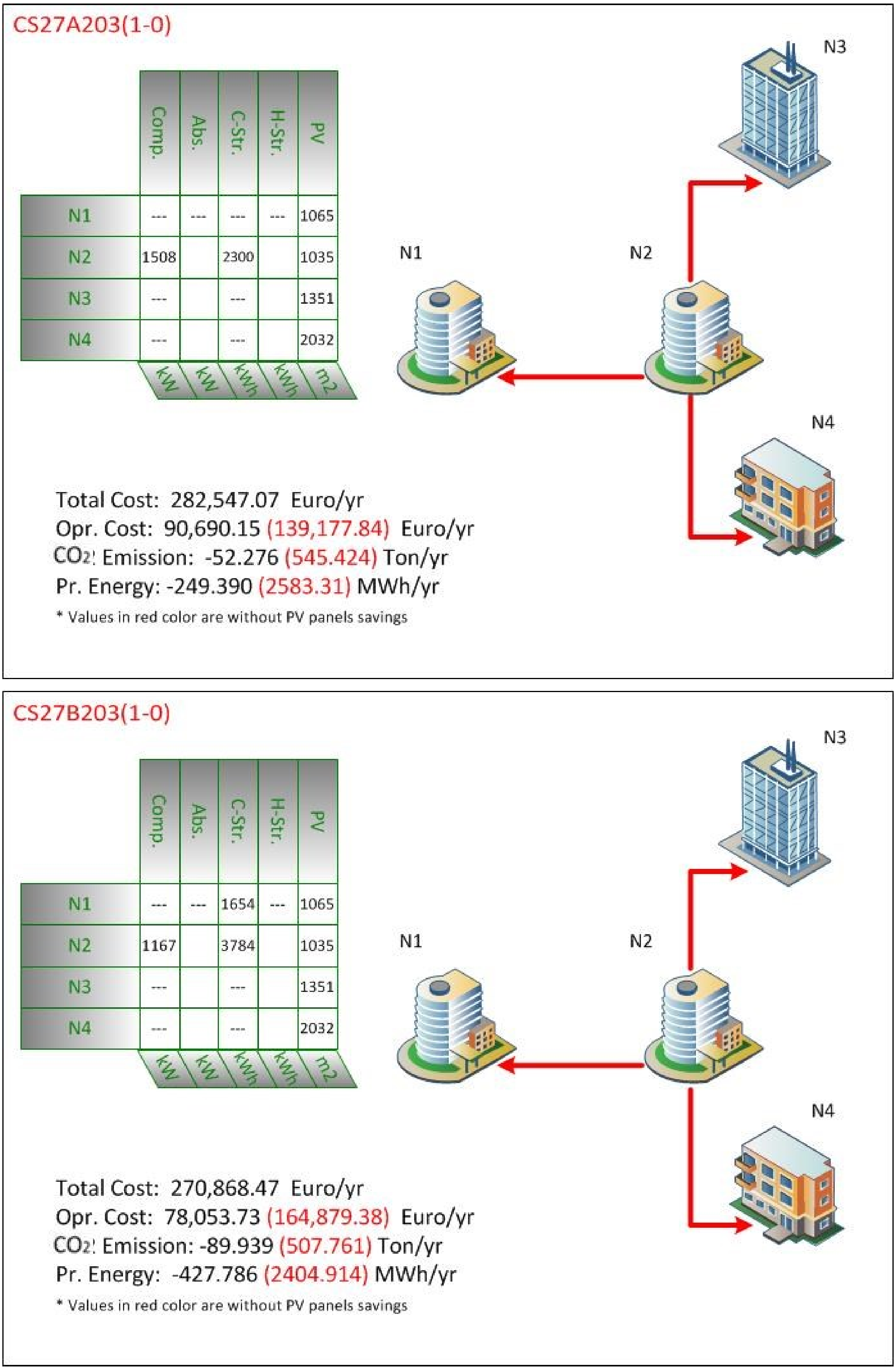


Figure 5.49: Centralized DC network scenario at single cost objective optimization stage with Outdoor Temperature Effect constraint for case study 2 with electricity tariffs A and B.

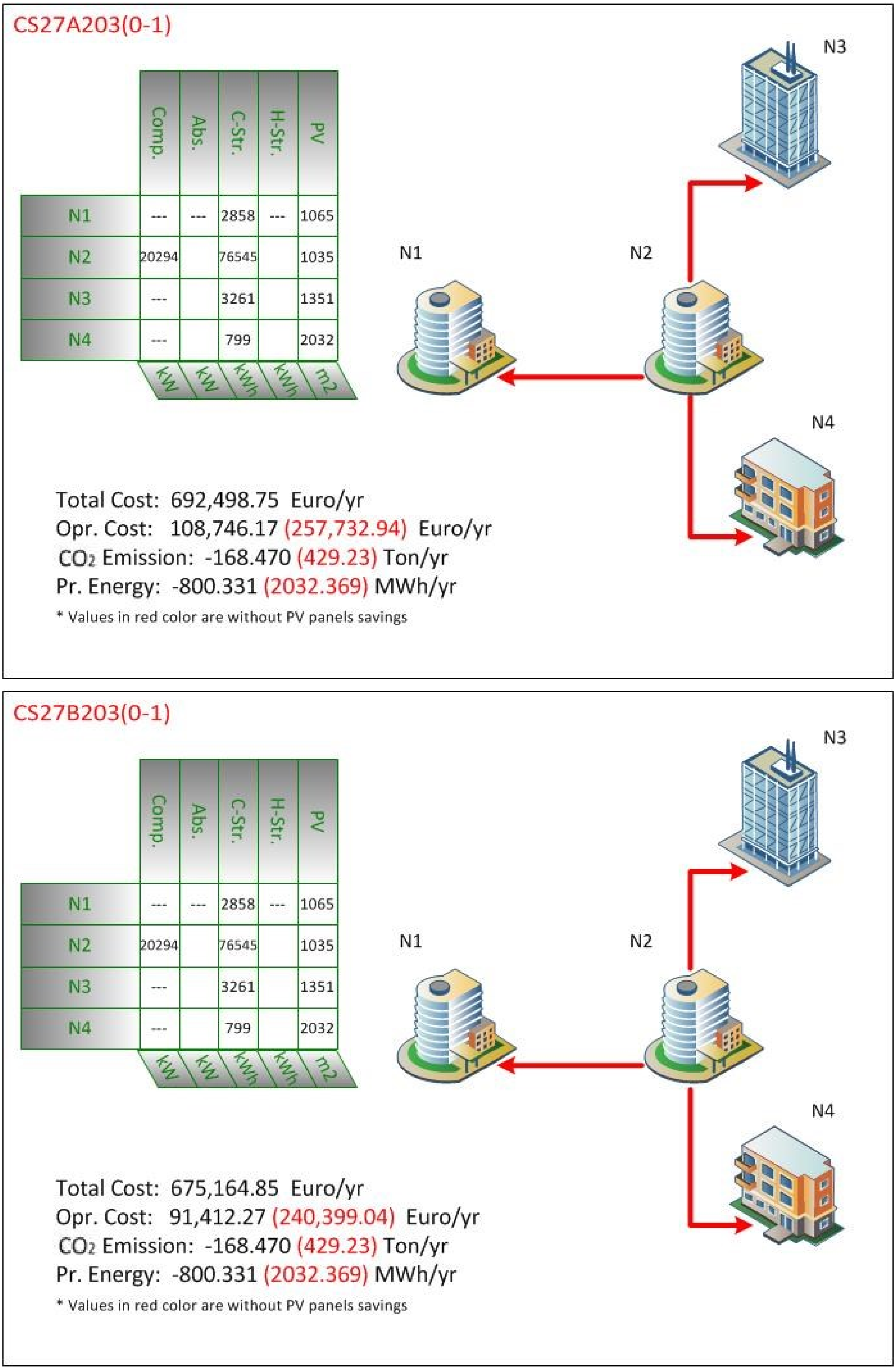


Figure 5.50: Centralized DC network scenario at single CO_2 objective optimization stage with Outdoor Temperature Effect constraint for case study 2 with electricity tariffs A and B.

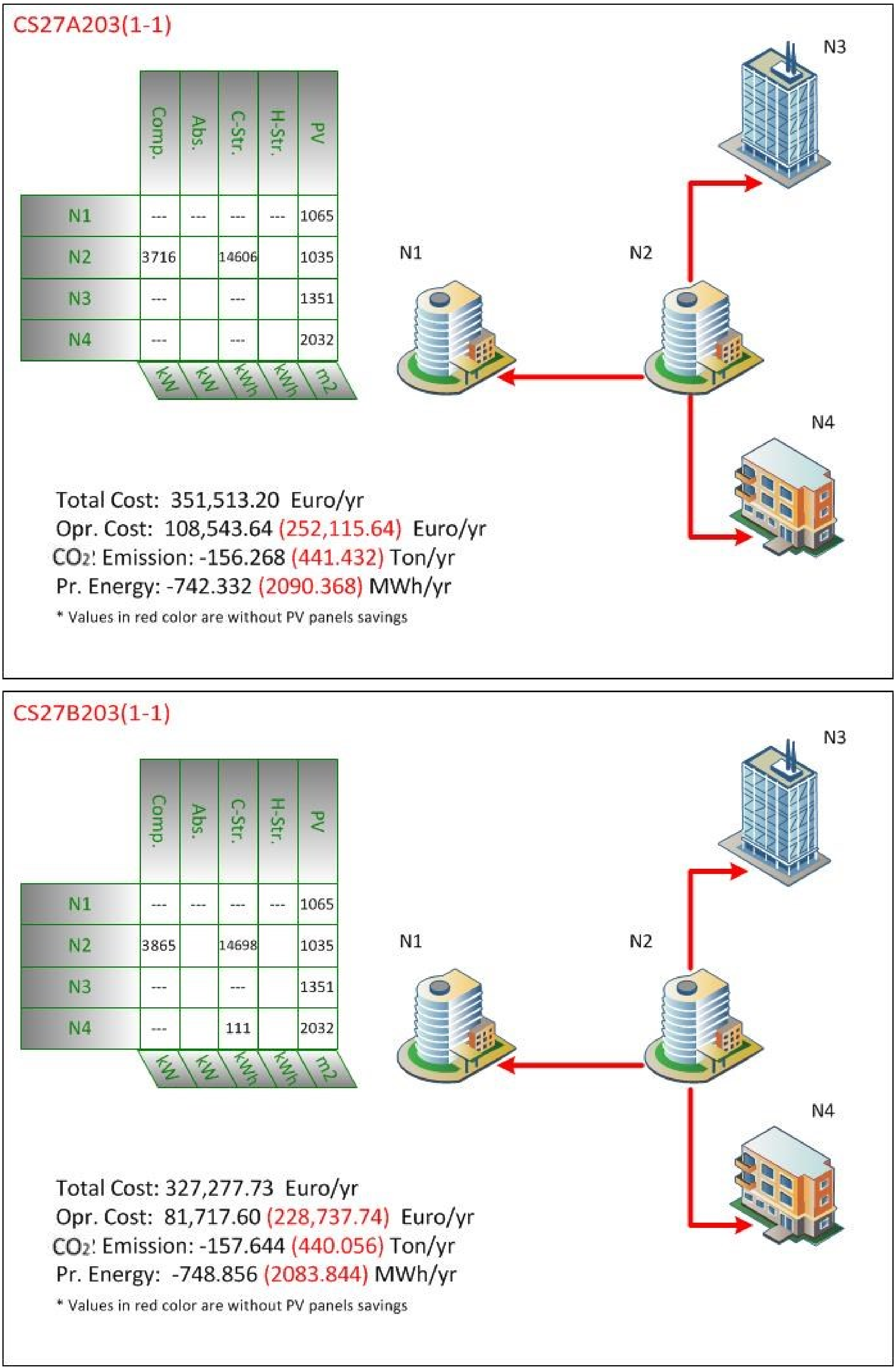


Figure 5.51: Centralized DC network scenario at Multi objective (cost 1-1 CO_2) optimization stage with Outdoor Temperature Effect constraint for case study 2 with electricity tariffs A and B.

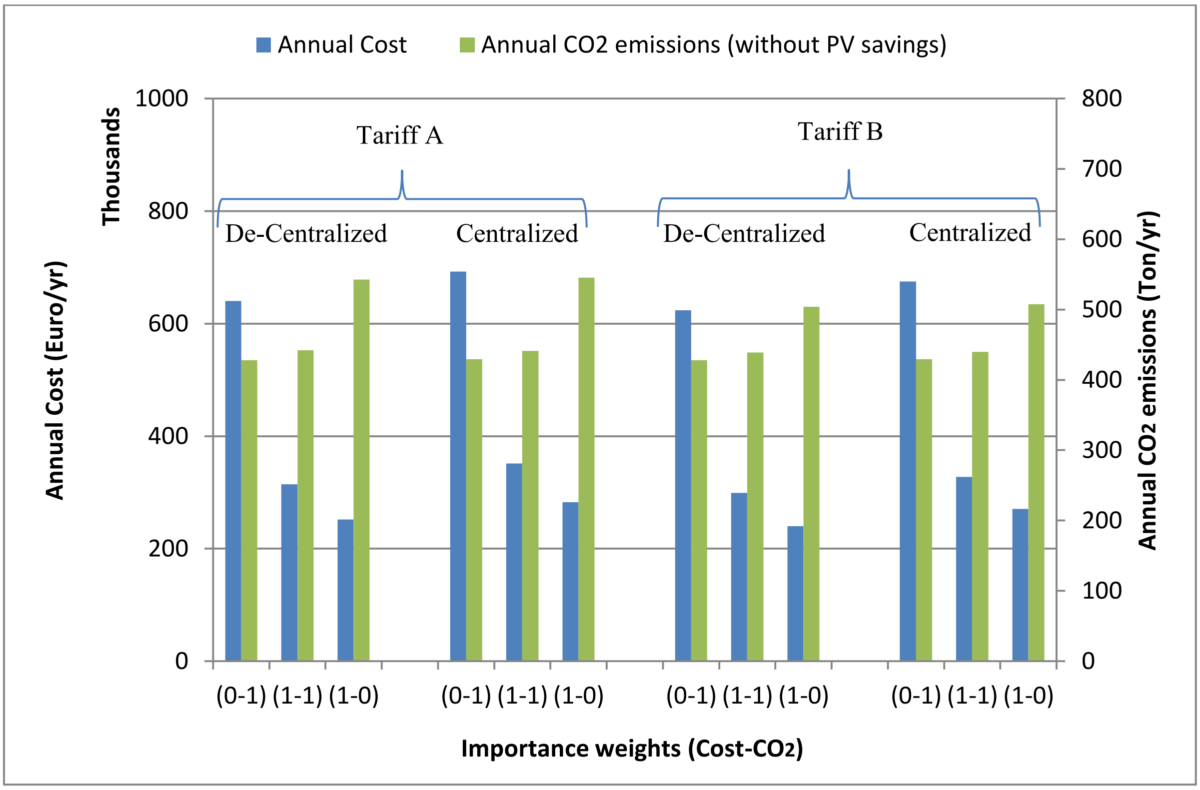


Figure 5.52: Annual cost and CO2 emissions for the multi objectives de-centralized & centralized DC scenarios at different importance weights for case study 2.

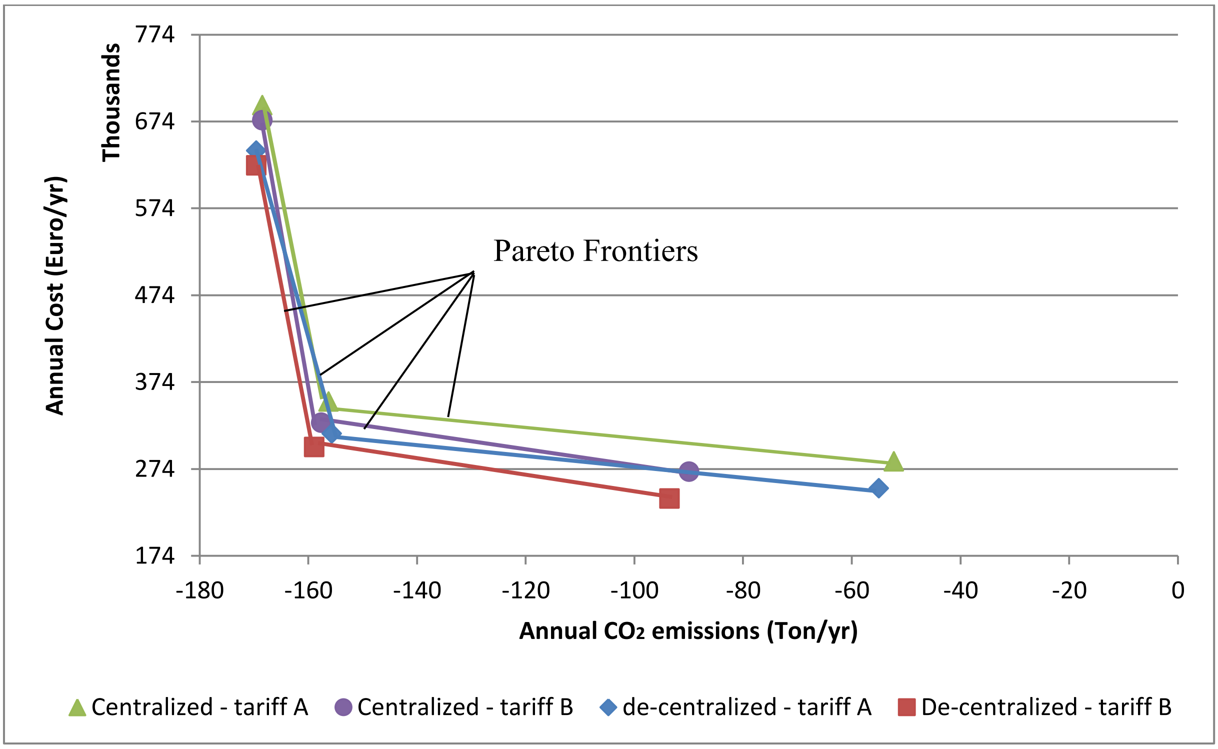


Figure 5.53: Pareto Frontiers for Centralized and De-centralized DC systems for case study 2 with taking outdoor temperature Phenomena into consideration.

Figures 5.52 and 5.53 illustrate how important and helpful the proposed multi objective analysis using Pareto solutions can be for decision makers. It is clear that the gap between the Nadir and Utopia values is too big that it reaches up to 150-160% of the Utopia value for the cost objective and around 17-27% of the utopia value of the CO_2 emissions objective. Adopting a multi objective optimization with importance weights of (1-1) has achieved a significant enhancement on both objectives as presented in Figure 5.53. The reduction in the (Nadir – Utopia) gaps for both annual total cost and CO_2 emissions objectives is around 80-90% for all the investigated scenarios. That means that the total annual cost and CO_2 emissions of the resulting solution is very close to the Utopia values of both objectives. By adopting such a solution, decision makers can avoid a significant loss both economically, if the system was optimized only for environmental objectives, and environmentally, in case the system was optimized only for economic objectives.

It possible to expand this investigation into other scenarios with several importance weights which would provide the decision makers with more options and flexibility in the decision making process. However, the fact that the (1-1) weights scenario has managed to reduce both Nadir-Utopia gaps with up to 90%, indicate that this solution will be considered as compelling solution for the decision makers. If the decision maker is interested in paying more focus on one objective more than the other then carrying out further optimizations with different importance weights is entirely justified.

5.6 Summary

A detail description of the second case study and the characteristics of the buildings along with their cooling load profiles and the criteria of selecting representative days for each building were presented. Based on the results obtained in the first case study, only the variable COP model was adopted to investigate the second case study. The investigations focused mainly on Centralized and De-centralized DC systems as well as the impact of the PV panels' integration policy on these systems. The optimization approach adopted to investigate the case study was explained. The investigation was carried on three stages: Cost optimization, CO_2 emissions optimization, and Multi objective optimization. The results of the three optimization stages were presented and discussed

The obtained results have showed that different PV panel's integration policies had some significant impact on the Centralized DC systems layout. In addition, utilizing PV panels, with either integration policy, had a great impact on the total annual CO_2 emissions in comparison to the no-PV panel sub-scenarios. However, the new policy did not affect the design layout of the system. Thus it was concluded that the new PV integration policy makes it possible to optimize the cooling system in separation from the PV panels being integrated into it.

Analyzing the obtained annual total cost and CO_2 emissions at both single objective optimizations for this case study has indicated the following:

a. Centralized DC systems have 11 – 16 % increase in total cost in comparison to the de-centralized systems. Such increase in total annual cost is relatively high and it is up to the decision maker to decide whether to invest in a centralized system or not based on other preferences, e.g. environmental aspects.
b. CO_2 emissions level for the centralized DC systems, at both objective functions, were almost the same and very close to that obtained at de-centralized systems at CO_2 emission optimization. This validates the conclusion obtained previously that investing in centralized DC systems will automatically save CO_2 emissions even when it is not counted for.

c. The reduction in CO_2 emissions achieved by switching the objective function from minimizing total cost to minimizing CO_2 emissions was around 5%. Similar to case study 1, optimizing case study 2 under reducing CO_2 emissions objective did not achieve a significant impact in comparison to that obtained at cost objective. That is because cost optimizing process already includes reducing operational cost by lowering the amount of primary energy consumed and thus already having achieved enhanced CO_2 emission levels.

Observing the obtained DC systems at the single objective optimizations and their Utopia and Nadir values can provide a sufficient overview of where a multi objective optimization solution may lay. It is recommended for decision makers who want to take more than one objective into their consideration when designing a DC system to first obtain the Utopia and Nadir values of each single objective separately. A decision making approach has been developed in this work to help decision makers in selecting a specific solution based on the difference between the Utopia and Nadir values (ZN-ZU) obtained at the single objective optimizations. This approach was applied to the multi objective optimization investigation carried out for this case study. Different multi objective solutions where selected out of the Pareto solutions set for de-centralized DC systems and centralized DC systems. The same approach was implemented to select a solution for both de-centralized and centralized DC systems with outdoor temperature effect. By adopting the developed approach, decision makers can avoid a significant loss both economically, if the system was optimized only for environmental objectives, and environmentally, in case the system was optimized only for economic objectives.

Chapter Six

Conclusion and Outlook

Chapter Six

Conclusion and Outlook

6.1 Work Summary

To obtain an optimal, or even efficient, configuration and design of cooling systems for certain residential or non-residential sector is a very complex task. Critical decisions have to be made regarding a variety of opportunities, options and technologies. In addition to that, the high variability of the energy demand profiles of different buildings and the number of possible combinations when several technologies are to be considered to obtain high efficiency performance add to the complexity of the task. This complicated decision making process is usually the responsibility of a wide variety of people that often have different backgrounds such as local governments (e.g. municipalities) officials, urban planner, air-conditioning engineers, investors, business managers, and environment policy makers … etc. The design of a cooling system for an urban area or district that consist of a number of buildings with cooling load profiles should address several design issues such as:

- Which energy conversion technologies to be invested in and in which combination if more than one technology were to be installed.
- The size and location of each energy conversion technology and equipment in the system.
- The energy production and operation pattern of the installed technologies.
- Does it make sense to install one, or more, district cooling network or not at all.
- Which buildings are to be connected to the district cooling network and which not to be connected.
- The size and location of the each distribution pipeline within the district cooling network if any.
- The energy flow rates through the DC network pipeline.
- How the produced cooling energy should be stored in certain period to meet the peak load periods of the buildings in the district.

The main objective of this work is to develop a decision making approach to use it in obtaining preliminary design configuration and operation strategies for district cooling energy systems based on rough detailed optimization throughout performing environmental, economic and performance comparison for different design options with in the process. These preliminary solutions are intended to serve as preliminary suggestions for design engineers, urban planners and decision makers to ease the process of decision making at the design stage where extensive performance investigations are to be carried out later on by using scenario simulation tools. Therefore, it was concluded that a high detailed model is not a desired option especially at early stages of the design.

A brief survey in the state of the art was carried out reviewing several surveys presented by other researchers in the literature regarding different aspects of the subject. It has been concluded that multi objective optimization model can be a suitable instrument to support the decision making process. In the literature review, mathematical programming models are the most common technique for optimally configuring and designing cooling systems for urban areas. GAMS environment was commonly used to implement and solve optimization models.

Optimizing the design and operation of a district cooling energy system using mathematical programming is typically a nonlinear problem. Non-linear programming is more appropriate for detailed models, which have a lower number of time periods and possible configurations. However, when the model is relatively complex, due to high number of decision variables with several time periods, the problem might not be possible to solve. Therefore reducing the complexity of the problem is essential in mathematical programming. The most reliable simplification, without having to drop some options out of consideration, is to linearize the non-linear equations in the model by implementing binary variables to discretize non-linear functions into several linear sections. Binary variables are widely used in mathematical programming models and are necessary for unit selection, operational states (ON/OFF) and control purposes. In the literature most of the models for multi-period operational optimization are mixed integer linear programming (MILP) models.

Linear programming models are less complex and more flexible than Non-linear models and have shorter resolution times which mean that larger models can be implemented. This can be very useful at early design stages. Although the level of detail that can be obtained in MILP models is relatively lower, that level of rough detailed modelling was considered to be within the scope of this work. Thus, mixed integer linear programming MILP was chosen to develop a multi objective optimization model to address the main aim of this work.

A comprehensive mathematical multi-objective optimization model, based on MILP, was developed and introduced to address the complicated issue of decision making when designing an optimized cooling system for an urban area or district while considering various plant design options and possible DC network layouts as well as taking several fossil and renewable energy resources into consideration to achieve the basic goals of meeting the cooling demands in the district with best possible energy conservation, economic effectiveness and environment preservation levels. Two main conflicting objective functions, which are the total annual cost and CO_2 emissions, were considered in this work. Each type of technology, equipment, or unit was modelled using linearized equations and annuity method. The model facilitates the investment, operational and maintenance costs of these equipment as well as their environmental parameters. Two different electricity price patterns were considered. The model was implemented and solved in GAMS calculation engine.

Cooling load profiles are essential inputs for the optimization process. These profiles can be obtained either by statistical models or simulation models. In statistical models the cooling energy demand is estimated based on historical information and measurements collected for each particular building. While simulation models generate cooling load profiles by simulating buildings based on heat transfer and thermodynamic relationships. Simulation approach that can estimate cooling load profiles for non-existing, i.e. planned to be built, buildings where no historical information are available. In this work the cooling energy demand for each individual building was estimated using TRNSYS. Later, a selection methodology was developed to select 6 representative days representing the 6 months cooling season, i.e. April to September, since that selecting a minimum number of typical days was widely recommended in the literature.

Single- and multi- objective optimizations were carried out for two case studies to analyze a typical life cycle, approx. 20-50 years, for cooling systems while performing several scenarios where parameter such as: technology prices, energy prices, energy demand profiles, and operational constraints as well as environmental parameters vary from one scenario to another. Different major and sub scenarios were investigated for each case study such as:

- De-centralized DCS with constant COP (major investigation scenario).
- Centralized DCS with constant COP (major investigation scenario).
- De-centralized DCS with variable COP (major investigation scenario).
- Centralized DCS with variable COP (major investigation scenario).
- Reference Scenarios (based on reference assumptions).
- Fixed and Variable electricity tariffs scenarios.
- Available Area Constraints Scenarios.
- Chiller Location Constraints Scenarios.
- Storage Location Constraints Scenarios.
- Piping prices Scenarios.
- Investment Cost Optimization Scenarios.
- Solar energy integration policy scenarios.
- Waste Heat Availability Scenarios.
- Load Shifting Condition Scenarios.
- Outdoor Temperature Effect Scenarios.

Later on, Pareto Frontier was generated by obtaining several multi objective optimization solutions based on the decision makers' preferences. At the end, a decision making approach was developed to select the solutions that fit the designers' or decision makers' desires best based on the difference between the Utopia and Nadir values obtained at the single optimization stages.

6.2 Conclusions

A major task of designers and decision makers when designing cooling system for urban areas is to make tradeoffs between disparate and conflicting design objectives. Thus, multi-objective optimizations offer a significant opportunity in enhancing the engineering design, management, and decision making process. Ultimately, the art and science of decision making can be taken into a higher and more efficient level by implementing multi-objective optimization models. Addressing decision-making tasks by solving optimization problem using multi-objective optimization models yields a group of candidate solutions that prominently categorized as non-dominant to each other. Such a group of solutions is known as Pareto domain solutions.

In this work, two case studies were investigated using two single objective optimization models separately. First objective being the total annual cost and second objective is total annual CO_2 emissions. At first, reference scenarios were obtained for each single objective optimization under a certain set of assumptions. Later, several scenarios were investigated with different constraints to obtain optimized cooling systems taking into consideration changes in design parameters and operation conditions. The following points represent some of the conclusions, remarks, and observations obtained within these investigations:

- Within the two investigated case studies in this work it has been observed that the obtained results were highly affected by the type of the buildings in general and their occupation pattern in particular.

- It was noted that the well-known strategy of installing relatively small chiller capacity, e.g. 60 or 70 % of the peak load, accompanied with storage tanks is more desired at non-residential buildings due to the several zero load hours such buildings usually have in their load profile.

- At the early stage of the investigation certain assumptions have been implemented to the model including assuming fixed COP for chillers and no energy loses from the storage tanks. As a consequence the mount of primary energy consumption and thus CO_2 emissions would be the same for the same total sum of cooling energy demand regardless of the number and capacities of chillers and storage tanks installed as long as these assumptions are maintained. Thus, changing the optimization objective from minimizing total annual cost to minimizing CO_2 emissions had a significant impact on the total annual cost however it did not have any impact on the CO_2 emissions. It was concluded that carrying out preliminary DCS design investigation with the simplification of assuming constant COPs for the compression chillers would overlook one of the major advances of DC that is high capacity chillers operate with higher COP than stand-alone systems.

- Most of the investigations carried out for both case studies have showed that compression chillers come ahead of absorption chillers in terms of both investment and operational costs for the market prices provided in the case studies investigated. However, there are other sufficient cases where absorption chillers might be a cost-effective solution such as when electricity prices are high and fuel can be provided at adequate prices. Absorption chillers are also recommended when sufficient amount of waste heat is available.

- The amount of waste heat required to be available to switch the decision from investing in compression chiller into absorption chillers is dependent on many factors including not only the market prices of these chillers and prices of electricity and fuel available but also the cooling load profile, peak load and fluctuation, which makes the decision making process a complicated one. Therefore, the use of mathematical models, similar to the one developed in this work, emerge as a highly recommended method in taking on such complicated decision making task.

- It was observed that the PV panel's electricity integration policy into the cooling system has a significant impact on the system optimized design layout where the location of the central plants was decided by the amount of the available roof area. Therefore, a different PV energy integration policy was adopted. Adopting the second PV panel's integration policy had a different impact on the systems layout where the location of the central plants was decided geographical location of the building within the district. However, both investment and operational costs were close to each other with a slight advantage for the DC systems obtained with new PV integration policy.

- Systems obtained without utilizing solar energy have about half the investment cost of the systems when installing PV panels but a much higher operational cost. On the other hand, the advantage of having locally consumed PV energy is reducing amount of electricity purchased from the grid. Another advantage is PV income from selling the extra electricity to the grid when PV energy is not consumed by the chillers directly. These two advantages are reducing the electrical plant site cost and thus the operational costs of the systems with PV panels. This attribute residence in most of the investigations carried out in this work.

- Utilizing PV panels, with either integration policy, had a great impact on the total annual CO_2 emissions in comparison to the no-PV panel sub-scenarios. However, the second policy did not affect the design layout of the system that was obtained without PV panels. Thus it was concluded that it is possible to optimize the cooling system in separation from the PV panels being integrated into it if an appropriate integration policy was adopted.

- For most of the centralized DC system investigation, a central chiller with a capacity of 65 -75 % of the total peak load of all buildings combined together was adopted. The system is usually provided with a central cold storage tank at the production plant in case of no available area in other buildings or two cold storage tanks often at the far two ends of the DC network. This enables the system to have smaller sizes for the network pipelines which are used to transport a more steady flow of cooling energy to charge the cold storages during off-peak load hours.

- Once decided for centralized DC system, installing one central storage tank or an optimized number of storages is recommended, in case of constant electricity tariff, unless installing a storage tank at each building would provide some kind of flexibility in controlling the system. On the other hand, for variable electricity tariff, it is recommended to invest in a multi-storage system with one storage tank at each building because it provides a more steady cooling energy production profile even though there was no significant difference in total annual cost.

- It was found that operation cost has a higher impact on the optimization process and, consequently, the resulting cooling system designs. In fact, optimizing the investment cost alone causes an increase of around 20% in the total cost. For example, reducing the pipeline prices had little impact on the system design where investment cost of a DC network was very small in comparison to the total annual cost of the system.

- Investigating load shifting strategy has showed that optimized DCS systems can be adapted to operate with load shifting strategy, even if they were not designed to, with relatively low additional costs. Noting that Centralized DC systems require much less modifications than de-centralized DC systems. On the other hand, investigating the outdoor temperature effect on chiller performance has showed that it is very crucial for decision makers to count for this effect where it cause up to 50% increase in total annual cost. However, it was found that some simple, but expensive, modification on the reference scenario, such as replacing the storage tanks with bigger ones, is sufficient to adapt the system to operate with the effect especially for the Centralized DC systems which have shown more flexibility and reliability in dealing with this phenomenon. In addition, adopting load shaving strategies can serve effectively to deal with effect of high ambient temperature in hot climate regions for non-residential buildings. However, residential buildings might require different measure to deal with the phenomenon. As a general conclusion for choosing compression chiller capacity when designing under outdoor temperature effect in a hot climate, it is recommended to choose:

  a. For residential buildings: A chiller capacity that covers around 70% of the peak load of the building at constant electricity tariff. This capacity may be changed significantly when the electricity tariff is variable depending on the tariffs amplitude and at which hours of the day does the electricity price drop.

b. For none-residential buildings: A chiller capacity that covers around 50% of the peak load of the building within both electricity tariffs. However, individual cost investigation for each building is recommended especially for building with high peak cooling load.

- Adopting several values for chiller COP depending on the chiller capacity has made adopting DC network a favorable option. The installed DC networks in these case studies were de-centralized one. In addition, the total annual cost of the fully centralized DC systems was lower than that of the constant COP model by around 35% for both electricity tariffs.

- It is observed that optimizing the de-centralized DC system with a variable COP model under CO_2 objective function only would result in obtaining as much high capacity as possible for the chillers to secure a higher COP and that such oversizing would eliminate the need of installing storage tanks or DC networks.

- It was noticed that the two objective functions, i.e. total annual cost and annual CO_2 emissions, had a close influence on the optimization process. Both objectives seek to reduce the amount of primary energy consumed by adopting the highest COP possible and reducing the amount of operation hours as much as possible. Thus, optimizing the system under one of the objectives would automatically improve the other one. However, further enhancement is possible by adopting multi objective optimizations.

- Although changing the electricity tariff had a notable impact on the total annual cost of the systems, it did not have any impact on CO_2 emission values. This is because cost of energy consumed is not considered in the CO_2 objective which eliminates the effect of changing tariffs.

- Analyzing the obtained annual cost and CO_2 emissions at both single objective optimizations for both case studies has led to some important observations:

  a. Centralized DC systems cost about 2-4% more than De-centralized DC systems for the first case study. This slight increase in total annual cost can be easily deemed as reasonable in return of all the benefits that centralized DC systems offer such as higher operating reliability and availability, higher energy efficiency, lower maintenance costs, lower construction cost of buildings, and a more environment friendly impact. On the other hand, Centralized DC systems have 11 – 16 % increase in total cost in comparison to the de-centralized systems for the second case study. Such increase in total annual cost is relatively high and it is up to the decision maker to decide whether to invest in a centralized system or not based on other preferences, e.g. environmental aspects.

  b. The CO_2 emissions level for the centralized DC systems under the two objective functions were almost the same. However, they were not that far from the de-centralized systems levels. These results lead to the conclusion that investing in centralized DC systems will automatically reduce CO_2 emissions even when optimizing annual cost is the objective.

c. The reduction in CO_2 emissions achieved by switching the objective function from minimizing total annual cost to minimizing CO_2 emissions for both case studies was around 5% which relatively low. That is because cost optimizing process already includes reducing operational cost by lowering the amount of primary energy consumed and thus already having achieved enhanced CO_2 emission levels.

- Multi objective optimizations aim to generate non-dominant solutions known as Pareto solutions. Generating these solutions is an objective task. Later on, selecting a specific Pareto solution is the decision maker's responsibility. This selection is a subjective task that depends extremely on the decision maker preferences. Observing the obtained DC systems at the single objective optimizations and their Utopia and Nadir values can provide a sufficient overview of where a multi objective optimization solution may lay where each of the single objective optimization scenarios represents the far limit to which one can reach in regards to that particular objective. Therefore, it is recommended for decision makers who want to take more than one objective into their consideration when designing a DC system to first obtain the Utopia and Nadir values of each single objective separately

- A decision making approach has been developed in this work to help decision makers in selecting a specific solution based on the difference between the Utopia and Nadir values (Z^N-Z^U) obtained at the single objective optimizations. In this approach the decision making process go through three possibilities:

  a. If the gap between the Utopia and Nadir values for one objective is too small while the difference between these values for the other objective is relatively big, then it is recommended to focus only on the objective with high (Z^N-Z^U) value by either adopting the single objective scenario or adopting a multi objective scenario with a high importance weight for that particular objective.

  b. If the (Z^N-Z^U) gap was too small for both or all objectives, then it is recommended to obtain one multi objective scenario with importance weight of 1 for all objectives. This will guarantee that consideration has been paid to all objectives without wasting unnecessarily time and effort on multi objective investigations.

  c. If the (Z^N-Z^U) gap was high for both or all objectives, then more attention and effort should be paid through carrying out extensive multi objective investigations where shifting from one solution to another can achieve significant improvement of one objective but in the same time can cause significant damage to the other objectives. In this case, decision maker should be very careful in adopting importance weights that fit the projects goals and preferences.

- The gap between the Nadir and Utopia values for case study 1 was relatively small, 0-3% of the Utopia value for CO_2 emissions objective and about 7-8% of the Utopia value for the total annual cost objective. Therefore, a decision was made to carry out one multi objective optimization only. Both Nadir-Utopia gaps for CO_2 emissions and total cost objectives were reduced with significant margins: 88 and 85%, respectively, at the electricity tariff A and 57 and 70%, respectively, at electricity tariff B.

- Analyzing the Pareto solutions obtained for de-centralized DC systems for the second case study showed that the Nadir-Utopia gap for both single objectives are relatively small but still have a considerable margin of difference. Based on the approach developed in this work, a multi objective solution was recommended.

- For the multi objective centralized DC systems investigation for case study 2 the difference between Utopia and Nadir values were too small especially for CO_2 emission objective in comparison to that of the de-centralized DC systems which indicate that a Pareto Frontier analysis is not needed since the multi objective solutions will not achieve big enhancements. In such cases, it's recommended to either select the multi objective scenario with importance weights of (1–1) or to adopt the total cost single objective solution.

- Adopting a multi objective optimization with importance weights of (1-1) for case study 2 with Outdoor temperature effect has achieved a significant enhancement on both objectives where the reduction in the (Nadir – Utopia) gaps for both annual total cost and CO_2 emissions objectives was around 80-90% for all the investigated scenarios. That means that the total annual cost and CO_2 emissions of the resulting solution is very close to the Utopia values of both objectives. By adopting such a solution, decision makers can avoid a significant loss both economically, if the system was optimized only for environmental objectives, and environmentally, in case the system was optimized only for economic objectives.

6.3 Outlook

The main contribution of this work is introducing a an approach to help decision makers evaluating the economic viability, potential energy savings and thus potential greenhouse gas emission reduction at the very early design stage. The work presented in this thesis can be further improved in the future on several aspects:

- For a preliminary decision making approach or tool, several simplifications and assumptions are usually adopted to ease the decision making process. However, this work has shown that certain assumption can have extreme impact of the decision making process by overlooking some major advantages of certain solutions. Therefore, it is believed that more investigations need to be carried out on the amount of details vs roughness of model for a preliminary decision making optimizations.

- Adopting variable chiller COP model showed that DC networks make a better choice that installing separated stand-alone system at each building. However the chiller capacities were oversized because the developed model for implementing COP variation, depending on the chiller capacity, was a step by step linear model. To avoid such problem, COPs have to be integrated as a formula in terms of chiller capacity. This will lead into a non-linear optimization model where the objective function will be a function of two variables, chiller's capacity and COP. Developing such model might give some new insights however, it might result in a much complex model and thus extensive running time.

- It was concluded that integrating every single equipment and possible technology in the cooling system with a great deal of details is an extremely complicated task that would eventually overwhelm the computation power of the optimization tool. Therefore, breaking down the system components for separated performance analysis using detailed simulations is highly recommended however after the preliminary decision making process. Feedback from such performance analysis can be used later to validate and update the decisions made earlier.

- The conclusions drawn in this work are based on investigation carried out on two case studies. However, it was found that drawing general conclusions is not possible with 2 case studies only. To generalize any conclusion more investigations on several different case studies are required.

- A lot of research has been conducted in this work in effort to come out with general conclusions and recommendations in particular regarding the DC pipeline network and the connection between the peak cooling load of buildings and the distance separating them. It was found that the decision of installing a certain DC pipeline lay on many factors in in addition to peak cooling load and distance such as the type of building, operation pattern, market prices, electricity prices …etc. This particular aspect requires a detailed investigation for a wide range of building pairs.

- Further investigations on different case studies should be made in particular regarding the effectiveness of the CO_2 emission objective function in order to reach a permanent conclusion concerning whether to continue with the multi-objective optimization approach or to keep the decision making limited to single cost optimization approach.

- Another particular field to be further investigated is the integration policy of PV panels and their impact on the system design and DC network layout.

- Further development on the introduced optimization model can be performed in the future such as integrating power supply grid and district heating pipeline in addition to the district cooling to form a Tri-generation optimization model. Another suggested modification to the model is to count for bi-direction pipelines where energy can flow in different directions in each pipeline on different time steps.

References

References

[1] UNEP Sbci. Buildings and climate change: a summary for decision-makers. *United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris*, pages 1–62, 2009.

[2] RESCUE – Renewable Smart Cooling in Urban Europe. Cool conclusions: How to implement district cooling in europe. Co-funded by the Intelligent Energy Europe Programme of the European Union, 2015.

[3] Maurizio Burba. Improved energy efficiency of air cooled chillers. *REHVA Journal*, pages 50–53, January 2013.

[4] Norela Constantinescu et al. Reducing europe's consumption of fossil fuels for heating and cooling. *Euroheat & Power, Brussels, Belgium*, 2006.

[5] P Dalin, J Nilsson, and A Rubenhag. Ecoheatcool, work package 2, the european cold market, final report of wp2 of the project funded within the intelligent energy program, 2006.

[6] BRE Armines (lead contractor) and VHK. Final report of tasks 2 – air conditioning products. Carried out for the European Commission (DG ENTR), July 2012.

[7] CAPITAL COOLING. *EU District Cooling Market and Trends*, volume 64. Estocolmo: Capital Cooling, 2013.

[8] Frost & Sullivan. District cooling: Reviving the lost momentum in middle east. Whitepaper by Building Technologies Practice, Frost & Sullivan. www.frost.com, 2010.

[9] D. Connolly, H. Lund, B.V. Mathiesen, and M. Leahy. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, 87(4):1059 – 1082, 2010.

[10] J.-Emmanuel Samouilidis and Costas S. Mitropoulos. Energy-economy models: A survey. *European Journal of Operational Research*, 11(3):222 – 232, 1982. Fourth {EURO} {IV} special issue.

[11] E. Cardona and A. Piacentino. Optimal design of {CHCP} plants in the civil sector by thermoeconomics. *Applied Energy*, 84(7–8):729 – 748, 2007. Industrial Energy Analysis and Management: A European Perspective'.

[12] A. Piacentino and F. Cardona. On thermoeconomics of energy systems at variable load conditions: Integrated optimization of plant design and operation. *Energy Conversion and Management*, 48(8):2341 – 2355, 2007.

[13] Alta A. Knizley, Pedro J. Mago, and Amanda D. Smith. Evaluation of the performance of combined cooling, heating, and power systems with dual power generation units. *Energy Policy*, 66(0):654 – 665, 2014.

[14] P.J. Mago and L.M. Chamra. Analysis and optimization of {CCHP} systems based on energy, economical, and environmental considerations. *Energy and Buildings*, 41(10):1099 – 1106, 2009.

[15] Nelson Fumo, Pedro J. Mago, and Louay M. Chamra. Energy and economic evaluation of cooling, heating, and power systems based on primary energy. *Applied Thermal Engineering*, 29(13):2665 – 2671, 2009.

[16] M. Medrano, J. Brouwer, V. McDonell, J. Mauzey, and S. Samuelsen. Integration of distributed generation systems into generic types of commercial buildings in california. *Energy and Buildings*, 40(4):537 – 548, 2008.

[17] Gianfranco Chicco and Pierluigi Mancarella. Trigeneration primary energy saving evaluation for energy planning and policy development. *Energy Policy*, 35(12):6132 – 6144, 2007.

[18] J.O Jaber and S.D Probert. Environmental-impact assessment for the proposed oil-shale integrated tri-generation plant. *Applied Energy*, 62(3):169 – 209, 1999.

[19] Gianfranco Chicco and Pierluigi Mancarella. A unified model for energy and environmental performance assessment of natural gas-fueled poly-generation systems. *Energy Conversion and Management*, 49(8):2069 – 2077, 2008.

[20] Jiang-Jiang Wang, You-Yin Jing, Chun-Fa Zhang, Xu-Tao Zhang, and Guo-Hua Shi. Integrated evaluation of distributed triple-generation systems using improved grey incidence approach. *Energy*, 33(9):1427 – 1437, 2008.

[21] Jiang-Jiang Wang, You-Yin Jing, Chun-Fa Zhang, Guo-Hua Shi, and Xu-Tao Zhang. A fuzzy multi-criteria decision-making model for trigeneration system. *Energy Policy*, 36(10):3823 – 3832, 2008.

[22] Heejin Cho, Pedro J. Mago, Rogelio Luck, and Louay M. Chamra. Evaluation of {CCHP} systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. *Applied Energy*, 86(12):2540 – 2549, 2009.

[23] Wang Jiang-Jiang, Zhang Chun-Fa, and Jing You-Yin. Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in china. *Applied Energy*, 87(4):1247 – 1259, 2010.

[24] S.D. Pohekar and M. Ramachandran. Application of multi-criteria decision making to sustainable energy planning—a review. *Renewable and Sustainable Energy Reviews*, 8(4):365 – 381, 2004.

[25] Haiwen Shu, Lin Duanmu, Chaohui Zhang, and Yingxin Zhu. Study on the decision-making of district cooling and heating systems by means of value engineering. *Renewable Energy*, 35(9):1929 – 1939, 2010.

[26] Gianfranco Chicco and Pierluigi Mancarella. Distributed multi-generation: A comprehensive view. *Renewable and Sustainable Energy Reviews*, 13(3):535 – 551, 2009.

[27] Céline Weber, François Maréchal, and Daniel Favrat. Design and optimization of district energy systems. In *10th International Symposium on District Heating and Cooling, Hanover, Germany*, 3-5 September 2006.

[28] Jordi Ortiga, Joan Carles Bruno, Alberto Coronas, and Ignacio E. Grossman. Review of optimization models for the design of polygeneration systems in district heating and cooling networks. In Valentin Ple?u and Paul ?erban Agachi, editors, *17th European Symposium on Computer Aided Process Engineering*, volume 24 of *Computer Aided Chemical Engineering*, pages 1121 – 1126. Elsevier, 2007.

[29] X.Q. Kong, R.Z. Wang, and X.H. Huang. Energy optimization model for a {CCHP} system with available gas turbines. *Applied Thermal Engineering*, 25(2–3):377 – 391, 2005.

[30] A. Piacentino and F. Cardona. Eabot – energetic analysis as a basis for robust optimization of trigeneration systems by linear programming. *Energy Conversion and Management*, 49(11):3006 – 3016, 2008. Special Issue 3rd International Conference on Thermal Engineering: Theory and Applications.

[31] P. Arcuri, G. Florio, and P. Fragiacomo. A mixed integer programming model for optimal design of trigeneration in a hospital complex. *Energy*, 32(8):1430 – 1447, 2007.

[32] Si-Doek Oh, Ho-Jun Lee, Jung-Yeul Jung, and Ho-Young Kwak. Optimal planning and economic evaluation of cogeneration system. *Energy*, 32(5):760 – 771, 2007.

[33] Shu Yoshida, Koichi Ito, and Ryohei Yokoyama. Sensitivity analysis in structure optimization of energy supply systems for a hospital. *Energy Conversion and Management*, 48(11):2836 – 2843, 2007. 19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

[34] Li Chao-zhen, Gu Jian-ming, and Huang Xing-hua. Influence of energy demands ratio on the optimal facility scheme and feasibility of {BCHP} system. *Energy and Buildings*, 40(10):1876 – 1882, 2008.

[35] Hongbo Ren and Weijun Gao. A {MILP} model for integrated plan and evaluation of distributed energy systems. *Applied Energy*, 87(3):1001 – 1014, 2010.

[36] Miguel A. Lozano, Jose C. Ramos, and Luis M. Serra. Cost optimization of the design of {CHCP} (combined heat, cooling and power) systems under legal constraints. *Energy*, 35(2):794 – 805, 2010. {ECOS} 2008 21st International Conference, on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

[37] Jarmo Söderman and Frank Pettersson. Structural and operational optimisation of distributed energy systems. *Applied Thermal Engineering*, 26(13):1400 – 1408, 2006. Process Integration, modelling and optimisation for energy saving and pollution reduction - {PRES} 2004.

[38] Jarmo Söderman. Optimisation of structure and operation of district cooling networks in urban regions. *Applied Thermal Engineering*, 27(16):2665 – 2676, 2007. Selected Papers from the

9th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction – {PRES2006}.

[39] Dario Buoro, Melchiorre Casisi, and Piero Pinamonti. Optimization of distributed trigeneration systems integrated with heating and cooling micro-grids. *Distributed Generation and Alternative Energy Journal*, 26(2):7–34, 2011.

[40] Damiana Chinese. Optimal size and layout planning for district heating and cooling networks with distributed generation options. *International Journal of Energy Sector Management*, 2(3):385–419, 2008.

[41] Hongbo Ren, Weijun Gao, and Yingjun Ruan. Optimal sizing for residential {CHP} system. *Applied Thermal Engineering*, 28(5–6):514 – 523, 2008.

[42] Zhang Beihong and Long Weiding. An optimal sizing method for cogeneration plants. *Energy and Buildings*, 38(3):189 – 195, 2006.

[43] Tuula Savola and Carl-Johan Fogelholm. {MINLP} optimisation model for increased power production in small-scale {CHP} plants. *Applied Thermal Engineering*, 27(1):89 – 99, 2007.

[44] Tor-Martin Tveit, Tuula Savola, Alemayehu Gebremedhin, and Carl-Johan Fogelholm. Multi-period {MINLP} model for optimising operation and structural changes to {CHP} plants in district heating networks with long-term thermal storage. *Energy Conversion and Management*, 50(3):639 – 647, 2009.

[45] Céline Weber, François Maréchal, and Daniel Favrat. Design and optimization of district energy systems. In Valentin Ple?u and Paul ?erban Agachi, editors, *17th European Symposium on Computer Aided Process Engineering*, volume 24 of *Computer Aided Chemical Engineering*, pages 1127 – 1132. Elsevier, 2007.

[46] Alberto Coronas and Joan Carles Bruno. Polycity - cerdanyola / spain: Integration of renewables into the dhc network - optimisation and energy assessment. In *1st European Conference on Polygeneration*, pages 77–92, 16-17 October 2007.

[47] A. Messac, A. Ismail-Yahaya, and C.A. Mattson. The normalized normal constraint method for generating the pareto frontier. *Structural and Multidisciplinary Optimization*, 25(2):86–98, 2003.

[48] M. Martínez, J. Sanchis, and X. Blasco. Global and well-distributed pareto frontier by modified normalized normal constraint methods for bicriterion problems. *Structural and Multidisciplinary Optimization*, 34(3):197–209, 2007.

[49] P.A. Pilavachi, C.P. Roumpeas, S. Minett, and N.H. Afgan. Multi-criteria evaluation for {CHP} system options. *Energy Conversion and Management*, 47(20):3519 – 3529, 2006. Heat Transfer in Components and Systems for Sustainable Energy Technologies: Heat-SET 2005, 5–7 April 2005, Grenoble, France.

[50] Aiying Rong and Risto Lahdelma. An efficient linear programming model and optimization algorithm for trigeneration. *Applied Energy*, 82(1):40 – 63, 2005.

[51] Hongbo Ren, Weisheng Zhou, Ken'ichi Nakagami, Weijun Gao, and Qiong Wu. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. *Applied Energy*, 87(12):3642 – 3651, 2010.

[52] Hirohisa Aki, Tsutomu Oyama, and Kiichiro Tsuji. Analysis of energy service systems in urban areas and their {CO2} mitigations and economic impacts. *Applied Energy*, 83(10):1076 – 1088, 2006.

[53] K.C. Kavvadias and Z.B. Maroulis. Multi-objective optimization of a trigeneration plant. *Energy Policy*, 38(2):945 – 954, 2010.

[54] Lukas G. Swan and V. Ismet Ugursal. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13(8):1819 – 1835, 2009.

[55] J. Ortiga, J.C. Bruno, and A. Coronas. Selection of typical days for the characterisation of energy demand in cogeneration and trigeneration optimisation models for buildings. *Energy Conversion and Management*, 52(4):1934 – 1942, 2011.

[56] Ryohei Yokoyama, Yasushi Hasegawa, and Koichi Ito. A {MILP} decomposition approach to large scale optimization in structural design of energy supply systems. *Energy Conversion and Management*, 43(6):771 – 790, 2002.

[57] C.J. Renedo, A. Ortiz, M. MaÃ±ana, D. SiliÃ³, and S. PÃ©rez. Study of different cogeneration alternatives for a spanish hospital center. *Energy and Buildings*, 38(5):484 – 490, 2006.

[58] Hyonuk Seo, Jinil Sung, Si-Doek Oh, Hoo suk Oh, and Ho-Young Kwak. Economic optimization of a cogeneration system for apartment houses in korea. *Energy and Buildings*, 40(6):961 – 967, 2008.

[59] K.F. Fong, C.K. Lee, and T.T. Chow. Comparative study of solar cooling systems with building-integrated solar collectors for use in sub-tropical regions like hong kong. *Applied Energy*, 90(1):189 – 195, 2012. Energy Solutions for a Sustainable World, Special Issue of International Conference of Applied Energy, ICA2010, April 21-23, 2010, Singapore.

[60] Soteris A. Kalogirou. Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, 30(3):231 – 295, 2004.

[61] M Gebhardt, H Kohl, and T Steinrötter. Preisatlas e ableitung von kostenfunktionen für komponenten der rationellen energienutzung. duisburg, germany: Institute of energy and environmental technology ev (iuta). 2002.

[62] www.solarbayer.de. Pricelist of 2012/2013.

[63] www.solarwirtschaft.de/preisindex. (date: Nov. 2012).

[64] EUROTrough. Development of a low cost european parabolic trough collector. Publishable Final Report. Contract: JOR3-CT98-0231, 2001.

[65] Erneuerbare-Energien-Gesetz – EEG. veröffentlicht durch die bundesnetzagentur, Date: 31. Jan. 2013.

[66] DREWAG. Allgemeine preise strom - grundversorgung für den haushalt. www.drewag.de, Date: 1. Jan. 2013.

[67] M Großklos. Kumulierter energieaufwand und co2-emissionsfaktoren verschiedener energieträger und–versorgungen. *Institut Wohnen und Umwelt GmbH (IWU). Online-Veröffentlichung auf den Seiten des IWU vom*, 14(09), 2009.

[68] V DIN. 18599-1 â€œenergy efficiency of buildings–calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting–part 1: General balancing procedures, terms and definitions, zoning and evaluation of energy sourcesâ€? *Beuth, Berlin*, 2, 2007.

[69] Oleg Grodzevich and Oleksandr Romanko. Normalization and other topics in multi-objective optimization. 2006.

[70] I.Y. Kim and O.L. de Weck. Adaptive weighted-sum method for bi-objective optimization: Pareto front generation. *Structural and Multidisciplinary Optimization*, 29(2):149–158, 2004.

[71] G. Mavrotas and D. Diakoulaki. Solving multi-objective milp problems in process synthesis using the multi-criteria branch and bound algorithm. *Chemical Engineering & Technology*, 28(12):1500–1510, 2005.

[72] C.Henggeler Antunes, A.Gomes Martins, and Isabel Sofia Brito. A multiple objective mixed integer linear programming model for power generation expansion planning. *Energy*, 29(4):613 – 627, 2004.

[73] J Ortiga, JC Bruno, and A Coronas. A modular formulation of mathematical programming models for the optimisation of energy supply systems. *Proceedings of 19th European Symposium on Computer Aided Process Engineering-ESCAPE*, 19, 2009.

[74] B.E. A. Bhatia. Hvac made easy - selection tips for chiller compressors. www.PDH Center.com, 2012.

[75] Standard ASHRAE. Standard 90.1-2007. *Energy Standard for Buildings Except Low-Rise Residential Buildings*, 2007.

[76] ARI Standard. 550/590-2003. *Standard for Performance Rating of Water-Chilling Packages Using The Vapor Compression Cycle, Air-Conditioning, Heating, and Refrigeration Institute*, 2111, 2003.