Investigating the Feasibility and Soil-Structure Integrity of Onshore Wind Turbine Systems in Kuwait

By

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To the memory of my Mother, the greatest woman who I still miss every day

(1946-2016)

Abstract

Wind energy technologies are considered to be among the most promising types of renewable energy sources, which have since attracted broad considerations through recent years due to the soaring oil prices and the growing concerns over climate change and energy security. In Kuwait, rapid industrialisation, population growth and increasing water desalination are resulting in high energy demand growth, increasing the concern of oil diminishing as a main source of energy and the climate change caused by CO_2 emissions from fossil fuel based energy. These demands and challenges compelled governments to embark on a diversification strategy to meet growing energy demand and support continued economic growth. Kuwait looked for alternative forms of energy by assessing potential renewable energy resources, including wind and sun. Kuwait is attempting to use and invest in renewable energy due to the fluctuating price of oil, diminishing reserves, the rapid increase in population, the high consumption of electricity and the environment protection.

In this research, wind energy will be investigated as an attractive source of energy in Kuwait. This is because of its availability and low cost, reducing the dependency on fossil fuels and advanced technology compared to other forms of renewable energy.

An assessment of potential renewable energy resources and technologies will be investigated for power generation and its potential economic returns, energy supply impact, and environmental benefits for Kuwait, Shagaya area will be the study area for different reasons such as high wind speeds, land availability, distance to the next grid connection, and the selection of adequate wind turbine generator (WTG) technology based on the intermediate technical, economic and environmental impact.

The thesis is divided into three essential parts; 1) exploring the true cost of producing electricity from wind power to find the lowest cost and highest reliability design of a wind energy farm using a cost benefit analysis (Levelised Cost of Electricity (LCOE); 2) to assess the potential environmental impact and resources used throughout a product's life-cycle by conducting an environmental analysis (Life Cycle Assessment (LCA); 3) modelling the wind turbine structure and foundation stability using 3D Finite Element Analysis (FEA).

Different data is used in this thesis such as wind data, wind turbine types selection suitable for Kuwait, soil and foundation properties. The results show the total Carbon Dioxide (CO_2) emissions for a turbine with steel pile foundations is greater than emissions from a turbine with concrete foundations by 18 %. The analysis also shows the average CO_2 emissions from electricity generated using crude oil is 645 gCO_2/kWh and the carbon footprint per functional unit for a wind turbine ranges between 6.6 g/kWh to 10 g/kWh, an increase of 98%, thus providing cost and environmental benefits by creating a wind farm in Kuwait. Using a cost-benefit analysis, it was also found that the electricity produced from wind energy in Kuwait would cost ($0.0583/£0.04/17.6fils) per kWh, which is less than the cost of electricity currently being produced using conventional methods at ($0.073/22 fils/£0.06) per kW, i.e. a reduction of 20%.

A general finite element model of a typical 2MW-Gamesa G90 wind turbine sitting on piled foundation and sandy soil was modelled. The soil-structure-interaction was considered, using the elasto-plastic Mohr-Coulomb (MC) constitutive model. The results confirmed that the structural stability of the entire system (soil, pile, tower, turbine loads and wind loads) indicated that there were no failure points and the system structure is stable including the components of the structure.

Key words

Feasibility, Numerical modelling, Finite Element Methods (FEM), Renewable energy, Wind energy, GCC countries, Kuwait, Onshore wind turbine, Horizontal Axis Wind Turbine (HAWT), CO_2 emission, Life Cycle Assessment (LCA), Levelised Cost of Energy (LCOE), Soil-structure interaction.

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Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

The Middle East region's has development in the last few years has been based on fossil fuels, and most of their energy demand is fulfilled by burning these fuels. As reserves are limited and fossil fuel causes' environmental pollution, the countries of this region have shown willingness to use renewable energy, particularly wind, to reduce the dependency on fossils and enhance their total power generation(Alnaser and Alnaser, 2011).Utilisation of wind energy in generation of electricity is growing rapidly due to continued improvements in technology that make wind turbines cheaper and more efficient, resulting in a reduction of the overall cost of generation per kWh. In addition, wind energy is a clean, plentiful and sustainable energy source (RenewableUK, 2014). It does not create pollution like fossil fuels is inexhaustible. However, more and more countries began realising the consequences of climate change and have started to make efforts in the direction of greener solutions for their energy needs. The state of Kuwait has looked for alternative forms of energy, and has begun assessing potential renewable energy resources, including wind and solar. In this research, wind energy will be investigated as an attractive source of renewable energy. This is due to availability, low cost, and advanced technology compared to other forms of renewable energy, which will be discussed further in the next chapter.

The currencies quoted in this thesis will be those used in Kuwait: the Kuwaiti Dinar (1KD), British Pound (£), and US Dollar ($). The sub-denominations of these currencies are as follows: 1KD=1000 fils, £1=100 pence, and $1=100 cents.

Renewable energy, particularly solar and wind energy technologies is considered to be among the most promising type of renewable energy sources, and have since attracted broad interest throughout the recent years due to soaring oil prices and growing concerns over climate change and energy security (Komor, 2004; Authority for Electricity Regulation, 2008; Tremeac and Meunier, 2009; Taleb and Pitts, 2009; Lozano-Minguez, Kolios and Brennan, 2011; Oliveira and Fernandes, 2012; Chehouri et al., 2015). This study presents an assessment of potential renewable energy resources and technologies for power generation and their potential economic returns, energy supply impact, and environmental benefits for Kuwait. The study identifies various renewable options for concentrating solar power (CSP), photovoltaic (PV) and wind energy (WE) for the sustainable development of a significant renewable energy share in Kuwait by 2030 and onwards.

Fossil fuels are the main supplier of most of the energy that industrial society needs. The main problems of fossil fuels include their environmental impacts, unequal supply of fossil fuel resources worldwide and the fluctuation of global fossil fuel prices and limitations on supply. The total Carbon Dioxide (CO_2) emissions produced from wind energy was found less than the CO_2 emissions from both petroleum and PV solar energy by about 97.5% and 85% respectively (Üney and Çetinkaya, 2015).

There is an increase concern worldwide to find alternatives to fossil fuels for energy production, due to the growth in demand for energy, the high consumption of natural resources, and global warming. Many countries, particularly in Europe, shared the global renewable energy by 6 to 10%, and are expected to double the percentage by the year 2020 (Ibrahim, 2011). The Kyoto protocol set a long-term goal of reducing global greenhouse emissions by 50% before 2050. According to the International Energy Agency (2013), global CO_2 emissions from fuel in 2011 amounted to 31.342 Gt (Giga tonnes) which increased to be 32.4 Gt in 2014 as stated by International Energy Agency (IEA, 2016a). The Middle East's share of global CO_2 emissions was 5.1%, and is expected to increase to reach 7.7% in 2035.

Figure 1.1 shows the growth and presents the regional share of CO_2 emissions from fuel (oil,coal and natural gas). It is clear that China has the highest regional share of CO_2 emissions and Asia excluding China has the lowest, whereas the Middle East produces 5% of CO_2 emissions.

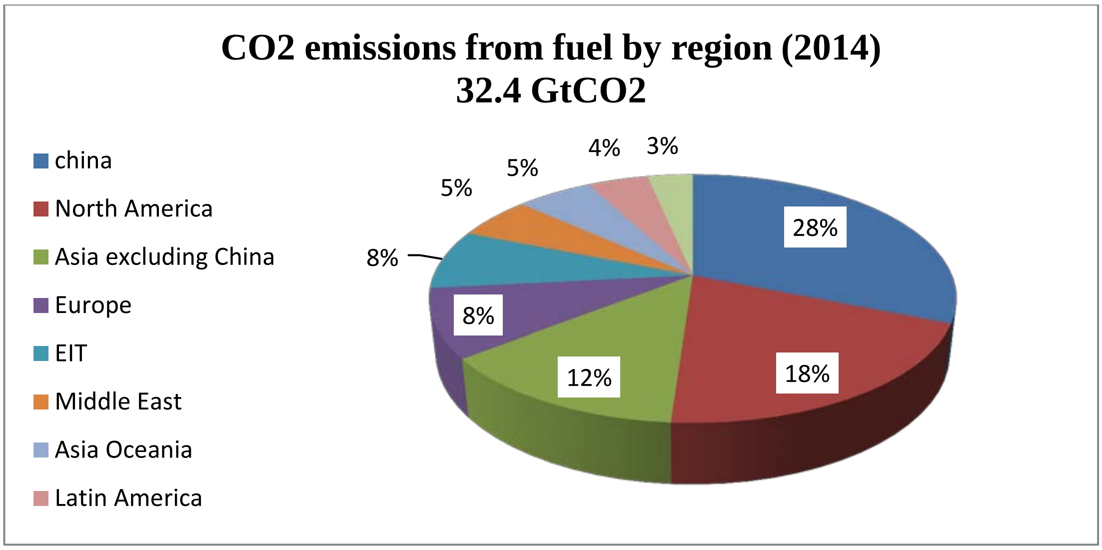


Figure 1.1 (2014) Regional shares CO_2 emissions (IEA, 2016a)

Asif (2016) listed the fifteen top countries in terms of annual CO_2 emissions (shown in Figure 1.2). It can be observed that Qatar has the highest CO_2 emissions, at 44 tonnes per year. Kuwait is in fourth position with 30.3 tonnes of annual CO_2 emissions. The United Arab Emirates is in sixth position with 22.6 tonnes per year, followed by Bahrain and Saudi Arabia with 20.7 and 16.1 tonnes per year respectively. Based on Figure 1.2, Oman has the lowest annual CO_2 emissions among Gulf Cooperation Council (GCC) countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates) at 15.2 tonnes per year.

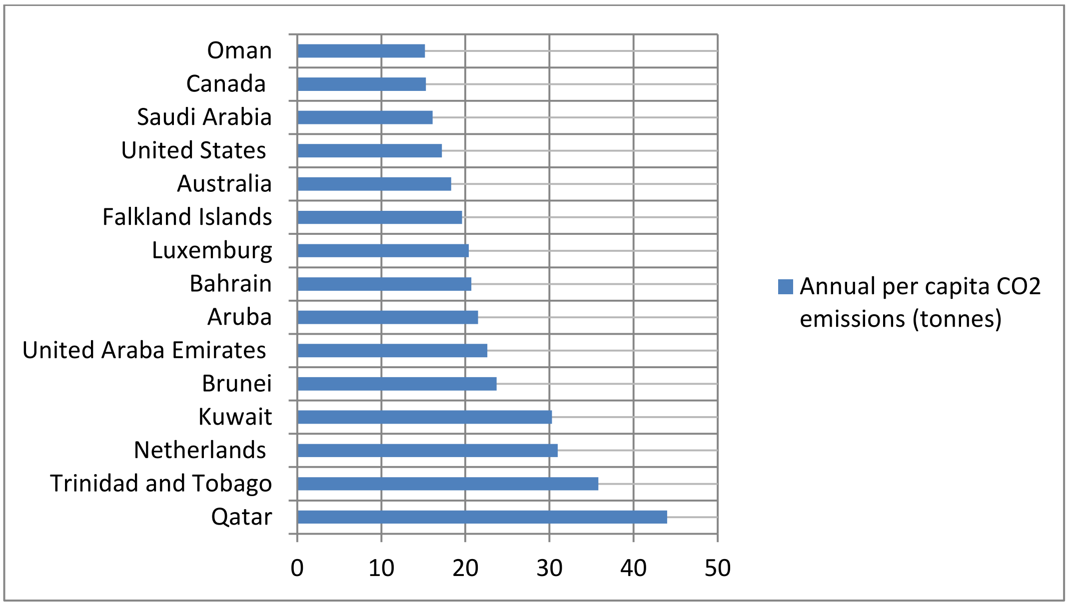


Figure 1.2 Top 15 countries in terms of annual per capita carbon dioxide emissions (Asif, 2016)

The Middle East region, characterised by rapid growth in population, economic activity and income, depends on two main fuel sources for producing electricity: crude oil, and natural gas. Electricity generation is expected to grow by 2.1% per year from 758 billion kWh in 2010 to 1405 billion kWh in 2040 (IEA, 2013a). Other energy resources play relatively minor and negligible roles in providing electricity for the Middle East (IEA, 2013a). Wind speed varies depending upon the geographical characteristics of the locations. The wind potential of the above mentioned Middle East (ME) countries is graphically presented in Figure 1.3 at 100m hub height above ground (AGL). The values shown in Figure 1.1 support the installation of wind turbines in these countries for small to large scale electricity generation.

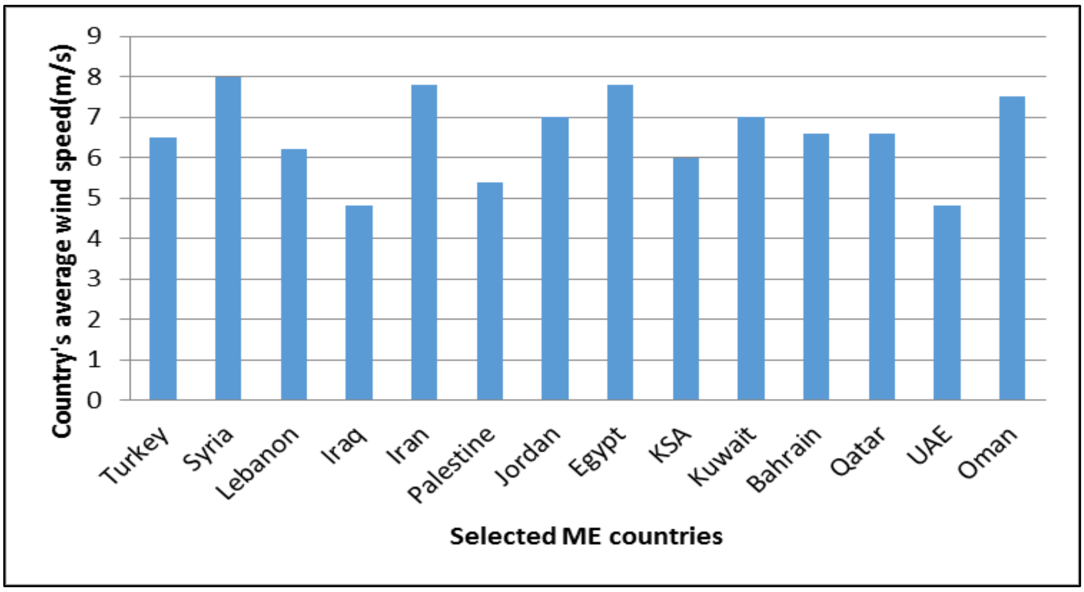


Figure 1.3 The ME countries' annual average wind speed at 100 m height AGL (Shawon, El Chaar and Lamont, 2013b)

Al-Maamary et al. (2017) reviewed the impact of heavy production of oil and gas on the GCC countries. They stated that, in the past decades the GCC countries failed in the separation between economic development and energy demand and the increase in oil and shale gas production will affect the GCC countries Therefore, the GCC economies are among the least competent in the world growth in energy consumption and faster than economic growth in the region. Suhail Bin Mohammed Al Mazrouei, energy minister of the United Arab Emirates (UAE) told CNBC (2017) "In the UAE we are diversifying the sources of energy and also we are diversifying the sources of income. We are developing our economy, and year on year we are seeing that the non-oil economy's contribution is growing".

The global oil demand grew by 3.8 mb/day (million barrels per day) from 92.7mb/day in 2013 to 96.5 mb/day in 2017. Kuwait crude oil production is 2.9543 mb/day and the proven crude oil reserves (million barrels) is 101,500 (OPEC, 2017). Moody's (2017) stated that at the current rate of the production ,the reserves in would last almost 90 years or 97 years according to (OPEC, 2017).

The limited supply and fluctuating price of oil, the rapid increase in population, the high consumption of electricity, and the protection of the environment encourage these countries to use and invest in renewable energy (Patlitzianas, Doukas and Psarras, 2006). The price of oil was ($111.67 /£65.78/33.5 KD) per barrel in 2012, an increase of ($0.40/£0.235/120 fils) per barrel from the 2011 level (BP, 2013). However, The price of oil is decreased by ($61.46/£46.41/KD18.57) in 2017 to reach ($54.54/£41/KD16.5) per barrel (Alwatan, 2017). The collapse in oil prices has meant lower exports and government revenue in the GCC. Export losses were estimated to be ($287 billion/£217 billion/KD87 billion) for 2015(IMF, 2016). As a result, Fuel, water, and electricity charges have been raised in GCC countries.

Limited effort has been made in the use of renewable resources to produce energy in the countries of GCC, due to the region's large oil and gas resources. Recently, GCC countries have started to take an interest in renewable energy in response to environmental and climate change issues, since they are involved in the United Nations Framework Convention on Climate Change (UNFCCC) and accessed the Kyoto protocol. Kuwait is aware of the critical challenge of the COP21 Conference to avoid a change in climate that would threaten our societies and our economies and submit the climate plan action to the head of 2015 Paris agreement(UNFCCC, 2015).

Moreover, Alnaser and Alnaser (2011a) reviewed renewable energy in the GCC. They found that in 2009 0.5% of global electricity was consumed by GCC countries, 9.8% by Europe, 8.8% by China, and 7.4% by the USA. The electricity consumption by GCC countries has been increased by 6.67% from 2005 to 2009. They stated that the average electricity consumption per person in 2009 was almost four times the world average, more than four times the average in China, about double the average in the EU, and 0.8 of the average in the USA. The average emission of CO_2 was presented as approximately 20 tonnes per capita in GCC countries.In addition, International Renewable Energy Agency (IRENA, 2016) stated that electricity consumption of GCC countries has grown at an average rate of 6% to 7% per year between 2003 and 2013.

In Kuwait, oil and natural gas are the sole resources of energy. The country will be forced to increase oil production or reduce oil exportation because of high consumption of energy; 10% of the produced energy was being consumed locally in 1980, which increased to 20% in 2005, and is expected to reach 40% by 2015 (Alotaibi, 2011). This was proven later by static report from Kuwait Ministry of Electricity and Water MEW (2016) to be 68288 million kWh in 2015.

From the above, it is clear that utilisation of renewable energy from sources that provide energy with zero or almost zero emissions, such as wind energy, solar energy, biomass energy and wave energy, has become essential .

Furthermore, renewable energy sources such as wind energy can help in reducing the dependency on fossil fuels. Wind energy has been estimated as the most continuously available energy in the earth by approximately 10 million MW of the total energy; it provides a variable and environmentally friendly alternative and national energy security at a time when falling global reserves of fossil fuels threatens the long-term sustainability of the global economy. In addition, wind turbines have an exclusive technical identity and unique demands in terms of the methods used for design. Remarkable advances in wind power design have been achieved through modern technological developments (Joselin Herbert et al., 2007).

Since 1980, wind turbine technology has improved and contributed to a 5% annual increase in the energy yield of the turbines. Over recent years, the weight of turbines, the huge annual increment of turbine output energy, and the noise they produce have been reduced in a very impressive manner. Wind energy is expected to play an increasingly important role in the future national energy scene. An experts predict that 5% of the world energy market will be controlled by wind power by the year 2020 (Joselin Herbert et al., 2007). In 2016, the total world cumulative capacity of wind energy reached 486,790 MW (GWEC, 2016).

In Kuwait according to(Alnaser and Alnaser, 2011) the power generated from solar energy is about five times the wind power However, Kuwait lies within the medium wind speed region among the Middle East and Northern Africa (MENA) (Shawon, El Chaar and Lamont, 2013a). The atmospheric condition has a significant effect on the PV cells, which is affected by cumulative dust and high air temperatures. The reduction in efficiency of PV cells is about 10% more than that of standard conditions and their rapid degradation is main cause of reducing the life time of the system and increasing the maintenance cost (Al-Sabounchi, Yalyali and Al-Thani, 2013; Authority for Electricity Regulation, 2008). The locations which would be suitable for implementing renewable energy schemes are unfortunately land areas owned by private citizens or the main oil company in Kuwait. This leads to a dearth of suitable land in Kuwait, leading to the difficulty of implementing a solar system optimally in Kuwait. However, wind systems use less land and can even be moved further to the sea by using offshore wind turbines. Wind turbine technology is less affected by the atmospheric conditions in Kuwait and has a lower maintenance cost. These all lead to wind turbine systems being easily implementable in Kuwait. Kuwait is following a mixed energy policy, which would result in the optimal use of any available energy to generate electricity for the long-benefit of the country (Alhajraf, 2013; Alnaser and Alnaser, 2011).

Figure 1.4 Map of Kuwait (Mapsofworld, 2013)

Kuwait, as shown in Figure 1.4, is an arid area situated in the Middle East, in the North western part of the Arabian Gulf. Some studies refer to it as the Persian Gulf; in this research, it will be known as the Arabian Gulf. Kuwait has a total land area of 17818 $km^{2.}$ It is located between 38^o to 40^o East and 28^o to 30^o North, respectively, and is characterised by a long hot and dry summer that lasts from April to October, where temperatures reaches 50 $^{\circ}$C in the shade, and a short winter. In the summer dust storms occur and humidity is high. The country experiences a mostly desert climate with significant differences in daily temperature, ranging being between 13^{o}C in winter and 40^{o}C in summer. The varying topography is expected to significantly change the spatial wind speed. The wind speed and direction at any location depend on many factors, including the morphological variations and gradients of the land in different directions (Jamal et al., 2010).

This study proposed the concept design for 10-MW wind farms, and wind power plant development appeared suitable for a renewable kickoff for power generation in Kuwait with the option for large-scale extension in the future. Environmental impact, job creation, integration with the national electric grid and risk assessment were also investigated in the study.

1.2 Research Aim and Objectives

The aim of this research is to assess the feasibility of using wind turbines within Kuwait as a source of renewable energy by investigating the financial, environmental and soil-structural stability of the system.

To achieve the aim of this research work, the following objectives were pursued:

1. To review the use of wind energy in the Middle East, particularly in Kuwait.
2. To assess the various types of wind turbine structures and associated foundations.
3. To assess the feasibility of future use of wind turbines within Kuwait, accounting for the various factors affecting their deployability, such as cost, engineering, strength, integrity, environment and location.
4. Recommend a strategy for feasible adoption of wind energy technology use in Kuwait.

In order to accomplish the above aim and objectives, a detailed literature review was carried out to include types of renewable energy, solar and wind energy in the Middle East. This was followed by an investigation of the study area and wind turbine categorisation and selection, economic financial analysis, and environmental life cycle analysis. Modelling and identified research methodology is presented in Chapter 3 followed the required data and parameters in Chapter 4. The fifth Chapter covers the economic financial analysis and then a life cycle assessment is presented in Chapter 6. Chapter 7 describes finite element modelling conducted in order to assess the stability of the wind turbine from a soil-structure point of view. Finally research conclusions, recommendations and future work are discussed in detail in Chapter 8.

2 Literature Review

2.1 Introduction

As explained in Section 1.2, the aim of this research is to explore the feasibility of the use of wind turbines in Kuwait by investigating factors affecting the system using numerical modelling techniques and a cost benefit analysis. It is therefore important to understand the types of renewable energy in the Middle East, particularly in Kuwait, and the relationship between wind turbine design and their contributing factors, in order to establish effective strategies and policies which can be implemented for their future use in Kuwait.

The aim of the literature review is to understand and examine previous work to obtain necessary parameters, and gather and classify a comprehensive range of state of the art literature to obtain a knowledge and understanding of the topic of wind energy in Kuwait. In addition, this will assist in the development of the optimum wind energy model for Kuwait.

The review starts by looking into the available types of renewable energy. The second section of this review investigates different experiences of using solar and wind energy in the Middle East. Because of the similarities in environment, such as weather conditions, terrain (which includes soil properties), economic position, lifestyle, and the availability of resources, it is worth investigating the findings and evidence regarding the feasibility of wind turbines in other countries within the Middle East region. This is followed by a review of the types of wind turbine, including their cost and design, and the characteristics of onshore and offshore turbines. The third section introduces an overview of the types of foundations for vertical and horizontal wind turbines. A review of different methods that have been employed to analyse wind turbine models, including experimental, field and numerical techniques, is presented in the fourth section. Finally, a summary of this chapter is provided.

2.2 Types of Renewable Energy

Hall & Scrase (1998) explained that the reason behind naming renewable energy 'green energy' is that the generation process gives off zero air pollution. The Kyoto protocol set a long-term aim of reducing CO_2 emissions by 50% before 2050. Nowadays, governments are giving serious consideration to renewable energy as a solution to environmental issues, particularly the high level of CO_2 in the atmosphere (Gross, Leach and Bauen, 2003). In addition, the international market understands the requirement of improving renewable energy sources (RES) due to the increasing cost of fossil fuels (Patlitzianas, 2011).

(Gross, Leach and Bauen, 2003) stated that an important developments in renewable energy have seen a decrease in the potential cost and a large spread in the market for certain types, yet others require further improvement. They studied and considered the advances and obstacles in the next decades, and also discussed the importance of collaboration between energy technology and policy development, identifying differences between renewable energies due to their technological and commercial development.

The next section will focus on renewable energies such as solar photovoltaic (PV), wind, biomass, and wave energy. These types of renewable energy have been chosen here as they are the types most commonly used.

2.2.1 Solar Energy

Solar energy is divided into two major technologies, a concentrating solar thermal power plant (CSP) and a photovoltaic plant (PV). CSP captures the sun’s heat, to be used immediately to generate electricity, which can be stored that heat and then use it to generate power later. CSP requires large amounts of land for the solar collectors compared to (PV), which are relatively smaller and light which can be placed on rooftops. In spite of that PV is that the storage is relatively inefficient when compared to storing CSP captured energy (Nader, 2009). Figure 2.1 shows a solar energy system in a farm.

Figure 2.1 CSP and PV Solar energy system (Al-Qattan, 2017)

Global solar energy capacity reached 100 GW at the end of 2012, an increase of 43.3% compared to the end of 2011, and increased by 30.8 GW in 2013 (BP, 2013).

Gross et al. (2003) studied the progress of several photovoltaic solar systems; this is a very important market and is predicted to expand. The PV solar system has a high potential cost, but the study predicted a reduction in the cost in the long term,

Sims et al. (2003) studied the carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation, and demonstrated that solar energy requires large amounts of land and equipment. Later, Tsoutsos et al.(2005) studied the environmental and socio-economic impacts of solar energy technologies. They showed that there were no noise or chemical pollutant impacts from using solar energy, although there was a visual impact, depending on the location of the PV system and the surrounding area.

Zhang et al.(2012) analysed the expansion of solar energy use in Hong Kong. They determined the main obstacles to establishing a solar photovoltaic (PV) system in Hong Kong by using information gathered from a survey. The researchers reported that the main barriers were the very high primary cost and maintenance costs, long-term repayments, insufficient areas for establishment and service infrastructure, the need for social involvement and participation in energy policy, and the need for motivation by legislation and regulation. They recommended reducing the high price of solar PV systems, and greater evaluation of mass production of low-cost fabrication technologies and efficient PV systems. They also recommended that the government of Hong Kong should encourage people and companies to utilise solar energy, and the government should share the main role with the private sector and the people of Hong Kong.

Bhutto et al. (2012) investigated the progress and challenges of solar power in Pakistan. They discussed the potential of solar energy in the region, including policy, roles and responsibilities. They concluded that the availability of conditions conducive to developing solar energy in Pakistan, such as the high level of solar radiation throughout the year and the easy access to low cost labour. They stated that PV technology has an advantage of low maintenance and no pollution, which makes it suitable for remote areas with no connection to the electricity grid. The most common PV applications in the Pakistani market are telecom power, railway networks, cathodic protection of pipelines, and defence services. Solar thermal technologies in Pakistan are used for cooking, heating and cooling of buildings, generation of high temperature steam, heating water for domestic and industrial applications, and drying agricultural products under controlled temperatures. The researchers concluded that solar energy can be used effectively by the textile industry in Pakistan. They found that heating water using solar energy in Pakistan was limited when compared to heating water using natural gas because of the high capital cost of a solar water heater. They also concluded that government institutes and private sectors must work to spread knowledge about solar energy systems in the Pakistani community.

More discussion of solar energy in the Middle East will be presented in Section 2.3.

2.2.2 Wind Energy

The Bureau Ocean Energy Management (BOEM) (2009) defined wind as "air in motion". As a result of the varying absorption of sun radiation by the earth; wind is produced.

The development of wind technology has accelerated throughout the last 40 years. In the 1980s, the first wind farm developed in California. By the end of the 1990s, wind energy was estimated to be the most significant sustainable energy resource in the world. Currently, wind energy is the leading source of renewable electricity worldwide, spread commercially across European countries, India, and the United States (Bilgili, Yasar and Simsek, 2011).

Recently, as shown in Section 2.1, there has been interest in using renewable energy, particularly wind energy, to produce electricity for the national grid and for water pumping and power supply to distant areas. There has also been significant advancement in the technology for manufacturing wind turbines to generate electricity. Rotors, controls, electronics and gearboxes were improved to increase the capacity factor from 25% to over 50% over the last 10 years. Figure 2.2 shows the wind energy system connected to the grid to generate electricity.

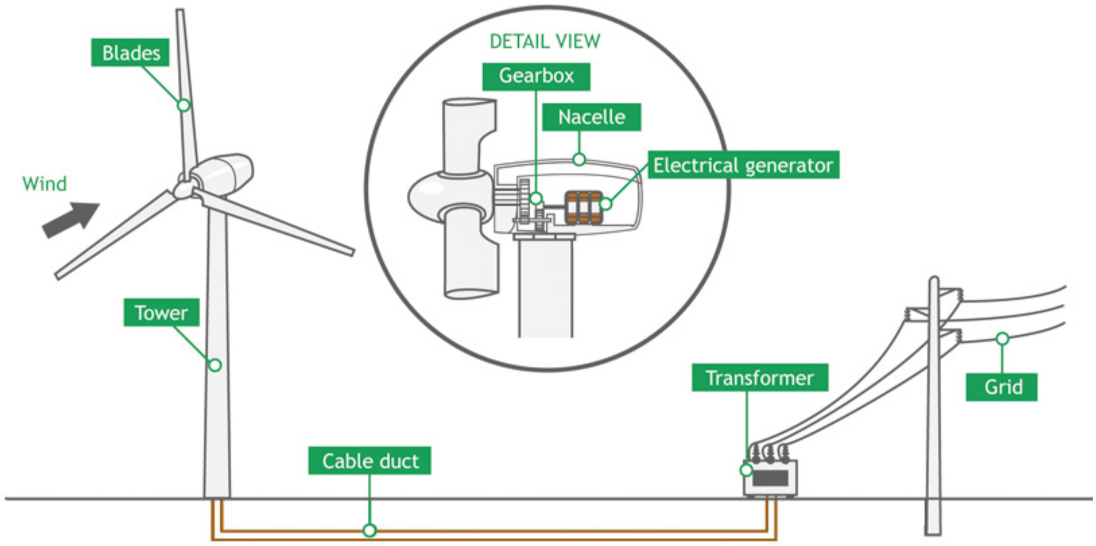


Figure 2.2 Wind energy system connected to a grid (GSE, 2014)

The World Wind Energy Association (WWEA, 2013) reported that the worldwide capacity of wind energy was about 318 GW in the 2013. However, in 2016 the total capacity was 540 GW by increase of 70%.

With all the challenges of climate change and greenhouse emissions that the world faces, wind energy technology with zero CO_2 emissions and low cost is a solution for supplying the world with safe energy (Cherrington et al., 2012).

McCubbin and Sovacool (2013) examined the health and environmental benefits of wind power in comparison to natural gas in the United States. They collected data on wind energy farms, a 580-MW wind farm at Altamont Pass, CA, and a 22-MW wind farm in Sawtooth, ID, for the period 2012-2031. They considered the advantages for both farms in terms of environmental and economic aspects. They found that the production of electricity using wind energy has fewer costs than using natural gas. They concluded that the gap between natural gas and wind energy will be bigger in the future, to the benefit of wind energy.

Coles and Taylor (1993) studied the environmental impact of wind farms in the UK. They analysed the environmental influence of six wind farms from several points of view, such as changes in the character of the landscape, the negative visual impact from the size and the shape of the turbines, the noise, and the impact on wildlife (plants, animals, and birds). They concluded that the wind farm policy needs more attention from the UK government.

Gross et al. (2003) reviewed progress in renewable energy. They concluded that over the last decade, wind energy has undergone significant improvement, rapid global expansion in the market, and significant technological progress, and also concluded that onshore wind turbines were a leading competitor as a first alternative to fossil fuel. They pointed out that there was some evidence to support the view that the down-grading of the cost will be slow over 10-20 years, but that a large reduction was expected, and recommended improvement in offshore turbines and the spread of wind energy into other areas of the world.

Rehman (2005) described the development in the wind sector around the world: the capacity of wind turbines is variable, establishing and operating wind turbines is not difficult, the cost of maintenance is inexpensive, a turbine life cycle is long, the cost of output energy is competitive, and development in wind technology is fast.

Saidur et al.(2011) also reviewed the negative and positive environmental impacts of wind energy. They found that wind energy is green, safe for the environment and inexpensive compared to other renewable energy sources. They concluded that using wind energy consumes less water compared to other energy production plants which use petroleum. It was also concluded that wind energy is considered to have less impact on the environment than other energy systems. The researchers also pointed out that there are negative impacts from using wind energy, such as endangering wildlife, noise, and the visual impact, and suggested that, with more developments in wind turbine design, fewer negative impacts would occurs.

Shafiullah et al. (2013) showed the potential challenges of integrating large-scale wind energy into the power grid. They investigated the environmental, economic, social and technical impacts of wind energy sources as the foundation of future development. They reviewed wind energy technology and its current technical limitations. They concluded that the negative impacts were as follows: socially and environmentally, in visual impact, sound and wildlife killed; economically, in the great initial cost; environmentally, during establishing and dismantling wind farms; and technically, in the impact on the performance of the grid. However, they concluded that there were more significant benefits and positive impacts from wind energy than from other energy sources: it is environmentally friendly, with zero CO_2, SO_2, and NO_2 emissions; it is more efficient at less cost; and it creates employment opportunities.

Oebels and Pacca (2013) assessed the CO_2 eq emissions of an onshore wind turbine farm of 141.5 MW in Brazil during its life cycle. They found that for a favourable CO_2-intensity of 7.1gCO_2/kWh, control of the production stage, which is responsible for 90% of CO_2-emissions, and reduced emissions during the component production phase, must be ensured. Moreover, Bonou, Laurent and Olsen (2016) evaluated the environmental impacts of onshore and offshore wind turbines in Europe. He studied two 2.3 and 3.2MW onshore turbines and 4.0 and 6.0MW turbines offshore. He found that the emissions of carbon dioxide CO_2 were less than 7 gCO_2 eq/kWh for onshore wind turbines and 11 g CO_2 eq/kWh for offshore wind turbines.
Different types of wind energy technology will be discussed in the next sections.

2.2.3 Wave Energy

Waves are generated by wind as it blows across the sea's surface. Energy is transferred from the wind to the waves. Waves travel vast distances across oceans at great speed. The longer and stronger the wind blows over the sea surface, the higher, longer, faster and more powerful the waves are (Enerlogy intelligent energy, 2014).
(IRENA, 2014) stated that wave energy converters capture the energy contained in ocean waves and use it to generate electricity. There are three main categories of converters; oscillating water columns that use trapped air pockets in a water column to drive a turbine; oscillating body converters that are floating devices using the wave motion to generate electricity; and overtopping converters that use reservoirs to create a head and subsequently drive turbines. Figure 2.3 shows the three different categories of wave energy convertors.

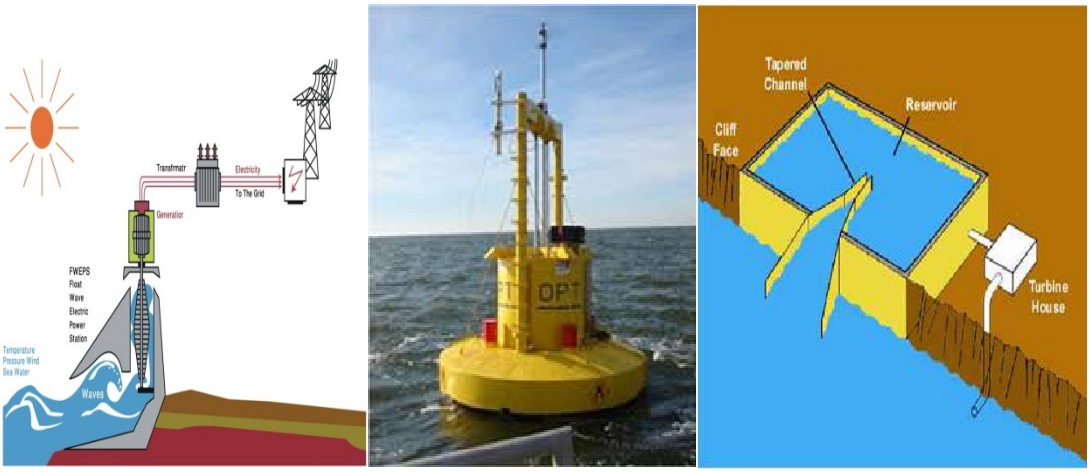


Figure 2.3 The three main categories of the wave energy convertors (IRENA, 2014)

Falcão (2010) reviewed the utilisation of wave energy technologies and the development of wave energy since the 1970s. He showed that the main disadvantage of wave energy is that it is irregular; there is a great variation between the scales of waves from season to season. Moreover, he pointed out that the development of wave energy faces commercial barriers because of the high cost of establishing, arranging, maintaining and examining the wind turbine prototype within a difficult environmental situation. He recommended that significant funding from governments would be very helpful in such cases.

Drew et al. (2009) reviewed wave energy converter technology. They evaluated the device types that represent current wave energy converter (WEC) technology, which are first generation devices focusing on work, particularly within the United Kingdom. They reported some important disadvantages of using wave energy: the difficulty of converting the input of high random motion to slow motion of electricity in the output to be used in the grid; the difficulty of harvesting the high-variability waves, especially around offshore areas; and the impact of random wave motion on the system's design and proficiency.

Gross et al. (2003) concluded that wave and tidal energy were in the initial phase of development, and showed that wave energy was rejected from government policy because of experimental failure during testing when they tried to connect to the natural grid.

However, Drew et al. (2009) showed that there are substantial advantages to using wave energy. For example, wave energy has a larger power density than other renewable energy sources; the influence on the environment is limited; the variability of sea waves meets the demand for electricity in climate change temperature; the amount of energy loss is small; and the production of the wave energy machines produce energy by 90% whereas wind and solar power machines produced energy by 20-30%.However,for this study viewpoint, wave energy would not be feasible due to the shallow of the Gulf Area sea.

Saket and Etemad-Shahidi (2012) studied wave energy potential along the northern coasts of the Gulf of Oman, Iran. They investigated the annual and average monthly wave energy potential by using hindcast data for 23 years, from 1985 to 2007, and characterised the wave energy resource in terms of sea state parameters. The SWAN model was implemented to simulate wave parameters. They found that the majority of annual wave energy occurs at wave heights between 1 and 3 m and energy periods between 4 and 8 s in the direction of South South East (SSE). They also found that the quantity of wave energy estimated along the coast of Chabahar in Iran is low. One of the greatest barriers to wave energy technology presented by the research is efficiently transforming wave energy into electricity, as this technology is still in the development stages.

Recently, studies have been conducted to evaluate the wave energy at coastal locations in Oman sea and Arabian Gulf (Kamranzad, Chegini and Etemad-Shahidi, 2016; Bassett et al., 2015; Khojasteh and Kamali, 2016). The studies found that wave technology is not cost efficient and uncompetitive efficiency compared with solar and wind energy. They concluded that in Arabian Gulf with current social and commerce conditions such as the UAE-Iran diplomatic relations, oil tanker traffic, lots of oil and gas fields and the local communities near the shore could demonstrate the barriers facing the wave energy. Moreover, Arabian Gulf has lower wave height than Oman Sea.

It’s clear from above that Kuwait is located on Arabian Gulf which has low wave energy as it is proven in previous studies.

2.2.4 Biomass Energy

The United Nations Development Programme (2000) defined bio-energy as "energy that is derived from wood and other plant matter—an important potential contributor to sustainable energy strategies, particularly when converted to modern energy carriers such as electricity and liquid and gaseous fuels". Another definition, presented by Al-Badi et al. (2009) states that biomass "is organic material made from plants and animals". They explained that chemical energy is produced in the form of heat from burning the organic material. Figure 2.4 shows the bio-energy system.

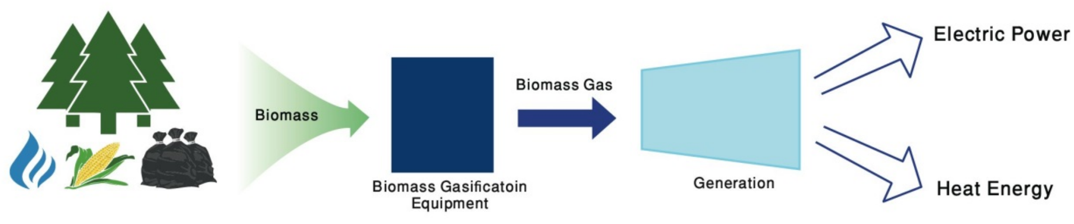


Figure 2.4 Biomass energy system modified after (ELITE, 2015)

Hall and Scrase (1998) claimed that 75% of the world's population in developing countries considers bio-energy to be the most important source of energy in developed countries depending on biomass as the main energy provider. On the other hand, IEA, (2016) reported that global electricity production from bioenergy in 2015 about 2% while the global energy production from wind and solar PV continued their fast growth by more than 11%.

Hall and Scrase (1998) highlighted problems associated with using biomass energy. First, they mentioned that the cost of bioenergy is high because of the labour and vehicles required for transporting the material used for biofuel, the need for places to store the fuel, and the processing costs compared to those of fossil fuels. In addition, wood fuel costs two to three times as much as coal in Europe and the USA. Secondly, biomass requires large areas. Finally, the energy consumed for fuel production and transport from wood biomass is greater than the output by ten to thirty times.

The United Nations Development Programme (2000) reported that biomass energy technology offers advantages and disadvantages, and that the advancement of the technology at present depends on non-technical matters such as policies and cost-effectiveness. The UNDP reviewed the disadvantages, which are the gas emissions created from the fuel process, fears regarding land use, the impact on food and grain prices, and the limitations in crops used in biofuel energy.

Furthermore, (Gross, Leach and Bauen, 2003) concluded that there are barriers to the production of electricity using biomass energy. In addition, they recommended that further development of policy in bio-energy will lead to a worthy capacity in the basic market.

(Evans, Strezov and Evans, 2010) studied the sustainability considerations for electricity generation from biomass. He stated that there are many biomass types available for the production of electricity, which are 1) Residues consist of two parts a) Bagasse which is defined as taking the waste products generated on-site and reusing them directly to power the process. Waste heat after power generation is typically applied to sugar refining which would be limited by sugar unavailability. The fact is that sugar cane is produced in over 100 countries worldwide; Kuwait is not one of them.

b) Forest and on-bagasse agricultural residues which are include the wastes of large amounts of leftover material, such as stalks, skins, shells and off-cuts from rice, grain, cotton. The waste can be obtained at very low or no cost which is an advantage However, the disadvantages is the need of specific locations for landfill and the height cost of transportation.

2) Dedicated energy crops which are the typical crops include poplar, willow, eucalyptus and non-woody perennial grasses, such as miscanthus. Limitations to be addressed are that crops are seasonal, not available over whole year and exhaustion of soil nutrients.

In Kuwait with a limited agricultural productions and landfills which are not suitably cited or designed (Al-Yaqout, Koushki and Hamoda, 2002; Al-Jarallah and Aleisa, 2014) made the biomass energy an unfavourable solution. Moreover, IRENA, (2016) stated that the technology of biomass energy in Kuwait is relatively underexplored.

Findings from the literature have been summarised below in Table 2.1, which presents the different types of energy and its advantage and disadvantages. It is clear from the table that both solar and wind energy have low CO_2 emissions and visual impact, but wind energy has a long life cycle and is a fast developing technology. Wind energy has low initial and maintenance costs, whereas this is not the case for solar energy, which has high primary and maintenance costs. Both solar and wind energy have been successfully connected to the electricity grid and have many applications around the world. It is also clear from Table 2.1 that biomass energy has a high cost due to the labour, vehicles and large working and storage areas. On the other hand, wave energy is difficult to examine and calibrate and has high establishment and maintainence costs. In Kuwait, both wave and bio-energy face several issues and complications such as avalibility of the energy, developing technologies, land use and cost. Low waves energy in Arabian Gulf and avilability of oil and gas fields, oil tanker trafic reduces the potential from harvesting of wave energy. Due to limited agricultural productions and lack of landfills, therefore they are not recommended to be used in this research. Wind energy is more competitive in terms of the initial, maintenance, and output energy cost than other renewable energy which makes it the first choice for this research work.

Table 2.1 Comparison between different types of renewable energy (solar, wind, wave and bio-energy)

Type of Energy	Advantages	Disadvantages
Solar Energy	• Low CO_2 emission. • No noise. • No chemical pollution.	• Visual Impact. • Large amount of land use. • Large equipment. • Long term repayments. • High primary cost. • High maintenance cost.
Wind Energy	• low CO_2 emission • Inexpensive initial cost. • Low maintenance cost. • Long life cycle. • Cost of output energy Competitive. • Fast developing technology. • Consumes less water compared to other energy production plants.	• Visual impact. • Noise. • Impact on wildlife. • Changes the character of the land.
Wave Energy	• Large power density. • Limited influence on the environment. • Availability of waves meets the demand for electricity in climate change. • Small energy loss.	• Difficult to harvest waves due to irregular scale. • High establishment cost. • High maintenance cost. • Experimental failure. • Difficult to examine. • Difficult to convert the input to use in the electricity grid. • Impact on the system proficiency. • Still in the development stages.
Biomass Energy	• Advancement of the technology depends on policies and cost effectiveness.	• High cost due to labour and vehicles required. • Needs place to store. • Large area use. • Wood fuel cost more than coal by 2 to 3 times. • Barriers to the production of electricity. • Gas emission. • Impact on food and grain prices.

2.3 Solar and Wind Energy in the Middle East

This section concentrates on wind and solar energy because they are estimated to be the most important of the various renewable energy sources in terms of future use (Weng, Liu and Zou, 2012). In the Middle East, the countries of GCC are the main investors in renewable energy. It is predicted that by 2022, the production of electricity via wind and solar energy in GCC countries will reach 10 GW (Alnaser and Alnaser, 2011).

Weng et al. (2012) presented environmental information on solar and wind energy facilities. They expected that in the near future solar and wind energy will become the world's main sources of energy. They analysed collected data on solar radiation and wind distribution based on satellite information and a mathematical weather prediction model. They found that as global temperature decreases, the level of sun energy that reaches the earth does not change. On the other hand, significant developments in wind distribution across the earth have occurred as the result of global warming. They studied the wind power averages in Asia from 1949 to 1958 and from 1999 to 2008. They found that, with the increase in global warming, the average amount of wind energy also increased and presented a positive critical movement. On the other hand, there has been no important trend in terms of solar radiation. The researchers stated that the Intergovernmental Panel on Climate Change (IPCC) claimed that a significant impact of global warming has changed the capacity and geographic allocation of renewable energy sources and technology.

(Patlitzianas and Flamos, 2016) illustrated the potential development of renewable energy sources (RES) in GCC countries. They looked at the opportunities to increase the application of renewable energy sources in terms of economic, regulatory, market, and technical aspects. They concluded that some of the GCC countries have no experience with RES projects, therefore to increase knowledge of RES, strong policies and strategies for RES should be put in place, Furthermore, and the development of the RES market is hindered by groups who benefit from the use of conventional sources being against it. Jamil et al. (2016) reviewed (RES) in the United Arab Emirates (UAE) and the challenges which face technology such as photovoltaic energy, concentrated solar power (CSP), wind, wave energy, and fuel cell energy. The researchers concluded that appropriate planning and implementation for renewable energy sources in UAE will offer a suitable solution for the UAE's concerns in terms of energy, economy, and environment. The great potential in use of RES in UAE will be influenced by meeting the energy demand of the country and reach the 2030 Plan for RES resources target.

2.3.1 Solar Energy

Alnaser and Almohanadi (1990) evaluated the accessibility of solar and wind energy in Qatar. They presented an empirical equation to calculate solar radiation at any site in the state of Qatar. They found that the annual potential wind power was

306kW/m^2 and the annual potential solar power was 2.5 MWh/m per year. They concluded that the density of sun power was larger by nine times than the density of wind power.

AL-Homoud et al. (1996) presented the results of experiments with solar cooling systems in Kuwait. They studied small and medium projects with solar cooling systems established in several buildings such as schools and buildings of the Ministry of Defence (MOD) in Kuwait. They used flat plate collectors with an area of 300 m^2 and three vapour absorption refrigeration (VAR) systems of 5 to 10 tones cooling capacity (Ton of refrigeration (TR), is a unit of power used to describe the heat-extraction capacity of refrigeration). They found that the most efficient system was that at the MOD and concluded that the MOD project and other solar cooling systems needed maintenance, and coefficient of performance (COP) which is defined as the relationship between the power (kW) that is drawn out of the heat pump as cooling, and the power (kW) that is supplied to the compressor. for VAR ranged from 0.6 to 0.7. Moreover, they found that there was a 25% to 40% annual saving in electricity from the solar cooling system. They recommended that more research should take place to reduce the auxiliary energy, and it is significant to consider the capital cost of solar cooling energy for commercial projects**.**

PV cells efficiency is affected by cumulative dust and high air temperatures. Reduction in efficiency of PV cells is about 10% more than that of standard conditions due to the environmental circumstances of Oman (Authority for Electricity Regulation, 2008). Furthermore, in Kuwait, Ramadhan and Naseeb (2011) studied the cost-benefit analysis of implementing a photovoltaic solar system. They analysed the costs of applying PV in the state of Kuwait, and found that the high levels of sun in Kuwait strongly support solar energy playing a role in producing electricity. They also pointed out that the establishment of PV systems will reduce the level of CO_2 emissions in the state of Kuwait. This study showed that, where the price of one barrel of oil is (100$/£58.88/ KD30), the levelised cost of energy (LCOE) of one megawatt of PV station will be about ($0.20/kWh/£0.117/kWh/ 60fils/kWh), and will fall to a range between ($0.05 and 0.17$/kWh/ £0.029 and £0.10 /kWh/15 fils and 51 fils/ kWh). However IRENA, (2016) stated that LCOE of the PV energy in GCC countries is ($0.0585 to $0.1 /kWh/ £0.044 to £0.08 /kWh/ 20fils to 30 fils/kWh).

Alnaser and Alnaser (2011a) concluded that in 2015 the manufacture of PV cells would spread in all Gulf Cooperation Council (GCC) countries, to meet the demand for electricity and to enter the world solar energy market. However, IRENA, (2016) stated that the equipment in all renewable energy projects in the GCC is manufactured by foreign companies.

However, suppliers are increasingly positioning themselves in different segments of the local value chain. For instance, First Solar, the panel provider for both phases of the Mohammed bin Rashid Al Maktoum solar park, has established itself not only as an equipment supplier but also as an EPC company and a developer in the region. The localisation of its manufacturing segment, however, may only happen with a substantial increase in the annual installed capacities in the GCC and MENA (Bkayrat, 2015)

Patlitzianas (2011) studied solar energy in Egypt and analysed all suitable business opportunities for investing in solar energy in the Egyptian market. He concluded that many economic, political, social and technical obstacles face investment in solar energy in Egypt. However, Egypt can take part in the solar energy sector because it has 250 days of sunshine per year. Egypt also qualifies to join the Clean Development Mechanism (CDM) projects, which is defined in Article 12 of the Kyoto Protocol, to “allow a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries" (United Nations Framework Convention on Climate Change(UNFCCC), 2014), and the Mediterranean Solar Plan (MSP): "The huge solar potential for the development of renewable energy of the Mediterranean could be the key to meeting rising energy demands in the region, to help partner countries make full use of this potential, the Commission supports the Mediterranean Solar Plan" (European commission, 2012).

Mekhilef et al. (2012) studied the effect of dust, humidity and air velocity on the efficiency of photovoltaic cells. They studied the influence of each individual factor and their influence on each other. They determined that the accumulated dust on the outer boundary of PV cells reduced the productivity of the system. Humidity had the same effect as dust on the system. The third factor was wind speed, where the high velocity diminished the heat from the PV cells, and at the same time, the high wind speed reduced the humidity. They concluded that it is essential to consider dust, humidity and wind speed together to evaluate their impact on the efficiency of PV cells.

Mokri et al. (2013) evaluated solar energy in the United Arab Emirates. They analysed data on the production and consumption of oil and measurements of solar energy in the current situation in UAE and the possibility of using solar energy. They reviewed the impact of surroundings on the performance of the various kinds of technology, the most economical way to establish PV systems, and the advantages of using solar energy for electricity, water and transportation in the country. They found that PV technologies with self–cleaning coatings and wet cleaning and organic solar cells are more suitable for the arid environment of the UAE with its dust and high temperatures. They pointed out that the expected production capacity of the UAE solar market in 2013 was approximately 135 MW.

Al-Sabounchi et al. (2013) studied the design and evaluated the performance of a photovoltaic grid-connected system in hot weather conditions. The researchers evaluated the efficiency of a PV solar system according to several parameters - output energy, transition proficiency, consistency of voltage and frequency - in the hot and dusty climate in Abu Dhabi. They studied the impact of the high temperature and the accumulation of dust on the top surface of PV cells and concluded that the efficiency and power energy production of PV modules were not affected by the weather conditions and high temperature. However, the cumulative dust had a significant impact on PV performance; resulting in an approximate 27% reduction in the power production recorded over July. In addition, Mokri et al. (2013) evaluated solar energy in the United Arab Emirates. They discussed methods of self-cleaning coatings and wet cleaning to study the impact of dust on the PV system and found that the most suitable and efficient technology for the local atmosphere was organic solar cells, but that their rapid degradation remains an issue. The researchers concluded that, in arid areas such as the UAE, the very high temperatures and abundance of dust affected parts of the PV solar system. In conclusion, they claimed that PVs are the best technology for the UAE environment.

2.3.2 Wind Energy

Alnaser (1989) studied the characteristics of the available wind energy in Bahrain using data gathered from 1976 to 1986. The long-term average wind speed, the variation at a height of 10 m, and the power density were estimated to be 4.90 m/s, 0.823 m/s, and 69.2 ± 0.34 W/m^2 respectively. He found that the average wind speed was not more than 7 m/sec; the windiest month was June, and the least windy was September.

Alnaser and Almohanadi (1990) evaluated the accessibility of solar and wind energy in Qatar. The average power density and the maximum attainable wind power density were found to be 59 W/m and 35 W/m respectively. The researchers presented mathematical calculations to determine solar radiation at any site in the state of Qatar. They found that the annual wind potential was 306kW/m^2 and the annual solar potential was 2.5 MWh/m, and concluded that the density of sun power was nine times larger than the density of wind power.

AL-Ismaily and Probert (1997) used 10 years' wind data for 12 different regions in Oman. They stated that the maximum wind speed occurred in the summer season from June to August. They found that the most suitable regions in Oman were Thumrait, Sur, and Masirah, with an annual average wind velocity of 5.7 m/sec, 5.1 m/s, and 5.0 m/s respectively. Later, Sulaiman et al. (2002) used a Weibull distribution and its parameters to calculate the average wind velocity and compared it with a theoretical distribution by using the Kolmogorov–Smirnov (K–S) test. They found that the wind speed was higher through the summer months, especially June, July and August, and was lower through the winter months of October and November; there was significant potential wind energy in both Sur and Masirah, with a wind power density of 222.10 W/m^2 and 167.44 W/m^2 respectively, and the average velocity of the wind was more than 5 m/s.

Al Malki et al. (1998) presented the first experimental study of the use of renewable energy in rural areas of Oman. They used solar energy to produce fresh water from a desalination station and employed a wind turbine with a minimum annual average wind speed of 3 m/s to pump water from a well 30 metres deep. They concluded that using solar power was acceptable, although a back-up generator must be added. On the other hand, using a wind turbine with maximum average wind speed along 20 hr/day was sufficient to produce fresh water as a source of water to a camp located approximately 70 kilometres north of Thumrait on the main tarred highway connecting Muscat with Salalah in Oman.

Rehman and Ahmad (2004) looked at the assessment of the wind energy potential of coastal locations of the Kingdom of Saudi Arabia. The researchers used the wind data analysis for five coastal locations, namely Dhahran, Yanbo, Al-Wajh, Jeddah, and Gizan. The data analysis utilised hourly mean values of wind speed and wind direction covering a period of almost 14 years between 1970 and 1983. They reported that the seasonal analysis of monthly mean wind data showed the availability of higher winds during the summer months at Dhahran, Yanbo and Gizan, while the effect of the season was insignificant at Al-Wajh and Jeddah. The higher values of monthly mean wind speed in summer showed a greater availability of wind energy, which matches the larger electrical load requirements during the summer months in Saudi Arabia. The diurnal variation of hourly mean wind speed at all the locations was quite visible, matching the daily load requirements of the locations. It was found that Yanbo is the best location among the sites analysed for harnessing the power of wind, while Dhahran is the next best location. The other three locations were found to have more or less the same results. In addition, (Rehman, 2004) analysed the data from 1970 to 1983 on wind energy resources for Yanbo, Saudi Arabia. Ten Nordex wind turbines models of different sizes were used to generate electricity. The researchers found that the maximum wind speed occurred during the summer with a value of 5 m/sec, and varied during the afternoon from 5m/sec to 8 m/sec, which reflects the increased electricity consumption during the summer months. The study concluded that the maximum wind energy was produced from the smaller wind turbines and the capacity factors were higher than for the large machine. Rehman (2005) studied wind energy development in Saudi Arabia and presented the energy produced from five wind farms located in different places in Saudi Arabia which used wind turbines of three different capacities: 600, 1000, and 1500 KW. He found that only Yanbo and Dhahran performed economically due to higher capacity factors and wind speeds. Both locations also reduced the emissions of greenhouse gases. At Yanbo, for 1500, 1000, and 600 kW machines, the reduction in greenhouse gases (GHGs) was 31369, 23601, and 26087tonnes/year respectively, while for Dhahran it was 26183, 19247, and 21533tonnes/year, respectively.

Al-Nassar et al. (2005) studied the potential for wind power generation in the state of Kuwait. They assessed the wind features of six locations. Using a Weibull distribution, the Weibull factors and power density were found at the normal height of 10 m, the yearly average wind velocity for the different six locations ranged from 3.7 to 5.5 m/s, and the mean wind power density (WPD) from 80 to 167 W/m^2. For heights 15, 20, 25, and 30m, they considered power of law by extrapolation of the 10 m. 70% increment in (WPD) to 282 W/m^2 at 30m height located in the southern desert part of the state of Kuwait. Moreover, the researchers analysed monthly WPD data and determined that the maximum WPD was found in the Al-Wafra area in the south of the country, with a value of 555 W/m^2 during the season of greatest demand for electricity in Kuwait (summer). They recommended further studies on the advantages of establishing wind farms in Kuwait for reducing the level of SO_2 and NO_x in the atmosphere and limiting the cost of fuel by reducing the consumption level. Finally, they concluded that in open flat locations in the northern, north-western and southern parts of the country, the WPD was higher than in other locations.

Using temporal and spatial data is required before any financial and environmental investment in wind energy. Al-Nassar et al. (2005) is one of the main research papers surveys in six locations in Kuwait to assess significant data of wind speed and wind density. General wind characteristics were given to make a clear decision in which area can implement the wind energy. Al-Wafra area is an inhabited area with agricultural land owned by Kuwaitis for this reason it was excluded from this thesis.

Al-Badi et al. (2009) evaluated the potential for renewable energy resources in Oman and identified the barriers to their significant utilisation. They stated that solar and wind energy would play a significant role in the future of renewable energy in Oman and would have important economic and environmental benefits. They recommended that the government should introduce policies for new energy in Oman. Moreover, Albadi et al. (2009) analysed wind data from the meteorological station at Duqm in Oman. Using a Weibull distribution, the average monthly and annual wind speeds were found to range from 2.93 m/s to 9.76 m/s and 5.33 m/s. respectively. The researchers estimated the cost of wind energy by using five turbines as a case study. They found that the value of the cost of electricity (COE) was between ($0.05/£0.029/15fils) and ($0.08/£0.047/ 24fils) per kWh. However, wind power investment in Duqm can be advocated .

Studying the feasibility of offshore wind turbine installation in Iran compared with the rest of the world, Mostafaeipour (2010) predicted that wind energy generation would increase in forthcoming years. Data collected from a period of 57 years was used to analyse the characteristics of wind speed and direction over the Arabian Gulf. AL-Yahyai et al. (2010) assessed potential locations for wind energy generation in Oman using data from existing meteorological stations. They used five years' hourly wind data from twenty-nine stations scattered from the north to the south of the country to identify potential locations for wind energy applications in Oman. They investigated factors such as theoretical wind power output, vertical profile, turbulence and peak demand fitness, air density, and roughness length. The researchers concluded that Qayroon Hyriti, Thumrait, Masirah, and Rah Alhad have high wind power potential, and that Qayroon Hyriti is the most suitable site for wind power generation.

Khalil et al. (2010) presented a road map for renewable energy research and development in Egypt, and reviewed the available renewable energy technologies required to establish a market in Egypt. One year later, (Ibrahim, 2011) reviewed the renewable energy sources in the Egyptian electricity market. He found that very little electricity was produced from the available renewable energy sources in Egypt, such as hydro, wind and solar, compared to other energy sources. He showed that from 1981/1982 to 2004/2005 the generation of electricity increased by a rate of 6.9% per year to reach 500% of the former value. A strategy for using renewable energy to supply Egypt with electricity was presented. He discussed wind energy in Egypt and predicted that electricity production would reach about 3.5 GW by 2022. He also predicted that the energy production would reach about 19% of total installed power by 2022.

Jervase and Al-Lawati (2012) assessed the wind energy potential for Oman. Data was collected for a period of ten years from the NASA Langley Research centre, and daily, seasonal and height variations in wind parameters were analysed. The researchers presented contour maps for mean wind speed and direction, wind accessibility figures, and wind power density tables. It was found that the best windy season was in summer (June, July and August) in the south and south-east of Oman, with a mean wind velocity at 50 m of 6.96, 7.86 and 7.18 m/s for each of the three months respectively. However, In Oman, the generation of electricity is currently still dependent on oil and gas as the progress of renewable energy development is slow (Umar and Wamuziri, 2016). In 2017, Masdar Abu Dhabi's renewable energy company, signed a contract to build the first large-scale wind farm in the GCC in Oman of 50 MW (Kassem, 2017; GulfNews Energy, 2017).

El Alimi et al. (2012) investigated the potential wind resources in the Gulf of Tunis, Tunisia. They used the hourly mean wind speed and wind direction with a 10-minute time step provided by the NRG (National Resources Group) weather station. It has been shown that the Weibull probability function, with parameters predicted from the power density method (PDM), estimates the frequency distribution more accurately than other methods; it has also been shown that the moment method (M-M) estimates the wind power density more accurately than other methods. They found that the central coast of Tunis in Tunisia is an important region for exploiting the power of the wind for electrical energy generation.

Janajreh et al. (2013) analysed the potential annual wind energy in the city of Masdar in the United Arab Emirates; investigating wind data from high-resolution temporal records. Two sizes of horizontal axis wind turbine (HAWT) were used. The annual energy production from the large and small turbines was 3307.08 MWh and 28.73 MWh respectively. The researchers found that Masdar was considered a poor wind region with high unstable intensity, and concluded that the smaller turbine was favourable in terms of efficiency and economy.

Shawon et al. (2013) looked at an overview of wind energy and its cost in the Middle East (ME), and conducted a study of potential and existing wind energy conversion technology being used to harness the available wind in the Middle East, with a detailed analysis of the economics behind the deployment of wind energy conversion technologies using used long-term annual and monthly average wind data. The researchers divided the MENA into three regions based on wind speed, such that region 1 has a high wind speed, region 2 has a medium wind speed, and region 3 has a low wind speed as shown in Table 2.2. It was found that wind energy is economically more viable in the first two regions compared to the third region, and showed that wind speed has a greater influence on the charge per unit. In addition, they discovered that considering the environmental cost (external cost) can make wind energy more compatible with conventional energy. Finally, they found that the energetic and economic investigation of different locations in the MENA region can be expressed as prospective areas for regions 1 and 2, and below marginal areas for region 3 in terms of both wind profile and economy.

Table 2.2 The Middle East region classification based on wind speed

Regions	Countries	Wind Speed m/s
1	Syria ,Iran, Egypt and Turkey(Bozcaada)	≥8.00
2	Oman, Kuwait, Jordan, Qatar, Bahrain, Egypt(The Mediterranean Sea) and Syria (District3)	6.00 to7.98
3	The rest of the MENA countries	≤ 6.00

Khraiwish Dalabeeh (2017) studied the techno-economic analysis of wind power generation for selected locations in Jordan. He developed a simple model to evaluate the capacity factor and predicted costs of wind energy in pre-selected five locations in Jordan. The results obtained of final cost of electricity (COE) are acceptable between ($0.0259 and 0.0498 $/kWh/ £0.02 and £0.04/kWh/ 0.01KD and 0.02 KD/kWh) for the best site which is within the average range in the Middle East and North Africa region. He concluded that such results could benefit on policy makers, developers and investors planning to implement wind energy systems within the Middle East region.

Recently, MENA countries start to be aware of the important role of renewable energy. New wind energy project development and investment locations have been plotted on a map of the Middle east by this other, as shown in Figure 2.5, where the locations were obtained from (Eversheds, 2016; IRENA, 2016).

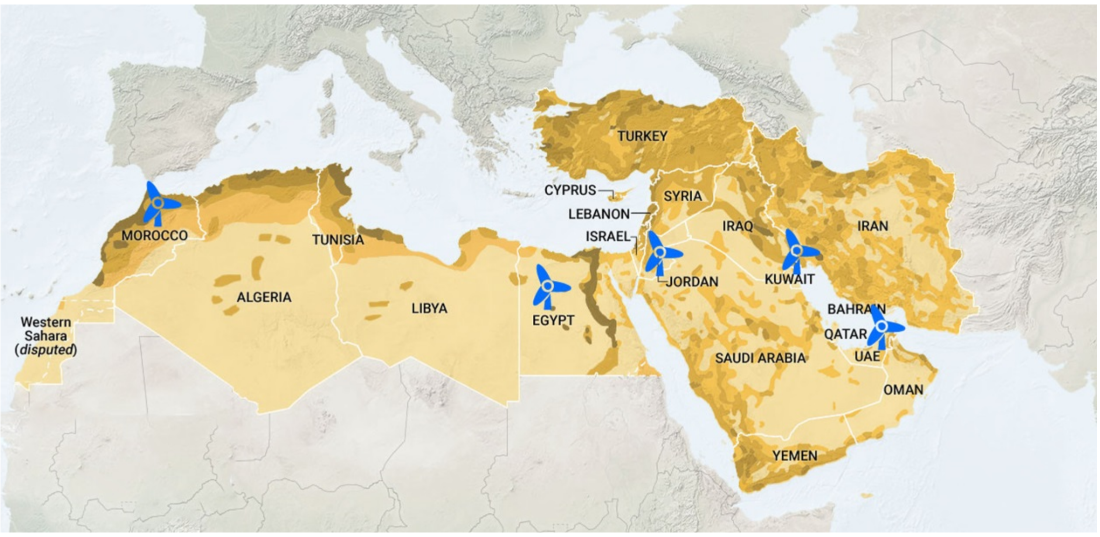


Figure 2.5 Wind energy project in MENA

2.4 Wind Turbine Categorisation

2.4.1 Offshore and Onshore Wind Turbines

Wind technology has improved step-by-step since the early1970s, with onshore and offshore wind turbines being the two main alternatives for wind energy. By the end of the 19th century, the typical European windmill used a rotor of 25m diameter, and the stocks reached 30m. The first person to generate electricity from wind speed, was Dane Poul LaCour in 1891, who lived in Denmark (Bilgili, Yasar and Simsek, 2011). In 1990 a company called 'World Wind' constructed and installed the first offshore wind turbine at sea. This offshore wind turbine was located in Nogersund, 250m offshore, in 7m water depth off the north coast of Sweden, and had a rated power of 220kW (Nikolaos, 2004).

2.4.1.1 Offshore Wind Turbines

Offshore wind power refers to the construction of wind turbines which consist of a tower and foundation fixed on land in large bodies of water to generate electricity (Bilgili, Yasar and Simsek, 2011).

Offshore wind power started in 1990, with the first offshore wind project in Sweden (Sun, Huang and Wu, 2012; Esteban et al., 2011). In 2009, the installed offshore wind turbines was 2000MW (Esteban et al., 2011). At present, there is significant interest in offshore wind power worldwide, and advancements in offshore wind energy technology have enabled large wind turbines to produce high MWs (Zhixin et al., 2009).

Blanco (2009) studied the economics of wind energy projects in Europe, and analysed the parameters which affect wind energy projects. He found that the production cost ranged from (4.5U.Scents/2.6pence/13.5fils) to (8.7U.S cents/5.1pence/26.1fils) per kWh for onshore wind farms, and from (6 U.S cents /3.5 pence/18 fils) to (11.1U.Scents/6.5 pence/33.3 fils) per kWh for offshore wind farms, based on the two parameters that had most impact, which were the number of full hours and the level of capital cost. The researchers predicted that the cost of generation would be reduced in the long term, thanks to the right policies, and research and development into new materials, operation and maintenance (O&M) with remote-control tools, offshore turbines, and infrastructure. In addition, Breton and Moe (2009) described the potential of offshore wind energy technology in

Europe and North America. They discussed the advantages and disadvantages of offshore wind energy compared to onshore wind energy, and stated that many challenges faced offshore technology, such as the high cost. It was concluded that the situation in North America was different to that in Europe; therefore the same solution was not possible for both regions. There are many advantages to offshore wind energy, such as reducing visual and noise impact due to their installation in areas far from the shore, which will reduce the associated restrictions on turbine design and improve their efficiency. In addition, the size of offshore wind turbines is not limited due to sea transportation and installation. On the other hand, there are several disadvantages, the installation is more difficult and expensive, the cost of offshore turbines is approximately double the cost of onshore turbines, and there are also difficulties involved in maintenance and repair at sea due to weather conditions. These factors result in sea turbines being 5 times more expensive than onshore equivalents.

Snyder and Kaiser (2009) conducted an environmental and economic cost-benefit analysis of offshore wind energy in United States. They estimated, by comparison with onshore wind energy, the expenses and profits of offshore wind energy and the current generation of electricity. They developed empirical cost functions based on publicly reported projects from 2000 to 2008 to study the growth of wind energy and found that the environmental impacts for onshore and offshore wind power are not directly comparable. It was concluded, after a comparison between offshore wind power and other competitors such as onshore wind power and offshore fossil fuels, that offshore wind power was expensive even when the costs of carbon offsets are not subtracted.

Due to the great wind capacity in Europe, particularly northern Europe, offshore wind energy is considered as one of the main sources of energy. It is expected that offshore wind farms will spread further in the near future because of the restrictions on the use of land and the limited availability of space that face onshore wind farms. Offshore wind energy could be utilised in Iran, which would reduce atmospheric gas pollution, create job opportunities, and produce electricity (Mostafaeipour, 2010).

Esteban et al. (2011) reviewed the situation of offshore wind energy and its growth in countries at the forefront of its development (the United Kingdom, Denmark, Holland, Sweden and Germany). It has mainly been influenced by the following crucial factors: limited space on land for the development of onshore wind farms due to competition for site usage, and smaller environmental impact of offshore wind energy. The researchers compared offshore wind energy with onshore wind, marine hydrodynamic, hydraulic, and solar energy, and a large gap was found between onshore and offshore. It was concluded that the cost per MW of offshore wind energy was high because the technology was in its early stages and because further knowledge was required to understand the ecological influence, electrical grid connection, design and construction of foundations, and wind sources.

Green and Vasilakos (2011) reviewed the economics of offshore wind power. There was a rapid rise in investment in offshore wind energy in Europe in an attempt to reach the target of EU countries for renewable energy in 2020. The researchers claimed that the most important problem facing offshore technology was the high cost of installation and connection. Different policies adopted in Europe were studied, such as those of Belgium, Denmark, France, Germany, Italy, The Netherlands, Sweden and the United Kingdom. They concluded that the arrangement of the feed-in tariff offered acceptable support if there was a reduction in the rent of the developer. (Esteban et al., 2011; Green and Vasilakos, 2011) recommended that there should be more support from governments in the development of the technology to reduce the high cost of offshore systems.

Bassi et al. (2012) predicted that the cost of onshore and offshore wind energy in the UK would fall. They considered the high and low discount rates (i.e. the cost of capital through time) of 10% in 2030 and 3.5% in 2011, and stated that the cost of onshore wind energy in 2011 ranged between (6.6 to 9.3pence/kWh /$0.09 to $0.12/kWh/ 30fils to 60fils/kWh) and would decrease by 2030 to between (5.2 and 7.4pence/kWh /$0.07 and $0.1/kWh/ 20 fils and 30 fils/kWh). The same situation for the cost of offshore wind energy was presented, with a range of (11 to 19.7pence /kWh /$0.14 to $0.25/kWh/40 fils to 80 fils/kWh) in 2011, and a range of (6.9 to 16.5 pence/kWh /$0.09 to $0.21/kWh/ 30fils to 60fils/kWh) in 2030. (Macalister, 2015) stated that the cost of onshore is ($0.07/kWh/ 5.5 pence/kWh/ 20 fils/kWh) in 2015 and the cost of offshore is ($0.15/kWh/ 11.7pence/kWh/ 50 fils/kWh) during the same year. Recently, 2017 the cost of offshore propped to ($0.07/kWh/ 5.75 pence/kWh/ 20 fils/kWh) according to (Thomas, 2017).

Sun et al. (2012) studied the current state of offshore wind energy technology development in Europe, North America, and China. They presented a number of advantages of offshore wind farms, such as reduced noise and visual impact, greater wind capacity, and greater availability of suitable locations at sea.

Perveen et al. (2014) presented the development of offshore wind farms and their challenges, and reviewed the mechanical, planning and environmental issues. The researchers showed that improvements in machinery partly help to reduce the capital cost, and improvements in the design of coordinated control of wind turbines could reduce the impact of wake. It was pointed out that there are several obstacles facing offshore wind farms, such as corrosion and the difficulty involved in installation and maintenance due to special transportation requirements and the need for a stable atmosphere. They found that to increase the capacity of offshore turbines to reach the rated power of Giga Watt (GW) may increase the cost of the wind farms.

2.4.1.2 Onshore Wind Turbines

Onshore wind power refers to the construction of wind turbines which consist of a tower and a foundation fixed on land to generate electricity (Bilgili, Yasar and Simsek, 2011).

Onshore technology shares about 95% of the global market, while offshore technology has only 5% of the global market share. It is expected that by 2016 China will be the leader in onshore wind energy, whereas in 2010 the US had the largest capacity of onshore wind energy (Prnewswire, 2011). During 2013, onshore and offshore installation a cross the European Union accounted for 9,592 MW and 1,567 MW respectively, from a total installation of 11,159 MW (EWEA, 2014).

The most significant obstacle to onshore wind farms is the limitation in suitable land locations (Sun, Huang and Wu, 2012). There is an expectation of the role that onshore wind turbines will play in meeting demand for electricity as a source of low carbon emissions in many countries, including the UK. Of the available renewable technologies, onshore wind turbines are cost competitive and feasible (Jones and Eiser 2009). 10,000 MW of wind power capacity is the target that Denmark aims to reach in 2050, from about 3952 MW in 2011. Therefore, increasing the onshore wind power capacity may continue to accept wind power in Denmark (Ladenburg, Termansen and Hasler, 2013).

Ertürk (2012) analysed the onshore wind energy potential of Turkey to evaluate the feed-in tariff regulation. He concluded that with the current feed-in tariff, onshore wind turbines of 13GW with wind speeds of 7.5m/s will work productively and economically.

The United Kingdom will not meet its responsibility to the Renewable Energy Directive by 2020, or meet the recommendation of a near zero carbon electricity sector by the 2030s unless a significant increase in onshore wind energy use occurs (Bowyer et al., 2009).

2.4.2 Classification of Wind Turbines

Current wind turbines are classified into two main types: the Horizontal Axis Wind Turbine (HAWT), and the Vertical Axis Wind Turbine (VAWT). Classification is dependent on the position of the rotor and blades relative to the ground surface (Manwell, McGowan and Rogers, 2009). These types are described in the following sections.

2.4.2.1 Vertical Axis Wind Turbine (VAWT)

A VAWT is designed with an axis of rotation perpendicular to the ground. There are a number of advantages in the technology of vertical axis wind turbines which have made them more attractive recently. Because it is omni-directional and thus insensitive to wind energy, the blade of a vertical axis wind turbine is less sensitive to cross-winds and turbulence, and therefore has a longer life (Figure 2.6); it is also slower and quieter than the Horizontal Axis Wind Turbine(HAWT), creating fewer noise problems (Li et al., 2013).

Figure 2.6 Vertical Axis Wind Turbine (Gogreenenergyonline, 2014)

2.4.2.2 Horizontal Axis Wind Turbine (HAWT)

A HAWT is designed with an axis of rotation parallel to the ground (Figure 2.7). The concept of the horizontal axis is common for onshore and offshore wind turbines (Sun, Huang and Wu, 2012). Nowadays, HAWTs are the main choice for electricity production.

There are two types of HAWTs: upwind, and downwind. In the upwind design, the rotor and blades face into the wind. The downwind design uses wind interference by the tower upwind of the blades. The location of the generator and gears above the tower makes the design of HAWTs more complex than that of VAWTs (Mathew, 2006).

Figure 2.7 Horizontal Axis Wind Turbine (Gogreenenergyonline, 2014)

2.4.2.3 Types of wind turbine generator (1, 2, 3, 4)

According to Hansen and Hansen (2007),wind turbines are categorised into four main classes: These categorise are shown in Figure 2.8

i. Type 1: Fixed speed wind turbine concept:
   Fixed speed controlled wind turbine with an asynchronous Squirrel Cage Induction Generator (SCIG) directly connected to the grid through a transformer."

ii. Type 2: Variable speed wind turbine concept with variable rotor resistance:

Limited variable speed controlled wind turbine with variable generator rotor resistance and pitch control."

iii. Type 3: Variable speed wind turbine concept with partial-scale frequency converter (Doubly Fed Induction Generator (DFIG)):
‘Variable speed controlled wind turbine with a Wound Rotor Induction Generator (WRIG), a partial-scale frequency converter on the rotor circuit and pitch control."

iv. Type 4: variable speed concept with full-scale frequency converter:
"Full variable speed, pitch-controlled wind turbine with the generator connected to the grid through a full-scale frequency converter".

Speed control is divided into fixed speed and variable speed; each has advantages and disadvantages (Figure 2.8). In power control there are three main categories: stall, pitch, and active-stall control.

Hansen and Hansen (2007) also presented the advantages and disadvantages of fixed and variable speeds for turbine efficiency, and attempted to combine the two approaches into four main categories. It is clear that turbines with a fixed speed and active stall control approach are popular, but have a very slow control, fixed speed and stall controlled, a common approach from the 1990s with the onset of (MW) wind turbine power, and the third approach is fixed speed and pitch control, which is not attractive in manufacturing because of the large fluctuation in power due to high wind speed. For variable speed, stall control and active stall control are not considered because of the incapability of rapid power reduction when the wind turbine is running at maximum speed. Variable speed and pitch control is a very attractive approach due to it providing the possibility of increased ‘grid friendliness’ (Hansen and Hansen, 2007).

Based on the literature review and also according to the approaches and methodologies discussed above, it is clear that wind turbine generators are dependent on mechanical factors. However, this research will be investigating the soil- structure interaction of wind turbines, the economic and environmental aspects.

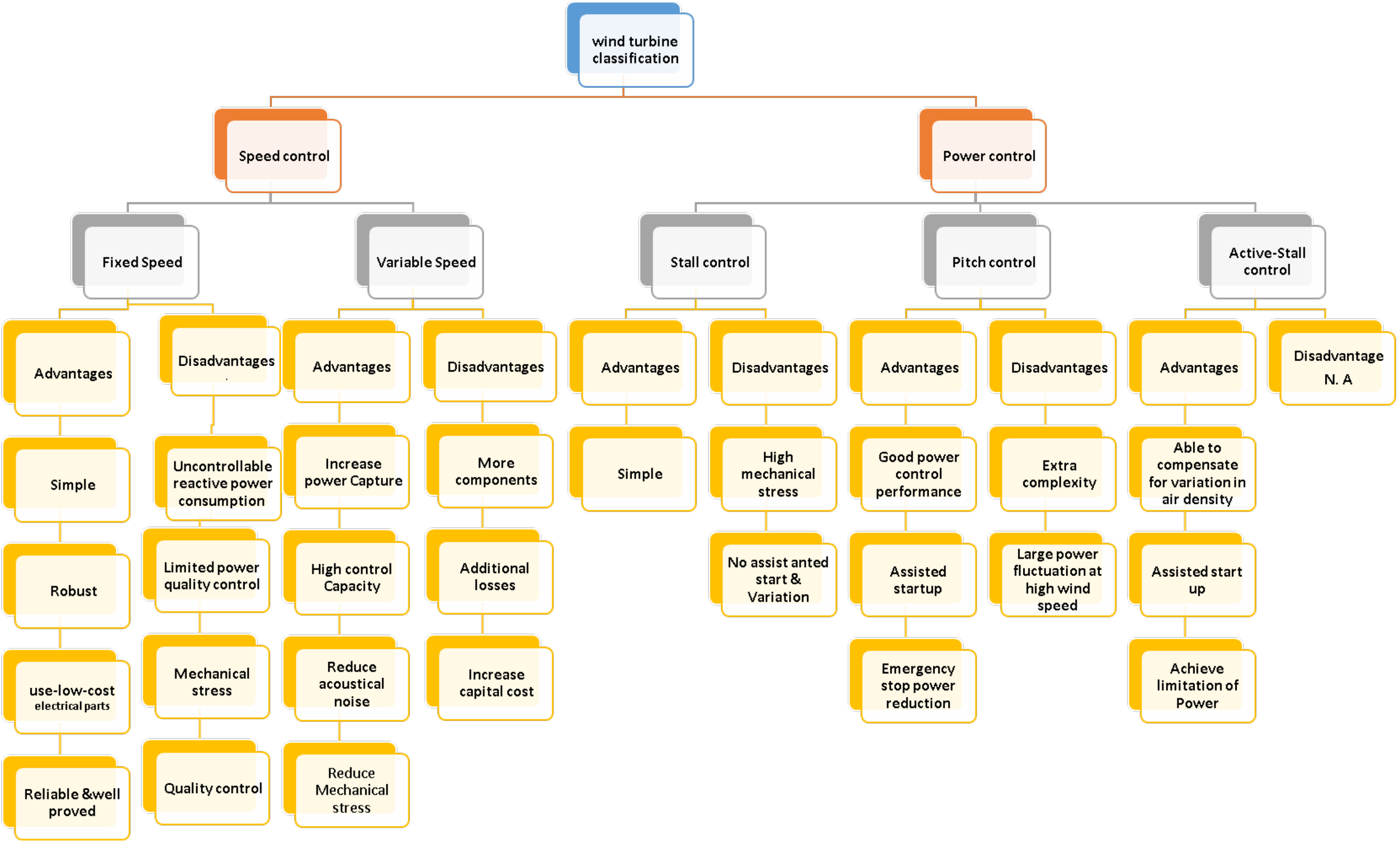


Figure 2.8 Wind turbine technical classification

2.5 Wind Turbine Selection

Marafia and Ashour (2003) suggested that small to medium size wind turbines are most convenient for water pumping and generating electricity for locations disconnected from the national electricity network in Qatar. They considered in their analyses the mean monthly variation of wind speed, mean hourly wind speed frequency, and an economic assessment. They concluded that utilization of the wind energy turbine systems can prove to be both efficient and competitive in Qatar.

Khalfallah & Koliub (2007) revealed that to design a wind turbine for specific wind conditions should involve not only the location of the maximum efficiency, but also a detailed shape of the efficiency curve (efficiency as a function of the wind speed). Placing vortex generators on the rotor blade surface leads to delaying stall and increasing the lift coefficient of the moderately-thick air foils. It also improves the power output from the stall-regulated horizontal axis wind turbines, which operate in low annual average wind speed sites.

Jowder (2009) analysed the potential wind power and site matching of wind turbine generators in the Kingdom of Bahrain. He studied the data of the hourly wind speed for 2003 to 2005 at 10 m, then extrapolation this data to obtain the wind data at 30m, and 60m heights and determined the potential of wind power generation. The study used Weibull probability functions whose parameters are estimated from two different approaches: the graphical approach, and the approximated approach. He compared 5 wind turbines at 60m height (Gamesa G58, Nordex N60, Nordex 70, Gamesa G80, and Nordex N80), and at 30m height (Mod-0, Nordex-150, Vestas, V-25, Nordex-250, MWT-300, and WD-34), determining that the most suitable turbine at height 30m is Mod-0, while Gamesa G58 is a better matched turbine for 60m height.

Al-Hadhrami (2014) evaluated the performance of small wind turbines for off-grid applications in Saudi Arabia. 24 wind turbines were studied. 16 were horizontal axis wind turbines, and 8 were vertical axis, categorised in terms of rated power and using wind speed data at different levels. The analysis considered annual energy yield and plant capacity as factors. They found that at the hub height of 40m the horizontal wind turbine (Aeolos-H 10kW) was produced 24.743 MWh with capacity of 28.2% is higher than the vertical wind turbine (Aeolos-V 10kW) the energy yield (MWh) was produced 14.223 MWh and the capacity was 16.2 25%.In general, it was concluded that horizontal axis wind turbines were more efficient than vertical axis wind turbines.

This is a good indication to consider the horizontal axis wind turbine instead to the vertical axis wind turbine for GCC region.

El Alimi et al. (2012) stated that, technically and economically, the selection of a suitable wind turbine depends on the evaluation of the potential wind speed in specific regions. Using eight wind turbines at different hub heights for wind power generation on the central coast of the gulf of Tunis (AnbonusMK III-30, V39-35, V82-0.9, Dewind 1250 kW, GE 1500 kW, Vestas V80, Repower (2000 kW) MM 70-65 and Nordex (2300 kW) N90-100), it is clear that the turbines used are 1.25MW and 2MW, Nordex, Vestas and Dewind wind turbine generators.

Montoya et al. (2014) used multi-objective evolutionary algorithms (MOEAs) to select wind turbines for a wind farm layout based on data collected during 2008 in Cancun (Mexico). To minimise the standard deviation of the daily generated energy and maximise the total output energy by the wind farm, they selected two different wind turbine models (from a list of 26 items available) and investigated, tested and compared different MOEAs based on algorithms such as SPEA2 (The Strength Pareto Evolutionary Algorithm) (Zizler and Thiele, 1999), NSGAII (non-domination based genetic algorithm for multi-objective) (Srinivas and Deb, 1994), PESA (The Pareto Envelope-based Section Algorithm), and msPEA (Modified Strength Pareto Evolutionary Algorithm). It was concluded that using multi-objective optimisation algorithms was useful for wind turbine selection in specific regions and for companies to develop wind farms.

Wind turbine manufacturers in terms of the share of cumulative global capacity for 2011, 2013, 2015 and 2017 are shown in Table 2.3, which has been created based on information from (Energy Digital, 2015; Wind Power Monthly, 2015; Windpower Monthly, 2017) The tables in Appendix A illustrate the specification of wind turbines provided for the top ten manufacturers.

Table 2.3 Top ten wind turbine manufacturers in the global market for years 2011, 2013, 2015 and 2017

Turbine Manufacturer 2011	**Market share% 2011**	**Turbine Manufacturer 2013**	**Market share% 2013**	**Turbine Manufacturer 2015**	**Market share% 2015**	**Turbine Manufacturer 2015**	**Market share% 2017**
Vestas Denmark	12.7	Vestas Denmark	13.2	Vestas Denmark	12.3	Vestas Denmark	9.0
Sinvel Brazil	9	Goldwind China	10.3	Siemens Germany	9.9	Siemens Gamesa Spain	7.5
Goldwind China	8.7	Enercon Germany	10.1	GE U.S	9.1	GE U.S	6.9
Gamesa Spain	8	Siemens Germany	8	Goldwind China	9.0	Goldwind China	6.6
Enercon Germany	7.8	Suzlon India	6.3	Enercon Germany	7.8	Enercon Germany	3.9
GE U.S.	7.7	GE U.S.	4.9	Suzlon India	5.8	Nordex Germany	2.7
Suzlon India	7.6	Gamesa Spain	4.6	United Power China	5.1	Senvion Germany	2.4
United Power China	7.4	United Power China	3.9	Gamesa Spain	4.7	United Power China	2.1
Siemens Germany	6.3	Ming Yang Wind Power China	3.7	Ming Yang China	4.4	Envision China	2.0
Mingyang Wind Power	3.6	Nordex Germany	3.4	Envision China	3.8	Suzlon India	1.1

2.6 Analysis of Wind Turbines

2.6.1 Numerical Modelling

Kellezi and Hansen (2003) have developed more rigorous finite element methods (FEM), which allow application of soil-pile non-linear interaction and soil constitutive modelling. A structure based on pile foundations and exposed to dynamic vibrations with small amplitudes can be analysed as a viscous-dynamic problem. However, the mono-pile wind turbine foundation at Horns Rev in the eastern North Sea, about 15 km / 10 miles off the westernmost point of Denmark was analysed for maximum static and dynamic loads. A 3D non-linear FEM design was conducted for static loads employing ABAQUS. 3D axisymmetric viscous-dynamic analysis was also performed for dynamic loads, as small vibration amplitudes are expected for the foundation of a wind turbine.

In this thesis the dynamic loads have been considered to be out of the scope, due to the time constraints imposed on this present study.

As the size and capacity of wind turbines increases, structural flexibility becomes a critical concern, and earlier parameter models may be inadequate. To address this problem, Ahlström (2005) applied a commercial finite-element software package (MSC Marc) which is a nonlinear finite elements analysis software used to simulate behavior of complex materials and interaction under large deformations and strains to develop a flexible structural dynamic model based on models of horizontal axis wind turbines, Alsvik 180 kW and the 2MW Tjæreborg wind turbine. The models were employed to investigate the system's dynamic response due to wind load on the blades for a range of blade slenderness ratios and wind conditions. The analysis concluded that large blade deflections have a major influence on power production and structural loads. Loads exposed to the wind turbine are illustrated in Figure 2.9.

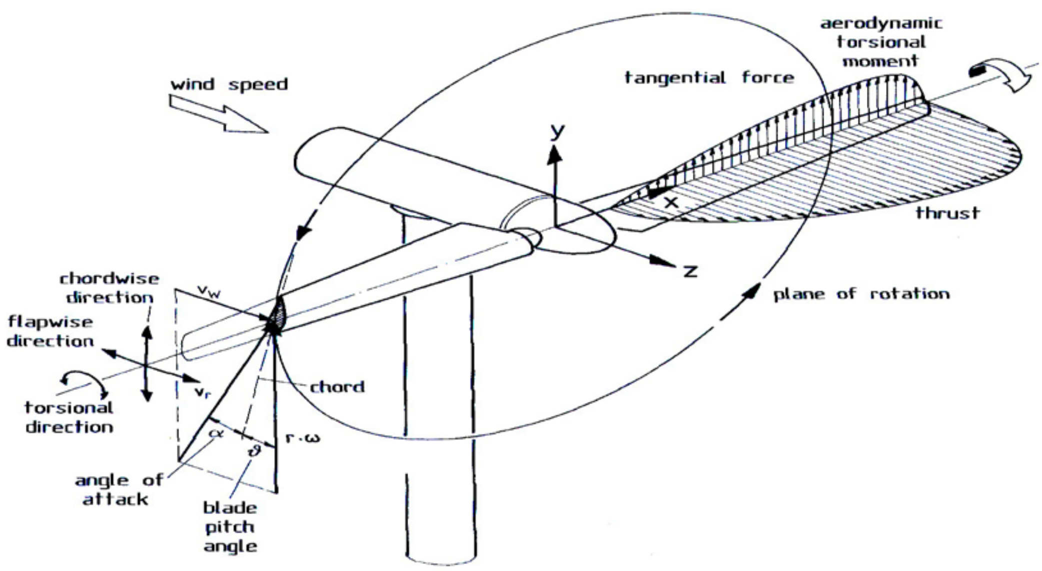


Figure 2.9 Terms used for representing displacements, loads and stresses on the rotor (Ahlström, 2005)

In another pair of finite element studies, (Lee, Hodges and Patil, 2002) constructed a wind turbine model comprising both rigid body and flexible body subsystems. The model applied the traditional 1-D finite element to represent the flexibility of the rotor and tower while the rest of the wind turbine components were assumed to be rigid bodies. The system's governing equations were obtained by coupling the rigid-body equation of motion to the linearised flexible-body model of the tower–rotor subsystem. The resultant system equations of motion were treated using the Floquet theory to extract the wind turbine dynamic characteristics. Since this model was mainly developed for a wind turbine control study, which already requires high computational efficiency, the structural model was made quite crude from the viewpoint of structural dynamics.

Later, Larsen & Nielsen (2007) studied the non-linear parametric instability of a wind turbine wing using a model with two degrees of freedom. Their model was used to analyse the blade vibrations in the flapwise and edgewise directions. They computed the combination of amplitudes and frequencies that would lead to instability of the wind turbine.

Wang et al. (2010) proposed a mixed flexible/rigid multi-body mathematical model to predict the deformation state and dynamic stress distributions of a wind turbine system. From the analysis, it was found that the proposed model not only inherits the simplicity of the traditional 1-D beam element, but is also able to provide detailed information about the tower and rotor response, owing to the incorporation of the flexible thin-walled beam theory.

AlHamaydeh and Hussain (2011) illustrated design optimisation for multiple wind towers located at different villages in Alaska. The towers are supported by two different types of foundation: large mat, and deep piles foundations. The new all-steel design was found to reduce the natural frequencies of the structural system due to softening the foundation. Thus, the tower–foundation system could potentially become near-resonant with the operational frequencies of the wind turbine. Consequently, the likelihood of structural damage or even collapse is increased. A detailed 3D finite-element model of the tower–foundation–pile system with RC foundation was created using SAP2000. Soil springs were included in the model based on soil properties obtained from the geotechnical investigation. After considering different loading conditions, the foundation system design was controlled by the natural frequency of the soil–foundation–structure system, rather than by strength or serviceability. The use of all-steel pile foundations lowered the natural frequency of the system. This had to be reflected into lower operational velocities.

Harte et al. (2012) investigated the along-wind forced vibration response of an onshore wind turbine. The study includes the dynamic interaction effects between the foundation and the underlying soil. A Multi-Degree-of-Freedom (MDOF) horizontal axes onshore wind turbine model was developed for dynamic analysis using an Euler–Lagrangian approach. The soil-foundation interaction was modelled by complex impedance functions generated using a cone model and included in the overall model using a sub-structuring approach. Two soil profiles were examined in this study: a uniform profile used to validate the cone model by comparison with the DNV/Risø standards, and a more complex soil profile with multiple soil layers of different stiffness. No significant difference between the shear and moment in the foundation and tower base was discovered, as the foundation inertia was found to be negligible. The rotation of the foundation was shown to increase significantly with decreasing soil stiffness and violated the prescribed limits of DNV/Risø standards for lower soil stiffness conditions.

Shi et al. (2013) studied the impact of various modelling parameters on the dynamic response of a jacket structure to support a 5MW offshore wind turbine at a water depth of 33m in the environmental conditions of Korea. They investigated modelling parameters (including joint can, overlap, flooding of the member, marine growth and mass of the transition piece) by using modal analysis and aero-servo-hydro-elastic simulation. It was concluded that the effect of joint can, overlap and marine growth on the dynamic response was high, where the effect on the natural frequencies of the designed structure was small. The researchers recommended that careful selection of the transition piece mass may reduce the extreme loads on a jacket structure.

Liu et al. (2014) studied the behaviour of wide-shallow bucket foundation for offshore wind turbines in drained silty sand. They used elastoplastic analyses of three-dimensional finite element models to define the failure mode of the bucket foundation. They also used the ultimate bearing capacity of shallow foundations equation to calculate the vertical load-bearing capacity and overturning stability. They found there was no effect of the yield surface of the wide-shallow bucket foundation on the ratio L/D (length to diameter) or the skirt height; applying vertical load would increase the horizontal load-bearing and moment capacity of the bucket foundation.

2.6.2 Experimental Modelling

Zaaijer (2006) stated that the dynamic behaviour of wind turbines at offshore locations is more complex than that of onshore wind turbines and that of offshore platforms used in the oil and gas industry because of the effect of wave and rotor excitation frequencies on the offshore wind turbine while fixed platform for the offshore oil industry and onshore wind turbine are designed to be well above the main wave or rotor frequencies respectively. In order to reduce the computational burden, this study aimed to simplify the dynamic model of the foundation, while maintaining sufficient accuracy. A stiffness matrix at the mudline is found to be the best solution for mono-piles. With respect to the required accuracy, the sensitivity of dynamic behaviour to variations in several parameters was investigated. An inaccuracy of about 4% can be expected for the first natural frequency. For five wind turbines in an offshore wind farm, the results corresponded to expectations, but two wind turbines in another farm gave unexplained higher errors.

Ou et al. (2007) developed a damping isolation system to control the vibration of a steel jacket offshore platform structure. A 1/10 model of the structure was fitted with the damping isolation system and tested on a shaking table. Dynamic loads including wind, wave, current, and earthquake were simulated. Numerical simulations were conducted and the numerical and experimental results were compared. Numerical simulations for the undamped and the damped structure were obtained using systems with a single degree and with two degrees of freedom, respectively. Simulations and experimental results were in agreement. While the damper design was discussed in detail, few details were given about the model of the jacket structure.

Elshafey et al. (2009) investigated the dynamic response of a scale model of a jacket offshore structure, both theoretically and experimentally. The experiments were conducted both in air and in water. The in-water experiments took place in the towing tank of Memorial University to simulate realistic operating conditions, and the model was subjected to random wave loads. Froude's law of modelling was used to obtain the dimensions of the scale model on the basis of the dimensions of an existing structure. The effects of varying the structure's weight and the characteristics of the wave loading were investigated. The structure's weight was changed by adding weights to the structure's deck. A finite element model was designed to determine the dynamic response of the model. The experimental and theoretical results obtained were consistent when the reaction force at the foundation was estimated from strain measurements and compared with the finite element calculations.

2.6.3 Field Modelling

El Alimi et al. (2012) investigated the potential of wind resources in the Gulf of Tunis in Tunisia. The hourly mean wind speed and wind direction with a 10-minute time step provided by the NRG (National Resources Group) weather station were used to analyse the wind speed characteristics and the wind power potential. Weibull parameters were estimated according to the most frequently used methods, and their accuracy was compared on the basis of different goodness-of-fit tests. Wind speeds and power densities were modelled using a Weibull probability function whose parameters are identified by four different methods: moment, cumulative probability, maximum likelihood, and power density. The four probability density functions have been fitted to the measured probability distributions and the power density on a yearly basis (2008–2009), given in terms of the correlation coefficient (R^2) and the root mean square error (RMSE) of each Weibull distribution considered in the survey. It was found that the Weibull probability function with parameters predicted from the power density method (PD-M) estimates the frequency distribution more accurately than the other methods. The results show that the central coast of Tunis in Tunisia is an important region for exploiting the power of wind for electrical energy generation.

Janajreh et al. (2013) recorded annual wind data at Masdar City, UAE, in an attempt to assess wind energy potential. First, annual data was collected at different heights and different temporal resolutions. The data was then subjected to an FFT spectrum analysis. As the intermittency is identified for the collected data, wavelet analysis was further explored to remedy the shortcomings of the FFT spectrum. The annual collected data categorised Masdar City as a poor wind region with high turbulence intensity. Next, the data were fitted with an appropriate Weibull probability distribution, and the Weibull distribution model was coupled with two different sizes of commercial HAWT power curves. The estimated power obtained by the Nordtank 500/41 at a height of 30m is equivalent to the power obtained from approximately one hundred 3.5KW wind turbines at locations at the same height in Masdar City. In other words, the vertical wind profile was inferred and was appropriately fitted with a power law profile. The spectrum of the temporal data which was obtained exhibits the type of turbulence. Investigation of high-resolution temporal records also emphasised the turbulence, non-periodicity, and intermittency of the wind data. Accordingly, frequency-scale wavelet decomposition was carried out, and the intermittency of the data was identified. The measured wind capacity categorised Masdar City as a poor wind region. Next, the measured wind data was fitted with the maximum likelihood Weibull distribution. The power curves of two sizes of horizontal axis wind turbines (HAWTs) were coupled with the Weibull distribution. The annual energy production was found to be 3307.08 MWh and 28.73 MWh at the height of 50m, for the large and small turbine, respectively.

Experimental modelling can be expensive and time-consuming, and is normally used only for high-cost and high-risk projects. In this research, the finite element method (FEM) will be used as it is one of the most popular numerical analysis techniques in geotechnical engineering because it allows the accurate representation of complex geometrics including various material properties and local effects; there are also a huge variety of applications of FEM, such as in multi-layered soils. The FEM is one of the most appropriate techniques for wind turbine design, is easily implemented, and has been widely adopted within the industry.

2.7 Economic and Financial Analysis

Cost Benefit Analysis (CBA) could be described as methodology deployed for the appraisal and evaluation of investments under consideration. This mechanism is most desirable in quantifying and thereafter applying discounted costs and benefits to be incurred in the future to present day tangible values in order to assign a value to the competing projects and those under consideration (Civil Aviation Safty Authority, 2007).

Alnaser and Alnaser (2011a) found that the cost to produce electricity of 287,342 GWh per year (the total production of electricity for GCC in 2009) from solar and wind energies would be ($90 billion/ £89.5 billion/ 27KD billion) using CSP (Concentrated Solar Power) with an efficiency of 50% and solar radiation of $500W/m^2$ and 9 daily average sunshine hours. For photovoltaic (PV), the cost would be approximately ($150/ £53.7 billion/ 45KD billion). On the other hand, installation of 11 wind turbines in GCC countries - each wind turbine power rated 5 MW with an assumed operation time of 60% per year - would cost ($ 50 billion/ £30 billion/ 15 KD billion). As mentioned in sections 2.2.2 and 2.3.2, wind energy incurs the lowest cost of all the renewable energies.

Desalination of sea-water in Kuwait is the main solution to addressing the need for drinking water, which is blended with brackish water. Production of distilled water during 2004 was 97,469 MIG(Million Imperial Gallons)/year (Zaghloul and Almutairi, 2010). Total production of distilled water in 2014 was 522 MIG/day, about 190,530 MIG/y, almost double that of 2004 (Ministry of Electricity and Water- Kuwait, 2014) The daily fresh water consumption in Kuwait increased from 137l/capita in 1973 to almost 500l/capita in 2003. Hence, daily electric power generation increased from 19.4 billion kWh in 1984 to 35.4 billion kWh in 2004 (Darwish, Al-Awadhi and Darwish, 2008).

The cost of desalination of sea water in GCC countries ranges from ($0.45/ £0.27/ 135 fils) (with subsidies) to ($1 /£0.596 / 300fils) per m^3. The state of Kuwait was ranked 53rd worldwide in consumption of electricity at 39,540 GWh/y, 41% of the total cost of desalination is for electricity and 26% for consumption. In Kuwait, natural gas and light hydrocarbon fuel is burned to produce electricity, which is mainly used for cooling (air-conditioning) and water desalination (Alnaser and Alnaser, 2011). Concern of oil depletion due to heavy consumption leads to search for alternatives to generate electricity in Kuwait, in this thesis wind energy is consider to be one of the promising alternatives of oil to generate electricity.

Kaldellis & Kavadias (2007) studied the cost–benefit analysis of remote hybrid wind–diesel power and investigated energy production cost analysis in order to estimate the optimum configuration of a wind–diesel-battery stand-alone system. This system could then be used to guarantee the energy autonomy of a typical remote consumer using different parameters such as wind potential, capital cost, oil price, battery price and first installation cost. The corresponding electricity production cost is investigated using the developed model. It was found that hybrid wind–diesel systems may be the most cost-effective electrification solution for numerous isolated consumers located in suitable (average wind speed higher than 6.0 m/s) wind potential regions.

Snyder & Kaiser (2009) discussed the costs and benefits of offshore wind relative to onshore wind power and conventional electricity production, and developed empirical cost functions for offshore wind based on publicly reported projects from 2000 to 2008. They also found that decreasing commodity costs or legislation capping greenhouse gas emissions could increase the profitability of offshore wind, but would not change the fact that onshore wind will be a less expensive alternative. In some cases, offshore wind power may be able to produce cheap electricity with insignificant environmental impacts; however, even when the costs of carbon offsets are included, in many cases, offshore wind power will be more expensive.

Blanco (2009) presented a range of current generation costs of wind energy investments in Europe, both onshore and offshore, based on a survey carried out among European Wind Energy Association members. This looked at the factors that most influence wind energy manufacturers and developers regarding the current generation costs of wind energy projects in Europe, including the reasons behind their recent increase and their expected future evolution. He found the generation costs of an onshore wind farm are between (4.5 to 8.7 cents/kWh/3pence to 7pences/kWh /10 files/ kWh to 30files/ kWh), and (6 to 11.1 cents/kW/ 5pences to 8pences/kWh /20 files/kWh to 30 files/kWh) when located offshore, with the number of full hours and the level of capital cost being the most influencing elements. Generation costs have increased by more than 20% over the last 3 years, mainly due to a rise in the price of certain strategic raw materials at a time when global demand has boomed. The researcher found that wind energy is a capital-intensive technology, with the fixed assets (wind turbine, grid connection and civil works) accounting for as much as 80% of the total cost and the capacity factor and wind turbine cost being the most influential factors.

Later, Green and Vasilakos (2011) presented an overview of the main issues associated with the economics of offshore wind, looking at various support policies used in Europe, and found that tender-based feed-in tariff schemes, as used in Denmark, may be most suitable for providing adequate support while minimising developers' rents. The Danish support method, which uses competitive bids to set the tariff actually required by each developer, has the prospect of minimising the cost of support while still ensuring that projects remain feasible. The researchers concluded that a number of EU countries would need to make significant investments in offshore wind power if they are to meet their targets for renewable energy in 2020. These stations will be expensive, but they will be more expensive than necessary if the recent sellers' market continues. Shawon et al. (2013) presented an overview of wind energy potential and existing wind energy conversion technology used in the Middle East. This included a detailed analysis of the economics behind deploying wind energy conversion technologies including wind characteristics while assessing suitable technologies for the Middle East. Three different types of wind turbines were chosen to investigate the economic feasibility of wind energy. It was found that Manjil and Roodbar which are the selected location in Iran have the highest potential wind energy for large scale electricity generation. UAE, Iraq, Iran (central part of

Yazd Province) and the western Aegean Sea region have lower feasibility for wind energy, yet are fit for small scale applications. In the proposed economic method, the cost per kWh charge of wind energy varies from (0.0528 to 0.0999$/kWh/4pences to 8pences/kWh/20files to 30files/kWh) to, (0.0567 to 0.098$/kW h/4pences to 8pences/kWh/20files to 30files/kWh), and (1.454 to 2.332$/kWh/ £1.1 to £1.76/kWh/ 440files to 700files/kWh) for regions 1–3, respectively.

Ahmed Shata and Hanitsch (2006) evaluated the wind energy potential and electricity generation of ten coastal meteorological stations along the Mediterranean Sea in Egypt. They have assumed that the lifetime of the wind turbine (t) to be 20 years, the interest rate (r) and inflation rate (i) were taken to be 15 and 12%, respectively, operation maintenance and repair cost (C_{omr}) was considered to be 25% of the annual cost of the turbine, Scrap value S was assumed to be 10% of the turbine price and civil work, and investment (I) includes the turbine price plus 20% for civil work and other connections. It was concluded that the 1MW wind turbine rated power was found to produce an energy output of 2718MWh per year at El Dabaa station, and the production costs were found to be (0.02€ /kWh/£0.02/kWh/0.01KD/kWh) , which was considered to be very competitive with other stations along the coast of the Mediterranean sea in Egypt.

2.8 Life Cycle Assessment (LCA)

The progress of the life cycle assessment (LCA) started in the 1980s, according to Davidsson et al. (2012), and became increasingly common during the 1990s when scientific publications began to reach wider audiences. As the concept of LCA evolved, many different methods and guidelines came on stream. There are recent developments which are very well described by (Finnveden et al., 2009; Guinée et al., 2011). According to Guinée (2001), LCA can be defined as “the compilation and evaluation of the inputs, outputs and potential environmental impact of a product system throughout the life cycle”. It can be said that life cycle assessments generally follow the same four basic steps: goals and scope, life cycle inventory, impact assessment, and interpretation.

There are several definitions of life cycle analysis (LCA). Al-Behadili and El-Osta (2015) defined it as the medium of measuring environmental factors that impact on a product's life cycle; from inception to decommissioning (i.e., from raw material extraction to materials processing, manufacture, distribution, use, repair and maintenance, and disposal). They stated that it is generally accepted that wind energy is one of the cleanest and most sustainable forms of energy generation, yet does create minuscule environmental pollution throughout the phases of its life cycle, such as during manufacturing and dismantling of the wind turbines.

In terms of life cycle inventory (LCI), entries and outputs of the whole life cycle are estimated in accordance with the chosen system boundaries and methods. There are several different ways to do this, and choices in methodology can have a large impact on final results. Ekvall and Weidema (2004) suggested two broad categories; attribution LCI, and consequential LCI. In terms of attribution LCI, this is described as the physical inflows that are associated with the environmental impact in and out of the life cycle system limits. By contrast, consequential LCI is a system which generates information about the outcome of actions made by describing how the physical flows which are relevant to environmental impact will change with certain variables in the life cycle. It is necessary at this stage to make the point that there is not always a clear practical distinction between attribution and consequential LCI.

Following that is life cycle impact assessment (LCIA), where the results from the inventory are translated into environmentally relevant information (Baumann and Tillman, 2004). Martínez et al. (2009) have compared several methods to perform an LCIA. At times, attempts are being made to express the impact on a base and common scale through weighting or further evaluating the results of LCIA. This can never be based solely on purely objective factors, as subjective values always must be introduced (Baumann and Tillman, 2004). For this reason, LCA may not necessarily be a method that fulfils the standards of strict natural science. This should be taken with caution and handled with regards to the interpretation of the results.

Tremeac and Meunier (2009) analysed the life cycle of 4.5MW and 250W wind turbines. In the study, they compared two wind turbines of 4.5MW and 250W in order to estimate the environmental impact. All phases of the life cycle were analysed; which included manufacturing, transports, installation, maintenance, disassembly, and disposal. They found that to provide an optimum environmental solution, significant factors include:

1) High efficiency turbines should be implemented in a high wind speed region

2) Transportation components should not spend too much energy

3) Recycling during decommissioning should be performed correctly

The researchers stated that there are two aspects which are considered important and are to be taken into consideration in regards to the deployment of wind turbines and their management:

- Component transportation must be as limited as possible. Factories should be distributed on the earth's surface in correlation with wind farms to be built. When, nevertheless, large distance transportation is necessary, boat or train should be preferred to truck.

- Recycling during decommissioning is an important step, and not to be underestimated, in order to achieve good environmental impact figures.

Martínez et al. (2009) studied a life cycle assessment of a multi-megawatt wind turbine. They investigated the emissions produced while the wind turbine was in operation; furthermore, the contamination and environmental impact resulting from their manufacture and the future dismantling of the turbines at the end of their working life was studied. They particularly looked at the application of the ISO 14040 standard in order to carry out an LCA study quantifying the overall impact of a wind turbine and each of its components. The researchers studied the wind turbine from inception to decommission with regard to the manufacture of its key components (through the incorporation of cut-off criteria), transportation to the wind farm, subsequent installation, start-up, maintenance, and final dismantling and stripping down into waste materials and their treatment. It was found that the cement foundation is the component which most significantly affects the environment because of the impact on the inorganic respiration (IR) category, which is one of the categories from the Eco-Indicators guideline.

In a similar study by Martínez et al. (2010), which investigated the four phases of life cycle analysis (LCA) of a system: maintenance, manufacturing, dismantling, and recycling using the Eco-indicator 99 life cycle analysis (LCA) method, examined the significant options available in the development of the wind farm. From the derived outcomes, it is reasonable to assert that it is necessary to more precisely analyse and define the average of major corrections that a turbine may encounter throughout its 20 year life, as, without a doubt, the decisions taken at the maintenance phase of the turbine have a significant effect on the outcome of the LCA. Another problem that significantly affects the final results of the LCA study of wind turbine megawatts in question are is the issue of recycling and reusing components and materials. A clear example is the impact of materials such as fibreglass blades for wind power when not recycled but sent directly to landfill.

Life cycle impact assessment (LCIA) has been established to estimate potential environmental burdens, according to (Klöpffer and Grahl, 2014). Although it is not statistical and mathematical in nature, it represents what would be referred to as a 'balance of probabilities'. It is important to note that LCA is not essentially geared to estimate the impact of extremely unlikely, catastrophic events, such as the effect of an earthquake on a costal nuclear station. The authors begin Part 4 by reviewing mandatory and optional elements of LCIA as per the ISO standards. They then define mid-point and damage categories.

Al-Behadili and El-Osta (2015) analysed and evaluated life cycle analysis (LCA) by examining the impact of the commissioning of a wind farm in Dernah, east of Libya, by considering the whole life cycle of the project. They concluded that the energy payback period is just under 6 months (5.7 months), and the corresponding pay back ratio is given as 42.1, which is found to substantiate results found in similar studies. It is found that the electricity generated by one wind turbine is given as 1.65 MW (TWT 1.65/82). This wind farm is expected to diffuse approximately 10.42, 0.02713, 0.03823, 0.0001474, 0.0001065, 0.0003469 and 0.0112237 grams per kWh CO_2, SO_2, NO_x, N_2O, CH_4, NMVOC and CO respectively. This study found that wind energy produces the lowest CO_2 emission per kWh of electricity (10.4 g/kWh) generated in comparison to non-renewable sources such as fossil fuel. It was found that when there is recycling of the wind turbine material the specific emission of CO_2 is 4.65 g/kWh of energy generated. Furthermore, the amount of fuel savings is given as 85,700 m^3 per year or 79,013,800 kg fuel per year, which is now translated to ($2.8 million/year £2.11million/year /0.85 million KD/year)(which is more than (($66 million/ £50 million/ 20 KD million) over the lifetime of the wind farm) if the local subsidised price of heavy fuel oil is considered. The savings could reach a value as high as ($63,404,570/year/ £47,883,131/year /19,156,423KD)(($1.3 million/£0.98million /0.39million KD) over the entire lifetime of the wind farm) if the international prices of heavy fuel oil are considered.

2.9 Summary

In Kuwait the increase in population leads to an increase in consumption of electricity generated from oil, by 40% over the last 10 years. This leads to concern about the proven reserves, (Moody's, 2017; OPEC, 2017) shown to continue for 89 to 97 years. Moreover, the price of oil has decreased to reach ($54.54/£41/KD16.5) per barrel (Alwatan, 2017). The drop in price has meant lower exports and government revenue in the GCC which lead to increase in prices fuel, water, and electricity and living cost. As an example premium gasoline increased by 61% from ($0.215 to 0.35/£0.16 to £0.26 /65 to 105 fils), the ultra-gasoline increased by 83% from ($0.23 to $0.54/£0.22 to £0.41/90 to 165 fils)(Alanba', 2016).

Since Kuwait is involved in the United Nations Framework Convention on Climate Change (UNFCCC) and is part of the Kyoto protocol and COP21, it started to take an interest in renewable energy in order to reduce the CO_2 emissions level (30.3 tonnes of annual CO_2).

It can be seen in Table 2.4 that the highest use of solar power among the Arabian Gulf countries was in Saudi Arabia at 683 $W/m^{2,}$ followed by Kuwait at 673 $W/m^{2,}$ whereas the lowest solar power user was Bahrain at 563 W/m^2. However, it is clear that Oman and Kuwait have the highest use of wind power with 141 W/m^2 and 140 W/m^2 respectively. Oman has the lowest solar wind ratio of 4 (which is the ratio of the solar power to wind power), followed by Kuwait with 4.8, while the highest ratio is Saudi Arabia with 9.6. This make Oman and Kuwait more suitable to use or to implement wind energy among GCC countries.

Table 2.4 Solar versus wind power in the Arabian Gulf countries(W/m^2) (Alnaser and Alnaser, 2011)

Country	Solar energy (Wh/m^2)	Sunshine duration (h)	Solar power (W/m^2)	Wind power (W/m^2)	Solar/wind Ratio
Bahrain	5180	9.2	563	78	7.2
Saudi Arabia	5670	8.7	683	71	9.6
Kuwait	5990	8.9	673	140	4.8
Qatar	5260	9.3	565	85	6.6
UAE	5078	8.8	577	57	10.1
Oman	5410	9.6	564	141	4

As presented in Section 2.2, four main types of renewable energy have been investigated in this study: solar, wind, wave, and biomass energies. There is enough natural potential in sun and wind to meet requirements, especially in the summer, when the demand is at the highest, whereas biomass and wave energies are not very feasible in the state of Kuwait (Mondal et al., 2016; Alhajraf, 2013). Moreover, as shown from literature that in Kuwait the waves in Arabian Gulf are low and landfills are not suitably cited or designed. Furthermore, the literature shows that the main factors affecting the use of solar energy in the Middle East are social, political, economic and environmental. However, the negative impact from atmospheric conditions on the performance of PV cells reduces efficiency, which also leads to rapid degradation of the cells, even when using self-cleaning, which is neither favourable nor efficient. Moreover, it was also found that the primary and maintenance costs of PV systems were very high, with long term payback. Because of the GCC countries following a mixed energy policy and Kuwait's attempt to use any available energy to generate electricity for the benefit of generation on the long run, implementation of solar and wind energies in Kuwait become essential because both are environmentally friendly methods of producing electricity (Alhajraf, 2013; Alnaser and Alnaser, 2011).

The higher values of monthly mean wind speed in Kuwait is in summer (June, July and August), and it showed a higher availability of wind energy, which matches the larger electrical load requirements during the summer months in Kuwait. There are two main types of wind turbines: horizontal axis and vertical axis (HAWT and VAWT), however, it has been concluded that horizontal axis wind turbines are more efficient than vertical axis wind turbines. The materials used for the tower of the wind turbine are tubular steel, whereas the blades are made of glass fibre mats or carbon fibre. It is also clear that the maximum wind energy was produced from the smaller wind turbines and the capacity factors were higher than for the large wind turbine. Most of the GCC countries used Nordex and Gamesa wind turbine models of different sizes to generate electricity as shown in previous papers. It was concluded that the smaller turbine was favourable in terms of efficiency and economy. It has also been determined that the most suitable turbine for 60m height is Gamesa G58, because as the height increases the capacity factor will increase. Recently, new generation of wind turbines are in the market with 100m which is better to capture higher wind speed.

There is an apparent competitive cost benefit of wind energy comparable to other renewable energy and cost electricity generated from oil as is the case in Kuwait and GCC countries. A clear economic benefit of wind energy in Kuwait will be established in Chapter 5.

LCA has several different definitions, but generally it is seen as the medium of measuring environmental factors that impact on a product's life cycle; from inception to decommission. The objective of the LCA of a product or process is to capture a range of environmental liabilities or impacts that accumulate over the entire life cycle, from the cradle to the grave. That does will be conducted in Chapter 6.

In Chapter 7, previous examples of numerical modelling which have been used to predict soil structure interaction for wind turbine will be presented.

Based on the above, this research will look at the feasibility of wind energy in the state of Kuwait due to the absence of knowledge and research into the new technologies and lack of energy policy for wind energy in the Middle East. A detailed analysis of the economics behind deploying wind energy conversion technologies including wind characteristics while assessing suitable technologies for Kuwait will be concluded.

3 Methodology

3.1 Introduction

This chapter is divided into three essential parts in order to achieve the aim of the thesis, which is to assess the feasibility of using wind turbines within Kuwait as a source of renewable energy. These three parts are: 1) exploring the true cost of producing electricity from wind power to find the lowest cost and highest reliability design for a wind energy farm; 2) assessing the potential environmental impacts and resources used throughout a product’s life-cycle.; 3) modelling the wind turbine structure and foundation stability.

Based on Figure3.1 which shows the potential stages of the work of this research, first literature review and data acquision is conducted to understand and obtain relevant data to the research. To assess the feasibility of wind energy in Kuwait, economic and environment considerations have to be conducted. That's lead to identify the soil – structure integrity of the wind turbine on sand soil in Kuwait. Recommendation and future work will be generated.

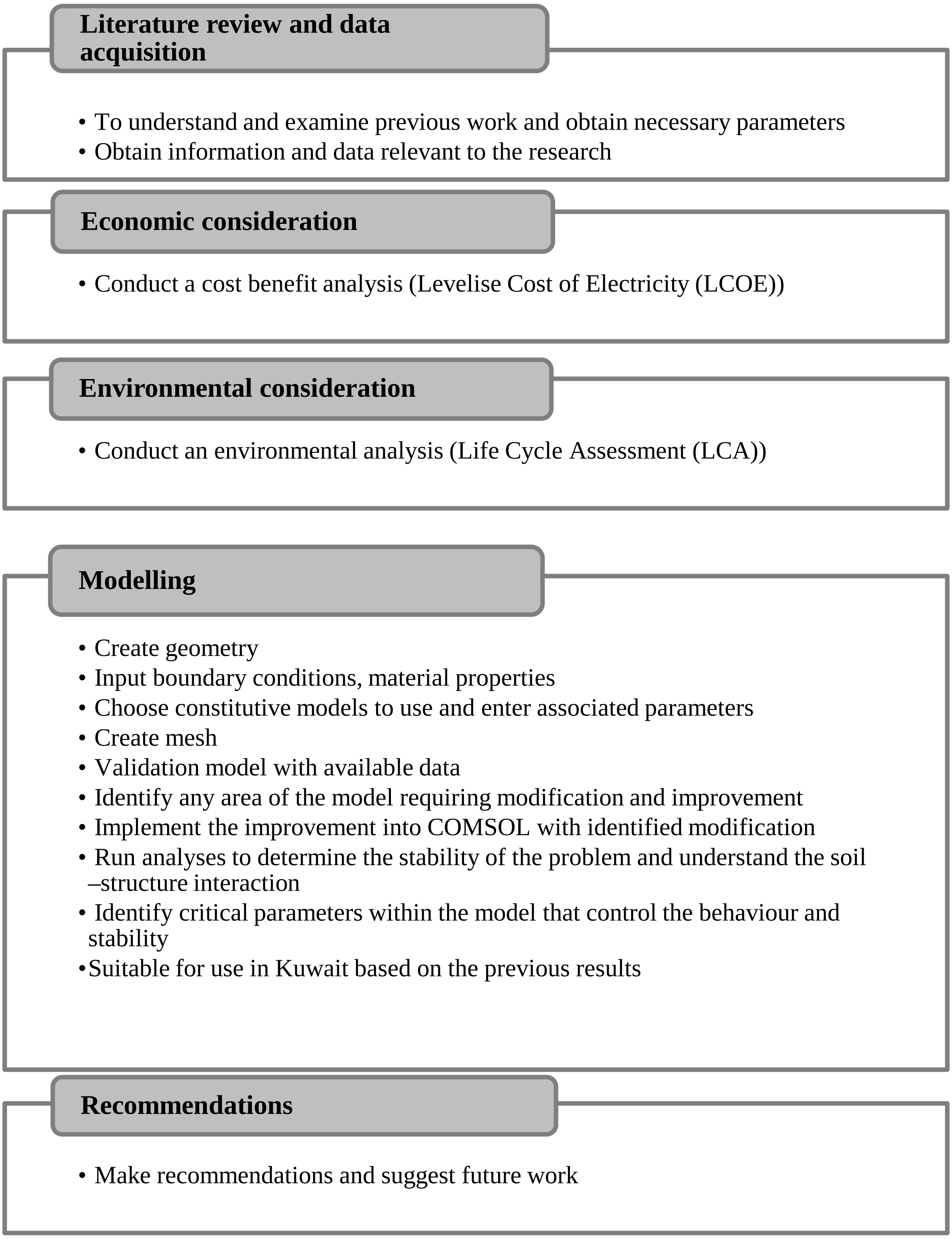


Figure 3.1 Potential stages of the work of this research

3.2 Economic and Financial Analysis

In different studies the cost of wind energy is evaluated based on several methods such as present value cost (PVC), life cycle cost Analysis (LCCA) methods and levelised cost of electricity (LCOE).

3.2.1 Present Value Cost (PVC)

Present value cost (PVC) (Ahmed Shata and Hanitsch, 2006; Ahmed, 2011; Ohunakin et al., 2012) is implemented because it considers the dynamic development of the relevant economic factors and different occurrences of costs and income of all payment flows to a common reference time.

(Ohunakin, Oyewola and Adaramola, 2013) LCOE takes into consideration the net present value of the current and future annual costs, whereas the PVC method takes into consideration the current value of the total cost of energy investment during the entire lifetime of the energy system.

3.2.2 Life Cycle Cost Analysis (LCCA)

(Myhr et al., 2014) divided Life Cycle Cost Analysis (LCCA) is into five main phases, distinguished by the different operating conditions and capital intensity; Development and consenting (D&C), Production and acquisition (P&A), Installation and commissioning (I&C), Operation and maintenance (O&M) and Decommission (DECOM) which has long procedures and phases. They suggested that it is advisable to utilise a levelised cost in order to define a similar reference for value of money at different stages of a project to increase the significance of the LCCA concerning concept comparison. It is convenient to level the LCCA results by expected energy production.

3.2.3 Levelised Cost of Electricity (LCOE)

Levelised Cost of Energy (LCOE) Analysis allows for a better analysis and evaluation of risk and total cost during the life span. The LCOE is a technique applied by the techno-commercial analysts to calculate the unit cost throughout the economic life of the project and it is one of the most important indicators for estimating economic performance of power supply systems (Hamza et al., 2017; Ashuri et al., 2014; Ramadhan and Naseeb, 2011; Myhr et al., 2014; Oliveira and Fernandes, 2012)

Perkin, Garrett and Jensson, (2015) stated that LCOE is the most robust objective function as it sufficiently describes the potential profitability of a wind turbine and by applying this method by developers during the planning stage could significantly improve the financial performance of their investment. Similarly, such techniques could improve decision making during the initial planning stage.

In this research Levelised Cost of Energy (LCOE) will be used which is represent the sum of all costs of a fully operational wind farm over the project. This method is widely used for making fair comparisons with electricity prices and the cost of other power generation technologies and most commonly used to rank the economic viability of a wind energy project. Most of the popular research associations and agencies such as (IRENA, EWEA, NREL, and EIA) have been used LCOE method to compare the cost of different sources of energy, useful comparison between the cost of wind energy in Kuwait and the different energy sources implemented in the world. In addition, LCOE is simple and useful and to make a decision of using generating technology so that it is widely used in policy-making and managers. (Perkin, Garrett and Jensson, 2015; Gualtieri, 2017).

The International Renewable Energy Agency (IRENA, 2012) represented the key findings of the cost of wind farm components as: Capital Expenditures (CapEx), Capacity Factor, Operation and Maintenance Expenditures (OpEx) which are the source data of Levelised Cost of Energy (LCOE).

Capital Expenditures **(**CapEx) include wind turbine price; civil works and construction, and grid connection. Operation Expenditures (OpEx) cover insurance, regular maintenance, repair, spare parts, and administration.

The Levelised Cost of Energy (LCOE) is relatively simple, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions (IRENA, 2012; Myhr et al., 2014).

The equation used for calculating LCOE of wind energy is:

$$\boldsymbol{LCOE} = \frac{(\mathbf{CapEx} \times \mathbf{FCR}) + \mathbf{OpEx}}{(\boldsymbol{AEPnet}/\mathbf{1{,}000})}$$ **Equation 3-1**

Where:

LCOE = levelised cost of energy ($/megawatt-hour [MWh])

FCR = fixed charge rate (%) = $\frac{d(1+d)^n}{(1+d)^n-1} \times \frac{1-(T \times PV_{dep})}{(1-T)}$

CapEx = capital expenditures ($/kilowatt [kW])

AEP_{net} = net average annual energy production (MWh/megawatt [MW]/year [yr.])

$MW_{net} \times 8{,}760 \times CF_{net}$

OpEx = operational expenditures ($/kW/yr.)= LLC + OPER + MAIN

d = discount rate (weighted average cost of capital [WACC]) (%)

n = economic operational life (yr.)

T = effective tax rate (%)

PVdep = present value of depreciation (%)

CFnet = net capacity factor (%)

LLC = annual levelised land lease cost ($/kW/yr.)

OPER = pre-tax levelised operation cost (operation and maintenance [O&M]) ($/kW/yr.)

MAIN = pretax levelised maintenance cost (O&M) ($/kW/yr.).

SAM is produced by the Department of Energy and National Renewable Energy Laboratory (NREL). It is a computer model that was used to calculate performance and financial metrics of renewable energy systems. SAM simulates the performance of wind energy and various other renewable energy projects. The economic model can represent financial structures for projects that either buy or sell electricity at marketing rates (NREL, 2014). To estimate the cost benefit of wind farms in Kuwait, a SAM model was used to simulate the financial aspects of a 2MW wind turbine project.

The results obtained from applying the above Levelised Cost of Energy (LCOE) equation for wind energy will be compared in Chapter 5 with SAM simulation results and the LCOE of the electricity generated in Kuwait. In order to compare the cost of different sources of energy, LCOE approach can provide the cost per power which will be easy to compare with and most of the popular research associations and agencies such as (IRENA, EWEA, NREL, and EIA). This comparison will lead to an assessment of the economic benefit of wind farm implementation in Kuwait.

3.3 Life Cycle Assessment (LCA)

There are a number of LCA software packages available on the market that have been used to simulate LCA, such as SimaPro, Gabi, and GEMIS.

To conduct the LCA, the Global Emission Model of Integrated Systems (GEMIS) simulation software is used, which is widely adopted for LCA in Europe. It enables a detailed description of all the process steps of an energy system and the calculation of the primary energy consumption involved in the process, the emissions, the mass, and energy flows. The model can perform LCA for a variety of emissions and can determine the resource use. Its database also provides information on energy carriers (process chain and fuel data) as well as different technologies for heat and electric power generation. In addition to fossil energy carriers (hard coal, lignite, oil, natural gas), renewable energies, household waste, uranium, biomass and hydrogen are also covered in GEMIS. Guezuraga et al. (2012) carried out a life cycle assessment and used a quantitative analysis of the material and energy balances over the entire life cycle of the environmental impact of a 1.8MW-gearless turbine and a 2.0MW turbine with gear box using the GEMIS simulation software. The results showed that the largest energy requirement is during the manufacturing phase, representing 84.4% of the total life cycle, and particularly from the tower construction, which accounts for 55% of the total turbine production. In addition, GEMIS software has been used to calculate the LCA of wind turbine farms in Italy and Brazil respectively. Ardente et al., (2008) found that a CO_2 emission varies from 8.8 to 18.5 g/kWh. Oebels and Pacca (2013) concluded that the reduced CO_2 emissions in the material production stage and the low emissions of the component production stage led to a favourable CO_2 intensity of 7.1 g CO_2/kWh.

Later, Garrett and Rønde (2013) presented a case study of the LCA approach used to assess the environmental impact of the 2-MW Grid-Streamer turbines. They assessed LCA using GaBi DfX software. The evaluation has been carried on all components of the wind turbine. They concluded that the manufacturing stage contributes the largest impact in terms of CO_2 emissions, in particularly the wind turbine tower. They found that 7 to 10 g CO_2 eq/ kWh is the emission and the payback energy was from 8 to 11 months for various 2MW onshore turbines.

Weinzettel et al. (2009) calculated the environmental impacts using SimaPro software, and input parameters and environmental, emission, and energy content and consumption values for various construction activities including transportation, manufacturing, and production of materials. Wherever possible, relevant data based on direct information from producers, and for generic inputs, the Ecoinvent database was used. Rajaei and Tinjum (2013) stated that the primary source for values of CO_2eq emissions and production energy through the life cycle of each of the major listed material types used in the construction of the wind farm was the SimaPro

‘‘Ecoinvent v.2 database’’. This database includes various material types and processes from different national and international sources. Martínez et al. (2009a) showed that the materials and energy used in the various components were incorporated into the model using data provided by Gamesa and SimaPro. Uddin and Kumar, (2014) have also used SimaPro 7.3.3 for life cycle assessment in Thailand to evaluate the life cycle embodied energy, emissions (air, water), environmental impacts, energy payback time and performance indexes of vertical axis and horizontal axis grid connected wind turbine using life cycle assessment technique. The vertical axis wind turbine is energy and emission intensive per kWh/ year energy delivered compared to horizontal axis wind turbine for base case system. The embodied energy and environmental impact could be reduced by more than 60% and 50% respectively by reusing materials strategy. The embodied energy of a vertical axis wind turbines could be reduced by 36% with thermoplastic and 40% with fiberglass plastic turbine instead of aluminium turbine, while an environmental impact reduction more than 15% has been observed.

Further researchers have used SimaPro; (Bonou, Laurent and Olsen, 2016; Carrascal, 2014; Crawford, 2009; Martínez et al., 2009b; a, 2010; Martı´nez et al., 2015; R.Díaz Martín et al., 2016; Nalukowe et al., 2006; Rajaei and Tinjum, 2013; Tremeac and Meunier, 2009; Vargas et al., 2015).

The literature review shows the most commonly used LCA software to be SimaPro. It offers standardisation; therefore stakeholders will trust its results as well as its ultimate flexibility. It has unique features such as parameterised modelling and interactive results analysis, and comes with a uniquely complete implementation of the world’s leading database, Ecoinvent, which is the world leader in LCA databases. All versions of SimaPro include the most complete implementation of Ecoinvent of any LCA software. Vogatlander, (2010) mentioned that the difference between SimaPro and Gabi is that SimaPro is more flexible than Gabi in relation to the ability to build your own system. He also advised that most modern software is available globally.

For reasons of completeness, different types of software have been discussed above. Initially, SimaPro was going to be used. However, after further research, it was found that the SimaPro PhD license will be cost (Eur. 3,780 /USD. 4,347/£3355.43/1343.41KD) (https://simapro.com/education) which is not a cheap option, based on the university resource availability. It was therefore decided to perform manual calculations, which also provide a better learning experience.

3.4 Finite Element Method (FEM)

Numerical modelling is used to investigate the effect of critical parameter variation on the behaviour of HAWT. Validation of the model is a vital step in developing an effective model; this involves verifying the model structure by testing whether the model outputs are appropriate under given inputs (Fellows and Liu, 2008). Validation is undertaken in Chapter 7. The finite element method (FEM) is one of the most effective numerical techniques for solving *partial differential equations* (PDEs) arising from mathematic, physics, and engineering as shown below:

$$\frac{\partial \sigma_x}{\partial_X} + \frac{\partial \sigma_{xy}}{\partial_Y} + \frac{\partial \sigma_{xz}}{\partial_Z} + \omega_x = 0$$ **Equation 3-2**

$$\frac{\partial \sigma_{xy}}{\partial_X} + \frac{\partial \sigma_y}{\partial_Y} + \frac{\partial \sigma_{yz}}{\partial_Z} + \omega_y = 0$$ **Equation 3-3**

$$\frac{\partial \sigma_{xz}}{\partial_X} + \frac{\partial \sigma_{yz}}{\partial_Y} + \frac{\partial \sigma_z}{\partial_Z} + \omega_z = 0$$ **Equation 3-4**

3.4.1 Finite Element Software

The different finite element software which analyse soil-structure interaction, ABAQUS, PLAXIS and COMSOL in relation respect to with regards to element, operating system, analysis, modelling, and constitutive models.

Plaxis requires less time to create a working finite element model compared to ABAQUS and COMSOL Multiphysics. ABAQUS was omitted because of unavailability of the software in the department. The researcher undertook an advanced Plaxis course in the Netherlands, and found that this software works well for foundations and structures under the ground, whereas COMSOL is well-able to deal with soil structure interaction problems (COMSOL, 2017). In this research, COMSOL was used.

3.4.2 COMSOL

COMSOL is Multiphysics finite element software; with it is possible to model a number of physical phenomena ranging from microscale electromechanical systems to chemical reactions. This can be accomplished in different physical modules. These modules can also be used together to create multiphysics analysis. In addition, COMSOL allows the user to add physical effects gradually. Furthermore, it can build complex problems without the need to rebuild a new finite element model (COMSOL, 2017).

In this research, a model will be used to investigate the effect of critical parameter variation on the behaviour of HAWT's. Validation of the model is an essential process in producing an effective model. Once the model has been validated, it can be used as a tool for a critical investigation of the impact of parameter variation on the behaviour of HAWT's.

Figure 3.1 demonstrates the stages in creating numerical models in COMSOL, implementing the chosen constitutive models and chosen variables. COMSOL Multiphysics 5.0 is a finite element package which allows the modelling of multiple engineering problems based upon Partial Differential Equations (PDE's). It is an extremely powerful tool that allows the coupling of different physics phenomena through its inbuilt modules. The software utilises the proven FEM together with adaptive meshing and error control (COMSOL, 2017)

The modelling stages are shown below:

- Create geometry including the dimension of the foundation (width and length) and the wind turbine (hub height, blade length, weight).
- Input boundary condition, material properties of the wind turbine, the foundation, and the soil.
- Choose constitutive models to use and enter associated parameters.

3.4.3 Constitutive Models

A constitutive model relates an applied stress to the motion of a body through the use of characteristics specific to the material of that body (Truesdell and Noll, 2004). Examples of these include linear-elastic and elasto-plastic models (Chen, 2008). In simpler terms, a constitutive model provides a relationship between the stress-strain characteristics of a material and is expressed mathematically below:

$$\{\Delta\boldsymbol{\sigma}\} = [\boldsymbol{D}]\{\Delta\boldsymbol{\epsilon}\} \quad \textbf{Equation 3-5}$$

Where, $\Delta\sigma$ = change in stress, [D] = constitutive matrix, and $\Delta\varepsilon$ = change in strain. Constitutive relationships can vary significantly based upon the initial assumptions made in developing the model.

3.4.3.1 Linear-Elastic

In general, the model's stress-strain behaves linearly in the elastic range, based on Hooke's theory in which the relationship between stress and strain, the model is simplest of all constitutive models, it is involved two basic elastic parameter, Young's modulus (E), Poisson's ratio (v). Soil behaviour is controlled by elasticity rather than plasticity under small strain (Potts and Zdravkovic, 1999).

3.4.3.2 Elastic-perfectly plastic

Most soils, if sheared to a large enough strain will continue to experience large volumetric strains even without any further variations in stress. Continued shearing even when the tangential stress has been removed is known as perfectly plastic and is the simplest of all elastic-plastic models (Muir Wood, 2004).

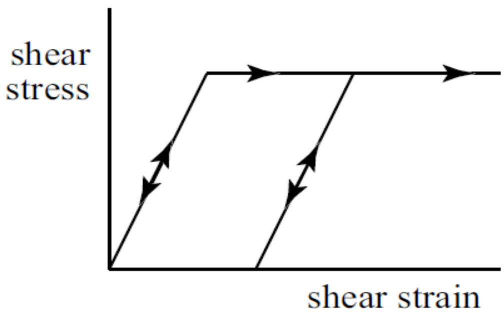


Figure 3.2 Elastic-perfectly plastic stress strain relationship (Muir Wood, 2004)

3.4.3.2.1 Mohr-Coulomb

The Mohr-Coulomb model is a combination of the generalised form of Coulomb's failure criterion and Hooke's law. It involves five parameters, namely Young's modulus (E), Poisson's ratio (v), the friction angle($\emptyset$), cohesion (c), and the dilatancy angle (Ψ). In general, the elastic perfectly-plastic Mohr-Coulomb model is often used to model soil behaviour, and it performs better in strength behaviour (Brinkgreve, 2005). This model is a perfect elastic-plastic model, which means that the behaviour of the soil is linear elastic up to a certain stress limit, after which the soil is perfectly plastic, meaning that the strain is irreversible after a stress decrease. Both parameters, the cohesion (c) and stiffness (E), are chosen as a representative value that is consistent with the stress level in the soil. It is possible to model both the stiffness and the cohesion with a linear increase in depth (Svensson, 2010).

The Mohr-Coulomb model is based on plotting Mohr's Circle for stresses at failure in the plane of the maximum and minimum principal stresses. This model assumes that failure is independent of the value of the intermediate principal stress, whereas the Drucker-Prager model does not (EL-Hamalawi, 2011).

3.4.3.2.2 Von Mises Model

This model states that plastic yielding occurs when the second deviator stress reaches a critical value (see Figure 3.3)

Yield Function =

$$\boldsymbol{F} = (\{\boldsymbol{\sigma}\},\{\boldsymbol{k}\}) = (\boldsymbol{\sigma_1} - \boldsymbol{\sigma_2})^2 + (\boldsymbol{\sigma_1} - \boldsymbol{\sigma_3})^2 + (\boldsymbol{\sigma_2} - \boldsymbol{\sigma_3})^2 - 2\boldsymbol{S_u} = \boldsymbol{0} \qquad \textbf{Equation 3-6}$$

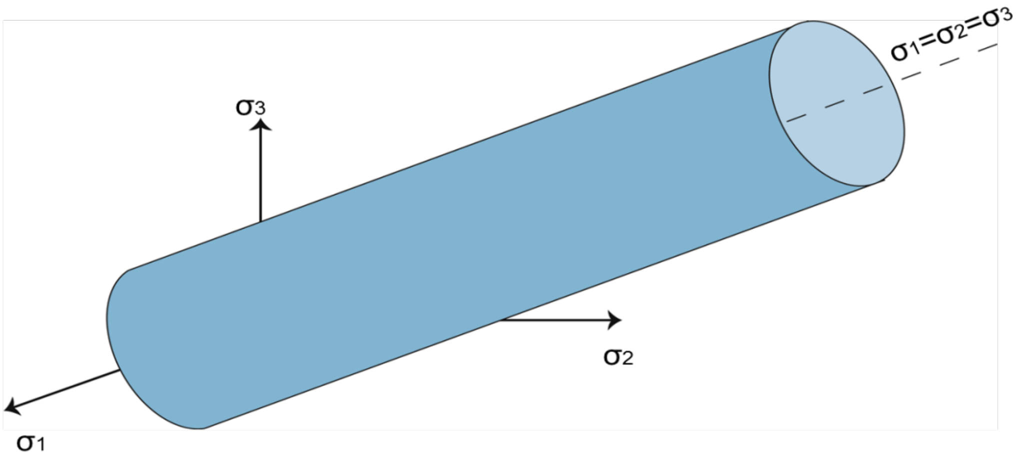


Figure 3.3 Von Mises yield surface (de Souza Neto E. A., Peric and Owen, 2008)

It is clear from the above that the difference between the models shown (Von Mises, Mohr-Coulomb) is their shape in the deviatoric plane (π plane). Furthermore, On the other hand, the Von Mises model is more suitable for metals than soils, whereas the Mohr-Coulomb model is preferable in soil mechanics theory. This has the advantage of the finite element analysis being compatible with conventional soil mechanics(EL-Hamalawi, 2011). Based on the above, in this research the Von Mises model will be used for modelling the conical steel tower of the wind turbine, and the Mohr-Coulomb model will be used for soil modelling. The overall modelling analysis process is shown in Figure 3.4.

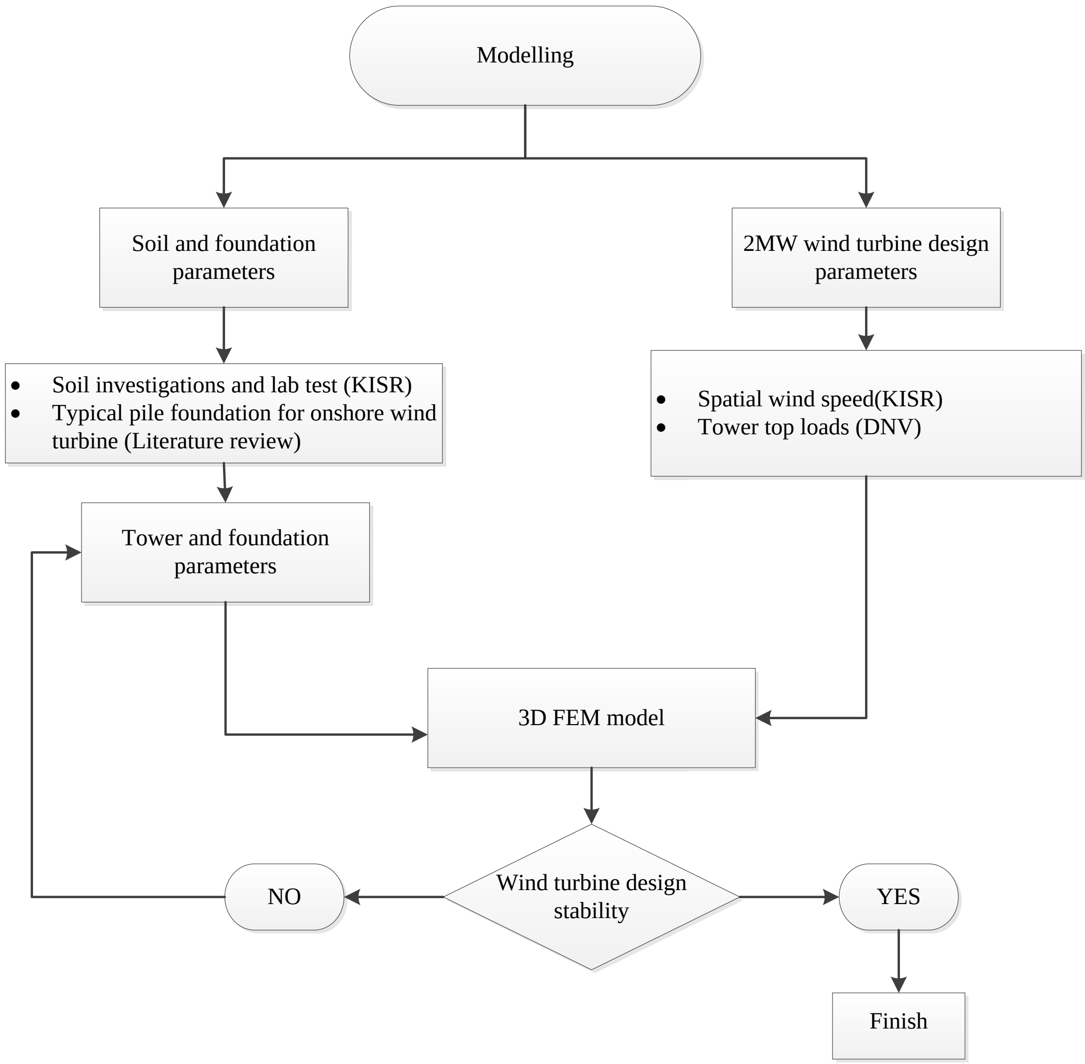


Figure 3.4 Numerical modelling analysis flowchart

3.5 Summary

The finite element method is widely used for modelling due to its ease of use and its compatibility with conventional soil mechanics. There are many different software programs that implement modelling, such as ABAQUS, PLAXIS, and COMSOL, and each has its advantages and limitations. COMSOL has been chosen due to availability in the university and it is capable to analyse soil-structure interaction.

Constitutive models within the COMSOL package provide a relationship between the stress-strain characteristics of a material by using the Von Mises model for modelling the conical steel wind turbine tower. The Mohr-Coulomb model will be used for soil modelling.

Levelised Cost of Energy (LCOE) will be obtained for wind energy to assess the economic benefits of wind farm implementation in Kuwait.

Of the different software considered, the most common was SimaPro. It is widely used for LCA and has distinctive features such as parameterised modelling and interactive results analysis. As most of this software is expensive, it was therefore decided to conduct manual calculations, which will provide a better learning experience for the researcher.

4 Data Description

With regards to Kuwait, boundary conditions have been defined. The sites have been chosen according to their high wind speeds, land availability, and the results of the wind map, because it is important to consider the spatial variations and geographical distribution while wind turbine selection in specific regions, when intended to develop wind farm; distance to the next grid connection shall be short as well as accessibility to the site, and the selection of adequate wind turbine generator (WTG) technology will be based on the intermediate technical, economic and environmental impact.

4.1 Selection of site location and site investigation

The proposed area of Shagaya is located in the western part of Kuwait in the direction to the border triangle of Kuwait, Iraq and Saudi-Arabia. The researcher made a field visit with (Al-Qattan, 2016) a Program Manager, Energy and Building Research Centre at Kuwait Institute for Scientific Research (KISR) (see Figure 4.1 and 4.2). The researcher looked at road access to the area and the different utilities available, such as electricity and water, as well as the terrain, soil properties and distance from the urban areas. The present wind measurement system at Um Omara and Salmi stations were also inspected.

Figure 4.1 Shagaya farm

Figure 4.2 The researcher at Shagaya area

As the area also has an insignificant population density and no industrial areas (except a fire station), after considering the wind potential as shown in the zero wind map Figure 4.3 and taking into account other important factors such as environmental impact, accessibility, infrastructure, grid availability and climatic conditions, the area was deemed to be suitable for wind farm construction. A potential wind farm site was identified within this region and made the focus of the visit. Figure 4.3 shows the Shagaya Area (blue rectangle on map). However, some of this areas is either already owned by the Kuwait Oil Company or is not feasible to use for environmental reasons such as the farms in Alwafra or other locations of Animal Wealth. Kuwait Oil Company's responsibilities involve the exploration, drilling and production of oil and gas within the state of Kuwait. The company is also involved in the storage of crude oil and delivery to tankers for export (Kuwait Oil Company, 2015).

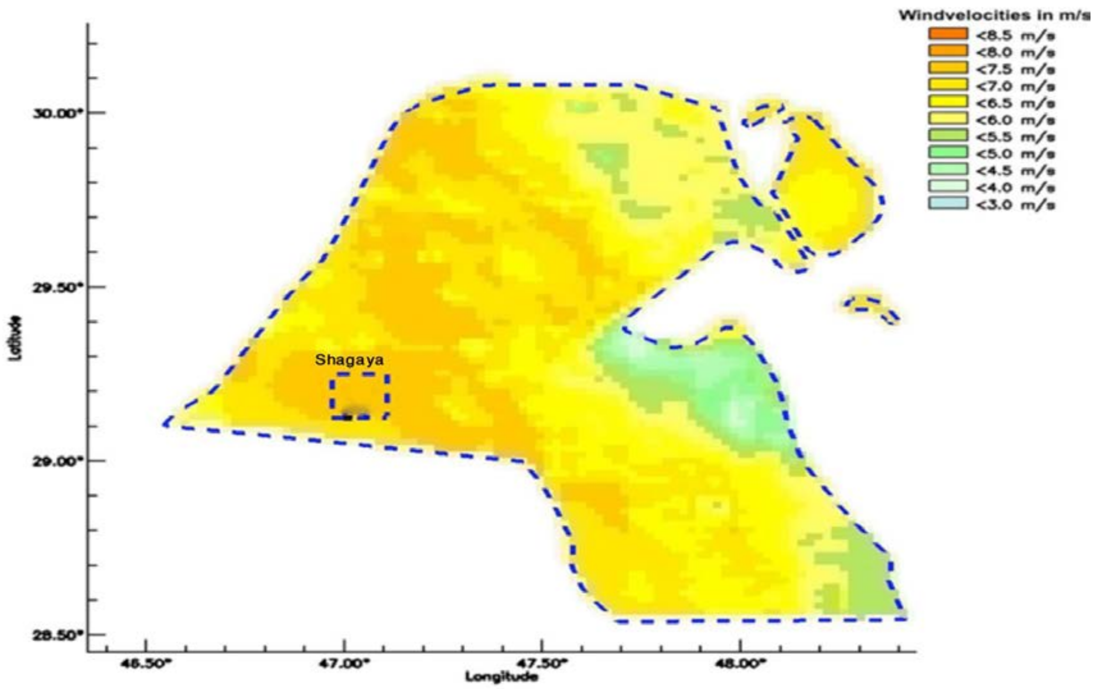


Figure 4.3 Wind speed map of Kuwait at 100 m(a.g.l) (KISR, 2010)

Based on the researcher's site visit to Shagaya, the site has been chosen according to: Wind conditions and resource assessment; wind distribution in the intended region such as wind direction, wind speeds, fluctuation, turbulence, climatic condition; sufficient wind measurement data for a period of 12 months in order to allow analysis of the energy production at the intended wind farm site, where it has been found that the annual average speed is 8.5 m/s in 100m above ground level. Based on the calibrated zero wind map approach by KISR, and guided by the site visit and available surface wind measurement data. Two sites are recommended for assessment and used for a detailed area analysis (Salmi site and northern site). Wind resource maps for the two sub-areas are depicted at 100 m. According to KISR, both selected sub-areas indicate reasonable wind regimes of more than 6 m/s, which suggests areas suitable for wind farm development. The lower left and upper right corner geographical coordinates provided in Table 4.1 below present the Eastings and Northings in degrees at Shagaya and Northern sites.

Table 4.1 Area map sites (KISR)

Site	Lower left corner E [deg] / N [deg]	Upper right corner E [deg] / N [deg]	Typical velocity range at hub height
Shagaya site	46.97033/29.12385	47.10782/29.25043	6 to 8.5m/s at 100 m
Northern site	47.47861 /29.62608	47.61092/29.74027	6 to 7.2 m/s at 100 m

Wind farm sites such as Shagaya are selected depending on land availability, the size of the wind farm, and distance to the 132 kV grid connection points as shown below in Figure 4.4, accessibility to the site, slopes and road bends, and suitable geological conditions where there are no mountains or hills. Wind turbine generator (WTG) technology grid connection and grid integration is based on the intermediate technical, economic and environmental impact, and suggested areas which are suitable for wind farm development. Researcher has been in a site visit with KISR to Shagaya and Northern sites. The ranking of area map sites depends on the infrastructure, network access, and wind regime available on site. Ranking ranges from (+), which indicates a less favourable site, to (++), which indicates a more favourable site as shown in Table 4.2.

Table 4.2 Ranking of area map sites (++ indicates more favourable, + indicates less favourable)

Site	Infrastructure	Network access	Wind regime
Shagaya site	++	++	++
Northern site	+	+	+

According to the ranking above, Shagaya is more favourable than the Northern site due to Shagaya could be extended in future, where area and having the infrastructure required for a large wind farm.

(A)

(B)

Figure 4.4(A and B) (132 kV) Shagaya substation

The wind potential appears reasonably good and network access is available. The Northern site will be the second option as wind potential is also reasonable and network access is available. Therefore, the Shagaya area is recommended as the primary option for wind farm development.

- **Accessibility to roads**

An asphalt road in good condition (as shown in Figure 4.5) makes Shagaya accessible from Kuwait City (approximately 60 km in the east). Figure 4.6 shows the road in from Shagaya farm to the two main harbours: Mina Ahmadi, and Mina Abdullah. As a result of the field visit, it was clear that these roads are suitable for heavy load trucks carrying wind turbine components on a flat terrain road with sufficient width. In addition, it is also clear that main roads link the Shagaya site with the harbour and other roads, which allows easy transport of the wind turbine equipment and labourers.

Figure 4.5 The main road to Kuwait City, airport and harbour in good condition, and highway road access

- **Environmental impact**

The impact of a wind farm on Shagaya's environment is seen to be minimal. The area is not inhabited and no industrial facilities are found there. There is one fire station operating in the east part of the area. Because the area is not inhabited, there is no cause for concern regarding noise pollution.

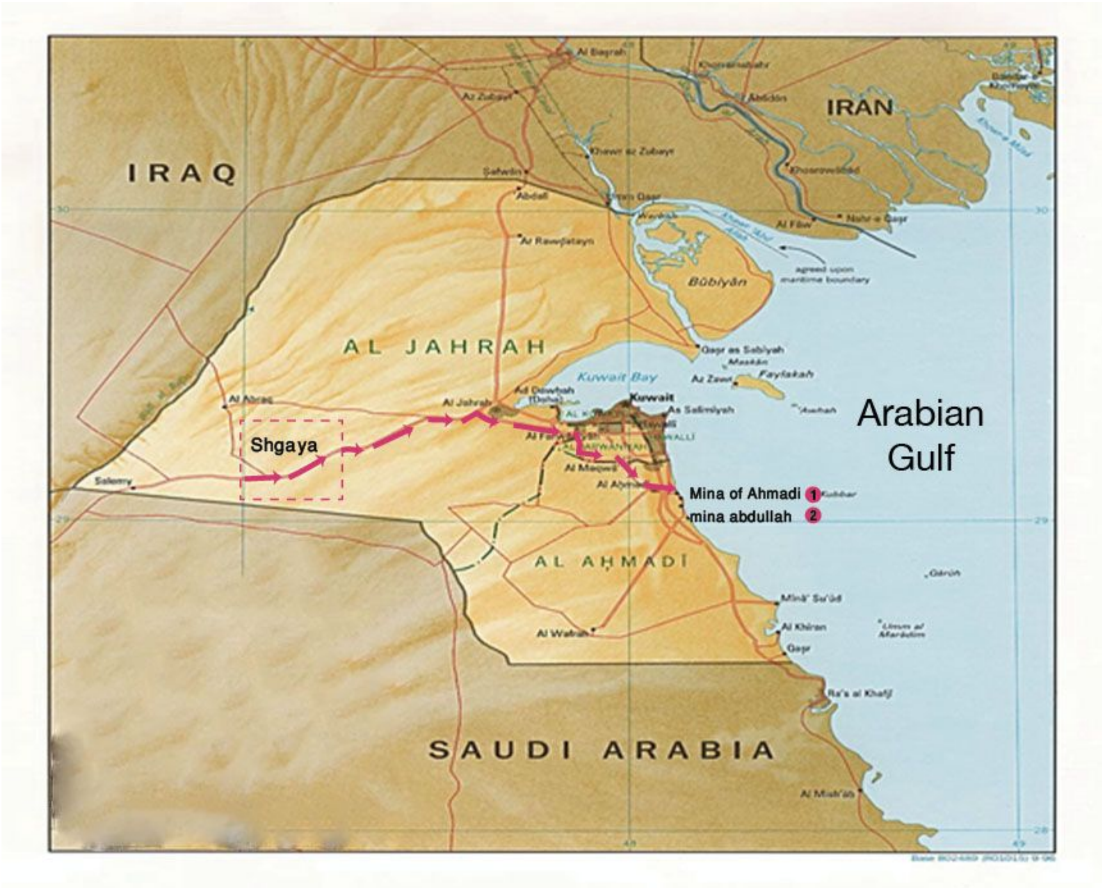


Figure 4.6 Road access to Shagaya modified after (University of Texas Libraries-Perry- Castañeda Library, 1996)

- **Climatic conditions**

The country experiences a mostly desert climate, with significant differences in daily temperature. According to the Kuwait Meteorological Department (KMD), temperatures vary from approximately 13°C in January, to 45 °C in July. Sand and dust is carried with the wind, which might affect rotor blades, and generator cooling is expected to decrease with increasing height above ground. Hence, the provided hub heights of around 100m will reduce these effects. Furthermore, all components, the nacelle and the tower entrance should be well sealed.

Based on the above and from the area resource analysis as well as the visit made by the researcher, it has been concluded that Shagaya will be the preferred site for wind farm development.

4.2 Wind Data

In Kuwait, four main agencies are carrying out instrument measurements of environmental and wind data in 40 locations.

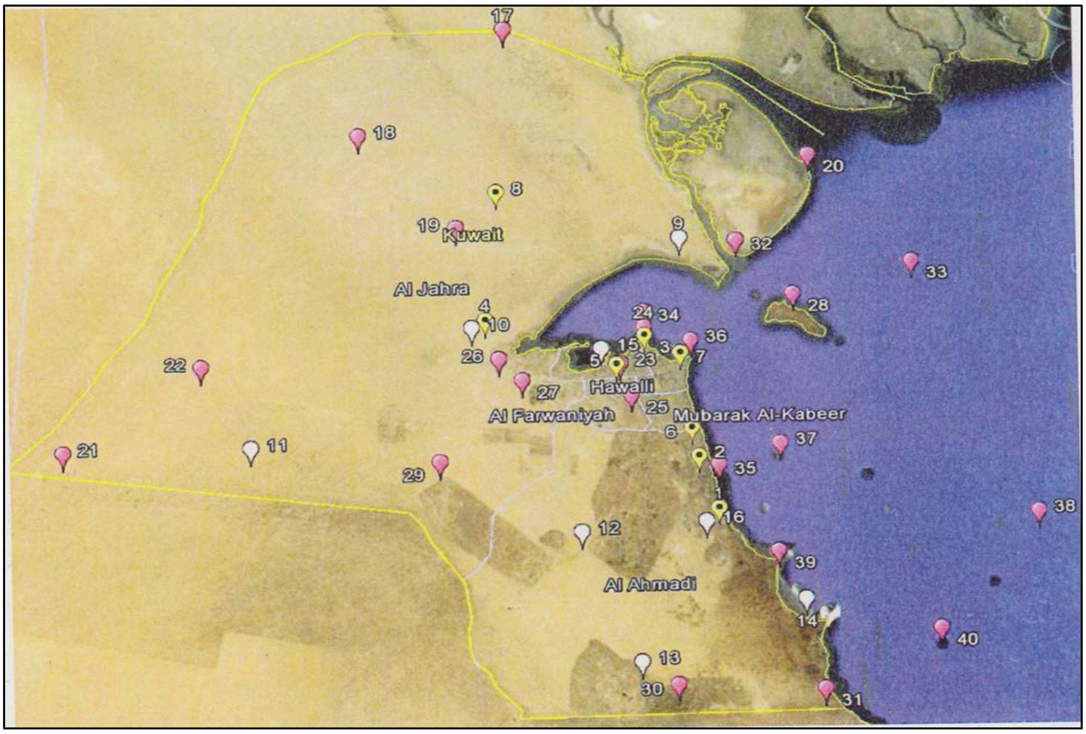


Figure 4.7 Spatial spread of anemometer stations managed by KEPA (stations 1 to 8), KISR (stations 9 to 16) and DGCA (stations 17 to 40)(KISR, 2010)

Figure 4.7 shows a spatial distribution of anemometer stations managed by:

- Kuwait Meteorological Department
- Directorate General of Civil Aviation (DGCA)
- Kuwait Institute for Scientific Research (KISR)
- Kuwait Environmental Public Authority (KEPA)

There is a small variation in potential wind speed from one location to another as the distance between instrument locations is approximately 30 Km.

Investigations must be performed according to the feasibility of the renewable energy technology approach by the researcher. KISR located an instrument to measure the wind speed in Shagaya at different heights: 100, 97.8, 80, 60 and 40 metres.

Table 4.3 shows that the annual average wind speed at different heights was found by the researcher from the wind speed readings for 2013 and 2014. The annual average wind speed at 100 m is considered because it is the closest height to that of the 100m

G90-2MW Gamesa wind turbine. Therefore, the annual average wind speed at 100 m 2013 and 2014 are 8.5 m/s and 8.0 m/s respectively.

Table 4.3 The annual average wind speed in Shagaya at different heights

Height(m)	2013	2014
Annual average wind speed(m/s)		
40	7.4	6.9
60	7.9	7.4
80	8.3	7.8
97.8	8.5	8.0
100	8.6	8.1

KISR has eight stations that measure the monthly, seasonal, and annual variations in wind speed, direction and height in the state of Kuwait. The average hourly wind speed in most major directions is stored in their databank. Data collected by KISR follows the international standard for measuring wind data. The wind speed map of Kuwait at 100 m above the ground level indicates areas of increased potential wind as shown previous in (Figure 4.3).

4.3 Selection of suitable wind turbine system

The selection of adequate wind turbine generator (WTG) technology is based on its technical, economic and environmental impact. Combination of technical and environmental impact has been presented for reasons of simplicity, and to reach the ideal design which will be presented in the following sections.

From the above it is clear that the literature review identified five factors that must be considered in the selection of wind turbines for Shagaya. These factors are as follows:

4.3.1 Operation Temperature (OT)

The typical range of temperature in Kuwait over the year is between 13°C to 45°C, and is rarely below 3°C or above 50°C (Kuwait Meteorological Department). Wind turbine generator operational temperature should not exceed 50°C degrees, if so; a cooling system must be implemented at additional cost. Two turbine manufacturers (Vestas and Nordex), having experience in desert turbines from sites in Egypt, have been selected for energy and economic estimations (El Kawy Saleh, 2003).

4.3.2 System Regulation (SR)

There are two main broad power regulation systems: pitch regulation, and stall regulation. Khalfallah and Koliub (2007) stated that dust affected the model with stall-power regulation more than the pitch-power model; therefore, in dusty areas such as Kuwait, pitch-power regulation is more efficient.

To control the power output from the rotor blades, “pitch control” and “stall control” methods are used. Pitch control is the most common method, whereby the angle of the rotor blades is actively adjusted by the control system. This system has built-in braking, as the blades become stationary when they are fully ‘feathered’, whereas the stall control method involves the inherent aerodynamic properties of the blade determining power output (IRENA, 2012).

4.3.3 International Electro-technical Commission (IEC) Wind Class

Katsigiannis and Stavrakakis (2014) considered that wind turbine class is a significant factor that should be taken into account during the planning phase of wind farm design. According to the International Electrotechnical Commission IEC (2005), there are four wind turbine (WT) classes at the chosen hub height as shown in Table 4.4. In Kuwait, the average annual wind speed ranges from 3.7 to 5.5 m/s, and the mean wind power density ranges from 80 to 167 W/m^2 at a standard height of 10 m (Al-Nassar et al., 2005). Kuwait can be within the fourth category class (IV), which is not available at market and not provided by manufacturers. Watson (2015) previously is a head of the Wind and Water Power Research Team in the Centre for Renewable Energy Systems Technology (CREST), stated that a Class III wind turbine is more rigid than a Class IV by virtue of its higher technical specifications. Katsigiannis and Stavrakakis (2014) considered wind turbine class to be a significant factor that should be taken into account during the planning phase of wind farm design. The International Electrotechnical Commission (IEC) defined classes of average annual wind speed at wind turbine hub height as shown in Table 4.4. For accuracy, the average annual wind speed for the chosen site in Kuwait must be measured at the chosen hub height.

Table 4.4 Basic wind parameters at rotor hub height for wind turbine type classes (Hau, 2006)

WT Classes	I	II	III	IV	S
v_{ref} (m/s)	50	42.5	37.5	30	Values to be specified by the designer
$\bar{v}_w$ (m/s)	10	8.5	7.5	6.0	
v_{G50}=1.4$_{verf}$	70	59.5	52.5	42	
v_{G1}=1.05$_{vG50}$	52.5	44.6	39.4	31.5	
A I_{15} α	 0.18 2	 0.18 2	 0.18 2	 0.18 2	
B I_{15} α	 0.16 3	 0.16 3	 0.16 3	 0.16 3	

There are four different classes of wind conditions, known as "wind turbine generator system classes" (WTGS Classes), which are defined by IEC64100-1. From the above table, v_{ref} is considered to be the annual wind speed in metres per second which is expected only once in 50 years and is measured over a ten minute period at hub height, and v_w is the one year annual wind speed in metres per second, also measured over a ten minute period at hub height,

The two categories A and B represent wind turbulence. Parameter α is the standard deviation of the longitudinal wind velocity change in the 10 minute mean values, and class S is for special site conditions which must be specified by the designer and also be agreed upon individually with the licencing authorities (Hau, 2006).

4.3.4 The size of the wind turbine depends on the rated power

Bansal et al. (2002) mentioned that the main criterion in selecting the size of the wind turbine is the availability of a commercial generator. In addition, it has been observed from reviewing the manufacturers of wind turbines that they tend to design megawatt sizes, which lead to limitations in the availability of small sizes of less than 1000 kW. From the literature review, it can be seen that wind speeds are higher at increasing levels above ground. For that reason, higher towers can explore regions of higher wind speeds and less turbulence. The Authority for Electricity Regulation, (2008) in Oman has recommended the utilisation of a 2MW wind turbine with a minimum hub height of 80 m and a rotor diameter of 90 m in Oman and Gulf Council Countries (GCC), in accordance with the information provided by (Watson, 2015), who confirmed the typical size of wind turbine is 2MW Therefore, Shagaya site towers should be in the range of 90-100 m, based on wind data at different hub heights. Thus a 2MW wind turbine with a 90m tower will be chosen.

4.3.5 Onshore Horizontal Axis Wind Turbine (HAWT)

It is clear from the literature review that horizontal axis wind turbines are more efficient, more widely recommended, and available from most manufacturers.

The wind turbine plays the most important part in the production of wind energy. Parameters which will potentially be included in the model analyses are wind turbine tower and blade materials, lifetime, concept, rated speed, rotor speed, rotor diameter, hub height, swept area of blades, and operation temperature. Appendix B shows the list of contacted companies. Emails sent to the top ten wind turbine manufacturers in the global market in 2013 and 2015 which are presented in Table 2.2. Some manufacturers did not respond, whereas others advised to look at the wind turbine models brochure, which is not sufficient to obtain the data requested (see Appendix C).

In accordance with the above factors, the data for wind turbine models produced by the top ten manufacturers (Appendix D) has been analysed to determine the best fit for Kuwait. Table 4.5 shows how the choice of wind turbines has been narrowed by an examination of the above selection criteria for the top ten manufacturers.

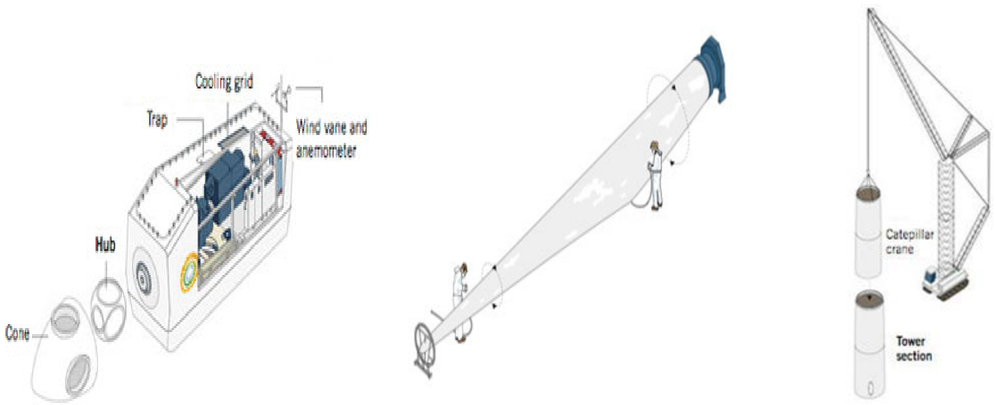
Table 4.5 The chosen wind turbine generators

Manufacturer name	Model name
Vestas	V100-1.8
	V110-2.0
Gold wind	GW82
	GW109
	GW121
Enercon	E48/800
	E82E2/2000
Suzlon	S9x suite-2.1
GE	GE1.7/100
	GE1.7/103
Gamesa	G90
	G97
	G114-2.0
Nordex	N117-2.4

Al-Qattan (2016) is ultimately, any future implementation of a wind turbine scheme in Kuwait will rely on his backing, in addition to that of other government officials. He has stated that the Gamesa G97 would never be accepted in Kuwait, as it is new on the market and has little experience in the field (no more than 5 years). Based on this discussion, it was decided that this type of turbine would not be investigated further in this research.

In accordance with the above, the choice was made to study Gamesa models, but exclude the G97. Gamesa G90-2MW designs and manufactures its own major wind turbine components, such as the nacelle, blades, and tower, which are shown in Figure 4.9 a, b and c respectively. This industrial capacity allows for the comprehensive control of the production process of the wind turbines. Figure 4.9 shows the main components of the Gamesa G90-2MW wind turbine.

The nacelle assembly is placed within the lower housing, and the power transformer and main gearbox subset are assembled. Typically, nacelles are made from glass and /or fibre composites. The blades Gamesa uses on its wind turbines are based on its own design and manufacturing process and involve the application of the latest technology, such as the use of carbon fibre components. The cylinders forming the wind turbine tower are made from plated sheets that are flame-cut and primed. The rings are submerged arc-welded, forming sections of different lengths. Depending on the model and the required height (between 14 and 29 metres), each tower may be made up of between 4 and 12 rings.

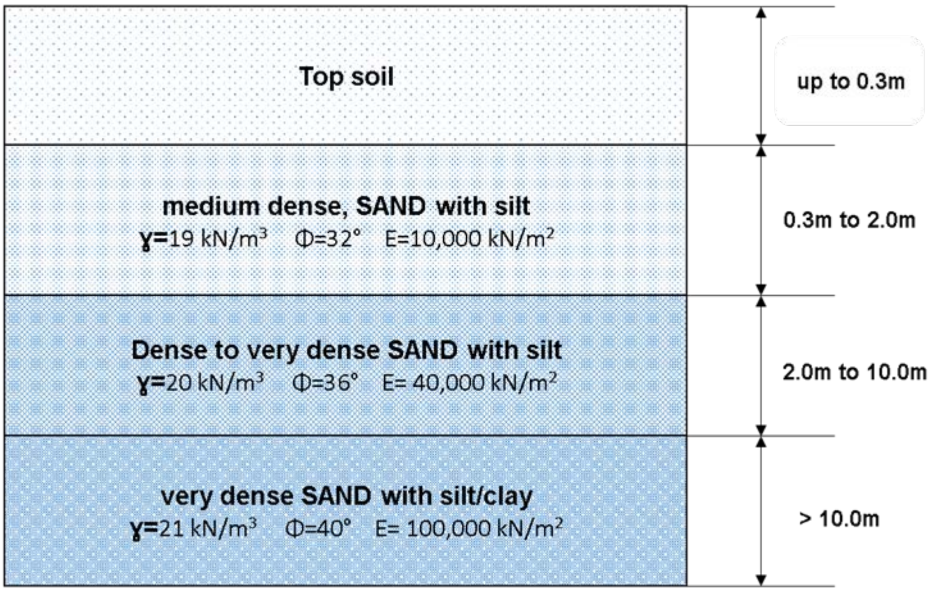


(a): Nacelle (b): Blades (c): Tower

Figure 4.8 Gamesa nacelle, blades and tower (Gamesa, 2015)

4.4 Soil Properties Data

Soil in Kuwait is characterised as a sandy soil with little organic material and a high amount of calcareous materials (Mahdi and Majda, 2002). Soil investigation by KISR measures soil density, Poisson's ratio, yield strength and Young's modulus, elastic modulus and dynamic shear modulus. Geotechnical investigation explores the subsurface conditions, performs laboratory tests on selected samples, and evaluates field and laboratory test data to develop soil parameters necessary for the design of foundations for the proposed site. According to KISR, field and lab tests have been carried out in the site investigation. Figure 4.10 shows the soil profile and the general site characteristics.



Where, γ is the bulk unit weight of soil (kN/m^3)

, Φ is angle of internal friction, and

E average modulus of elasticity (kN/m^2)

Figure 4.9 Schematic representation of the boundary conditions applied to the soil

4.5 Foundation Properties Data

In order to guarantee the stability of a wind turbine, an appropriate foundation should be provided, depending on the consistency of the underlying ground. The foundation, which is the main part of a wind turbine structure, combines with the tower to transfer the load from the turbine to the soil. A clear understanding of the force-transfer mechanisms, from the foundation to the soil, leads to increased confidence in the overall design (Byrne and Houlsby, 2003).

Kellezi and Hansen (2003) identified that basic three types of foundations applied to different wind turbines. The types of foundations are gravity based, skirted and piled foundations. The commonly used foundation is the pile foundation to support the wind turbines.

For onshore wind turbines, the foundation is the same as the typical foundation for building and bridge designs. Burton et al. (2011) stated that onshore wind turbines use three main types of foundations Gravity (slab), multi-pile and mono-pile foundations. The geometry of a gravity foundation is normally cylindrical or a square prism and the construction material is totally reinforced concrete. Smaller pressure with a larger area means that ground pressure doesn't exceed the maximum allowed pressure for the soil; to prevent the tower from turning over, the width of the plate must be sufficient. This foundation is mostly used on friction soils with high frictional angle, or other types of soils with a low modulus of elasticity and/or strength. The thickness of the foundation is an essential parameter of the shear strength, gravity foundation. The filling soil above the foundation prevents the tower from turning over, and the area of the plate can be reduced. This type of foundation has the advantage of reducing the amount of concrete, but requires major excavation and refilling work. A mono-pile foundation is considered to be a good solution to install piles to apply load at a greater depth in the ground with better soil if the soil properties are not sufficient to support the foundation on the ground. In this foundation, piles might be exposed to tensional loads due to the great bending moment from the wind. Generally, the soil along the boundary of the foundation can resist the horizontal forces on the plate. By increasing the height of the foundation and the weight, this could lower the tensional pile loads at the expense of increased compression for other piles. These factors usually result in fairly big plates, even for piled foundations (Svensson, 2010). In this study, pile foundation will be used because they are commonly used in the literature on wind turbine foundation design. (see Figure 4.10)

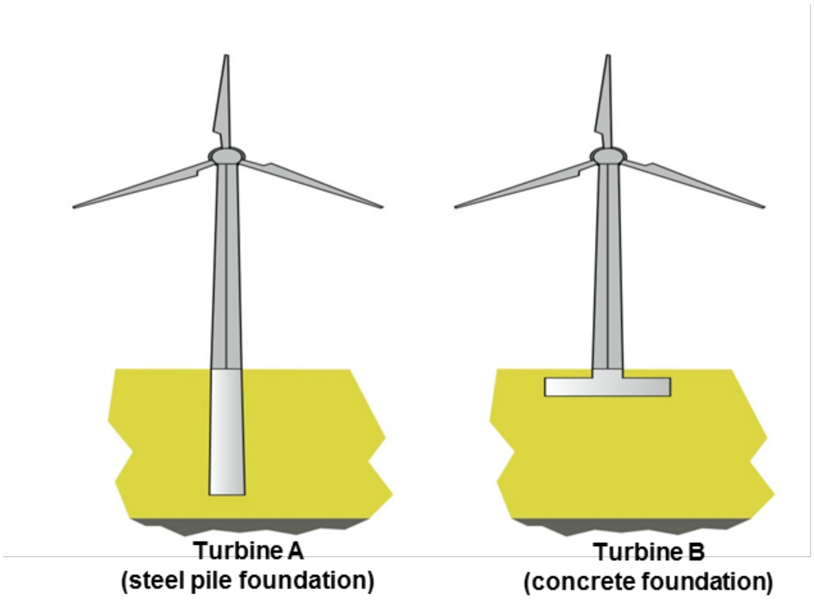


Figure 4.10 Types of foundation for wind turbine system (steel pile and concrete foundation)

Based on geotechnical reports by KISR for the location, the foundation type of wind turbine can be designed. The dimensions of the foundation and other properties such as Young's modulus and Poisson's ratio have been provided.

The type of foundation most suitable for the proposed structure will be dependent on considerations such as structural dimensions, loads, layout, and permissible settlements. Piled foundation will be considered in this study.

4.6 Data acquisition

4.6.1 Levelised Cost of Energy (LCOE)

It is difficult to find out the price of wind turbine generator due to confidential information of the manufacturers of wind turbine generators and because of the largest term of cost in Capex is the turbine price. Therefore, the price was obtained from an economic reports produced by (IRENA, EWEA, NREL, and EIA) as well as in literature review to assume the price. In 2016, the price of the turbine has been obtained from KISR directly after GAMESA wind turbines were obtained and will be described in detail in Section 5.5.2.1.1.

4.6.2 Life Cycle Assessment (LCA)

In order to assess the environmental impact of the entire life cycle of a wind turbine, a life cycle assessment (LCA) is carried out. According to (ISO 14040, 2006; ISO

14044, 2006), a LCA is carried out over four stages with Figure 4.11 illustrating the source of the data used in the inventory analysis:

1. Goal and scope definition (context and purpose of the study).
2. Inventory analysis which needed to collect data of the materials made of wind turbine and foundation and the embodied CO_2 and energy from that material which can be find as stander then calculations to find the output of energy and embodied CO_2 from the material input conducted (collecting all inputs and outputs of materials and energy in all processes and operations along the value chain of the product throughout its life cycle).
3. Impact assessment (evaluating the potential environmental impacts associated with those inputs and outputs).
4. Interpretation of results (evaluating the significance of the potential environmental impact of the system).

In order to get the total cumulative energy in kWh, it is important to calculate the energy MJ per kg for each material, which is defined as the energy required to produce a material from its raw form, per unit mass of material produced Deshmukh and More (2014). Both embodied energy MJ/kg and embodied carbon dioxide $kgCO_2/kg$ are obtained from the Inventory of Carbon and Energy (ICE) at Bath University. This is described by Glass, (2016) as a better and up to date source of CO_2 emissions. Information on the weight of the turbine components and sub-components is obtained from Gamesa. Figure 4.11 illustrates the source of the data used in the inventory analysis.

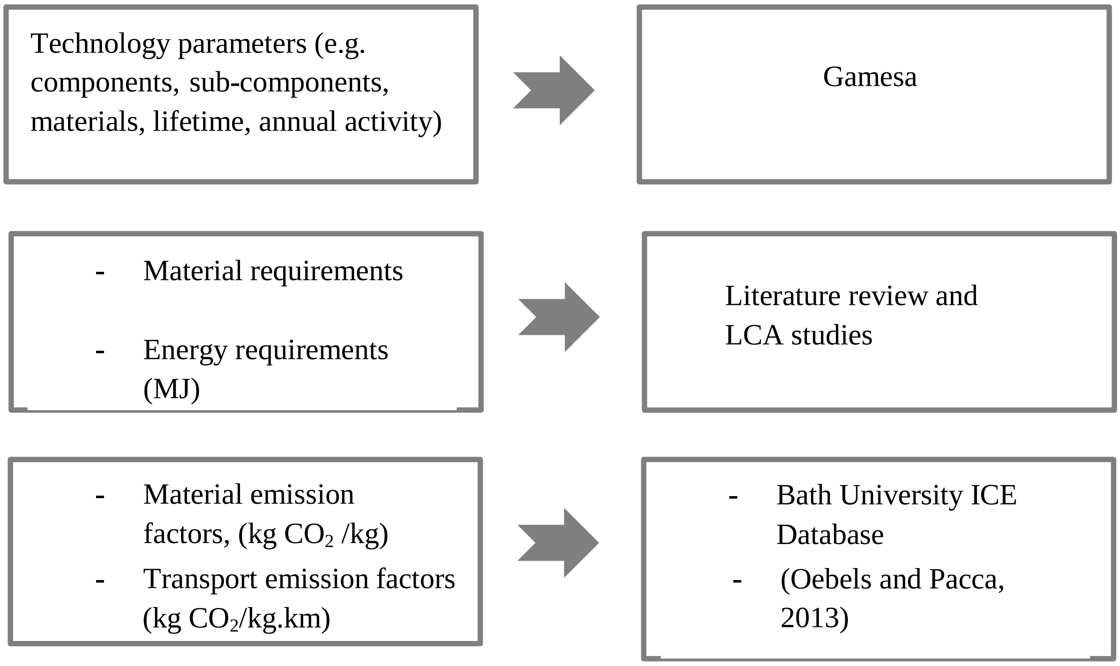


Figure 4.11 Source of data of LCA

4.6.3 Numerical Modelling

This was done to achieve one of the research objectives of assessing the future use of wind turbines within Kuwait, accounting for the various factors affecting their deployability such as strength, integrity. Data which needed to model the wind turbine using COMSOL includes geometry and material properties of the wind turbine tower, pile foundation, soil properties, and loads applied on the wind turbine.

4.6.3.1 Wind Turbine Tower

It can be observed from Appendix E that the ten top companies supply tubular steel towers for wind turbines. (World Steel Association, 2012) reported that the most widely available wind turbine towers in the global market are tubular steel. The base of the tower diameter is different than the top, and the thickness of the steel tower is between 8mm at the top and 65mm at the base. Due to transport limitations, the maximum tower diameter is approximately 4.3m. Conical steel towers are broadly used globally with a base and top diameter of 4.15m and 2.3m respectively. Due to transport restrictions, the diameter of the base of the tower is less than 4.9 m, and the tower must be divided into 3 or 4 pieces (Miceli, 2012). Due to the cost efficiency and time implementation savings of wind turbines, the tubular steel tower is the most common type the world. The conical shape increases strength and also uses less material. The thickness of a steel tower wall weighed around 100t (1MN) and is between 4 to 20 inches (101.6 mm to 508 mm) (www.renewable-energy-concepts.com, 2015). It is common in the literature for the wall tower thickness to be 65mm along the tower length (Lavassas et al., 2003). Rotor and nacelle have been simulated as a combined lumped mass at the top of the tower. Appendix E shows the total weight given in the G90-2.0 specification is 119 tonnes (1.19MN).

4.6.3.2 Loads applied on the wind turbine

There are several types of loading applied to the model, such as wind pressure along the tower length which are based on a Kuwait wind velocity of 8.5 m/sec measured at hub height 100m as stated in section 4.2, thrust from the wind turbine applied at the nacelle, moment about the horizontal axis of the rotor plane applied at the nacelle, and moment about the vertical axis on the rotor plane applied at the nacelle these were developed from guidelines given in (DNV, 2014; EN1991-1-4(2005), 2010) Gravity load was applied to the soil on COMSOL and the structure of both tower and pile as a self-weight.

The wind pressure along the tower length was applied as a varying uniformly distributed load (udl). With the tower height, the more conservative approach of applying the loading as a varying line udl load along the tower height was taken. This study calculated the wind force and calculation of coefficients for Kuwait, such as height of tower, turbulence intensity, and peak velocity pressure (N/m^2) and wind force (KN/m). The final output of the calculation procedure is given in Appendix F. This is in accordance with the guidelines given in (EN1991-1-4(2005), 2010).

4.6.3.3 Soil and Pile Properties

For simplicity, this research has dealt with the tower strength and Kuwaiti soil behaviour. Therefore, preliminary pile design which consists of a 4.3 m diameter and 22 m pile length (Papanastasiou, 2011) has been used as it is commonly used. With regard to the pile, material properties of the pile will be taken as the wind turbine steel tower. For the soil properties, Figure 4.10 in Section 4.5 demonstrates the field and lab works of KISR showing the soil properties and profile in the site investigation.

5 Economic and Financial Analysis

5.1 Introduction

In order to attract investors to renewable energy technologies, two main issues have to be considered: the stability of the mechanism, and the Levelised Cost Of Energy (LCOE) (Abdmouleh, Alammari and Gastli, 2015). This chapter explores the true cost of producing electricity from wind power. Estimating the true cost of wind power is inherently difficult, as a wide variety of factors depend on the assumptions of the cost analyst. Each study includes different factors in its estimate of the cost of wind power. These factors include: capital costs, operation and maintenance costs, and capacity factors. Other factors are more difficult to quantify, but nevertheless add to the true cost of wind power. Such factors include: opportunity cost of taxpayer dollars, reduced reliability of the grid, and higher electricity prices (Simmon, Yonk and Hansen, 2015).

Simmon, Yonk and Hansen (2015) reviewed the true cost of onshore wind energy by examining reports from the (NREL, 2015) and (Lazard, 2014). They stated that the true cost of energy is difficult to establish based on one specific method, and stated that many factors can be included in the calculation of the cost, depending on the main concept of the report which is obvious in Table 5.1 shows the various onshore wind energy costs from different studies.

Table 5.1 Various cost of onshore wind energy priced low to high from different studies (Simmon, Yonk and Hansen, 2015)

	LAZARD	NREL	EIA	HAMILTON	MODIFIED GIBERSON	TANTON/ TAYLOR
Total Cost $/MWh	$59	$72	$80.3	$97	$149	$151

The economic analysis of the wind farm system has been implemented and the key cost components have been taken into consideration in order to optimise the size of the systems. The main aim of this chapter is to find the lowest cost and highest reliability design of a wind energy farm by giving premium value to the initial capital investment, the present value of operation and maintenance costs, the inverter replacement cost, and the wind system replacement cost. With regards to wind power, there is no significant correlation or interdependence of energy cost and initial cost of investment, but it is usually high in comparison to conventional sources. However, the overall costs of renewal of wind farms are going down, thereby suggesting that the pattern of cost reduction is likely to continue to decrease due to the influence of several variables, which include larger and more efficient turbines. One of the key determinants that affect the cost of wind power is the capacity factor (Cp) of the wind power installation; defined as the ratio of the actual energy generated by the turbine (EwT) to the rated energy (Er) shown in Equation 5-1:

$$Cp = \frac{\mathbf{EwT}}{\mathbf{Er}} \qquad \textbf{Equation 5-1}$$

Capacity factor is generally taken to be 30% to a maximum of 40%, while non-renewable and conventional plants vary between 40% and 80%. In the last decade, the cost of generating electricity by wind has decreased by as much as 75%, and the available generation capacity has increased several folds from 100MW to over 30GW. Similarly, in the past decade the price of wind turbines has decreased by 5% each year, while at the same time revenue has increased by 30% (Zervos, A., & Kjaer, 2008).

It could be asserted that an accurate monetary value cannot be assigned to wind farms, as several key variables which influence the value exist, such as the turbines size, and the farm's location, amongst other external factors, such as political considerations, subventions and subsidies granted by public authorities. In order to determine the final cost, feasibility studies and initial capital costs (installation and commissioning) must be taken into consideration prior to arriving at the final price of a new technology. Generally speaking, the main variables that make up the production cost of wind energy are the investment costs of fuel, and operations and maintenance (Morthorst, P.E., Chandler, 2004).

There are considerable challenges that impede the growth of investment in wind energy projects. When a wind farm is to interface with the electricity grid, there is the need to check the following key variables: *power factor, voltage, and the final production of harmonics caused by the turbines*. Furthermore, investment costs are still higher than those of conventional hydrocarbon electricity generating plants, and the presence of wind turbines may threaten bio-diversity, birds, and have a visual and noise impact (Gipe, 1995; Heier, 1998).

With regard to wind energy production, economic optimisation and evaluation of projects in renewable energy, it is also necessary to consider other factors, such as potential exposure from this source in the energy world, especially in regions where wind speeds are expressive. In parts of the world where wind speeds are low, factors such as wind energy production and economic optimisation are key determinants in the evaluation of renewable energy projects.

Given that the energy output of a wind farm is majorly influenced by wind speed, variability significantly affects financial investments and operations and maintenance costs. It is therefore of immense importance to develop alternative assessment methodologies for economic, financial evaluation and management of energy projects, considering the uncertainties associated with this type of technology (EWEA, 2009).

Wind energy markets have unique characteristics that must be taken into consideration and receive inflows of significant public sector interventions, such as production tax credits (PTCs), modified accelerated cost recovery systems (MACRS), and others financial support which invariably distorts the market in comparison to other renewable energy technologies. Furthermore, given the exponential growth of the industry in recent years and the projection of the growth and penetration of the industry in the coming years, it would become imperative to have in place engineering and economic optimisation (Oliveira and Fernandes, 2012).

As mentioned in section 2.2, different types of renewable energy have been discussed and found to be unavailable or unfavourable in Kuwait. Solar energy is more expensive than wind energy and requires a large amount of land. Table 5.2 shows the cost comparison between solar and wind based on levelised cost of energy.

Table 5.2 Comparison of solar and wind energy based on levelised cost of energy for different countries

(PV)Solar energy LCOE(cost/kWh)	(CSP)concentrated solar energy LCOE(cost/kWh)	Wind energy LCOE(cost/kWh)	Country	Reference
-	-	$0.05/£0.029/15fils to $0.08 /£0.047/24fils	Oman	(Albadi et al., 2009)
$0.17/£0.13/50fils	-	-	Kuwait	(Ramadhan and Naseeb, 2011)
$0.27/£0.2/80fils	-	-	GCC	(Alnaser and Alnaser, 2011)
$0.2/£0.15/60fils	-	-	Oman	(Al-Badi, Malik and Gastli, 2011)
$0.33/£0.25/100 fils (0.289 Euro/kWh)	-	-	Germany	(Fraunhofer ISE, 2013)
-	-	$0.0668/£0.05/20fils	Oman	(Shawon, El Chaar and Lamont, 2013b)
		$0.0702/£0.05/20fils	Kuwait	
		$0.0801/£0.06/20fils	Jordan	
		$0.0980/£0.07/30fils	Qatar	
		$0.0824/£0.06/20fils	Bahrain	
		$0.0847/£0.06/30fils	Syria	
$0.11 to $0.48/ £0.08 to £0.36/ 30 to 150fils	-	$0.06 to 0.14/ £0.05 to £0.11/ 20 to 40fils	MENA countries. Middle East and North Africa	(El-katiri, 2014)
$0.08to $0.4/ £0.06 to £0.3/ 20fils to 120fils	-	$0.05 to $0.15/ £0.04 to £0.11 20fils to 50fils	global	(IRENA, 2015)
-	$0.275/£0.21/80fils	$0.083 /£0.06/30fils	global	(FS-UNEP, 2016)
$0.0585/£0.04/20fils	-	-	UAE	(IRENA, 2016)
US$ 3.60 c/kWh -	-	- US$ 3.0 c/kWh	Mexico Morocco	(Liebreich, 2017)

Onshore wind costs continue to decline, the average LCOE for wind ranged from a low of £0.05/kWh in China and Asia to a high of ($0.09/kWh/£ 0.07/kWh/0.03KD) per kWh in Africa. North America also has very competitive wind projects, with average LCOE of ($0.07/kWh/ £0.05/kWh /0.02 KD/kWh) due to excellent resources and a good cost structure. For hydropower, the estimated average LCOE by region varies between ($0.04/kWh/ £ 0.03/kWh/ 0.01KD/kWh) in Asia and South America to a high of (£0.09/kWh/ 0.04KD/kWh) in Oceania (IRENA, 2015).

5.2 Wind Energy System Cost Breakdown

In order to perform the economic analysis it is important to understand the cost structure of a wind farm. Figure 5.1 shows the structure of wind turbine cost, which can be broken down into two main components: Capital Expenditures (CapEx), such as wind turbine price, civil works, and construction and grid connection; and Operation Expenditures (OpEx), such as insurance, regular maintenance, repair, spare parts, and administration.

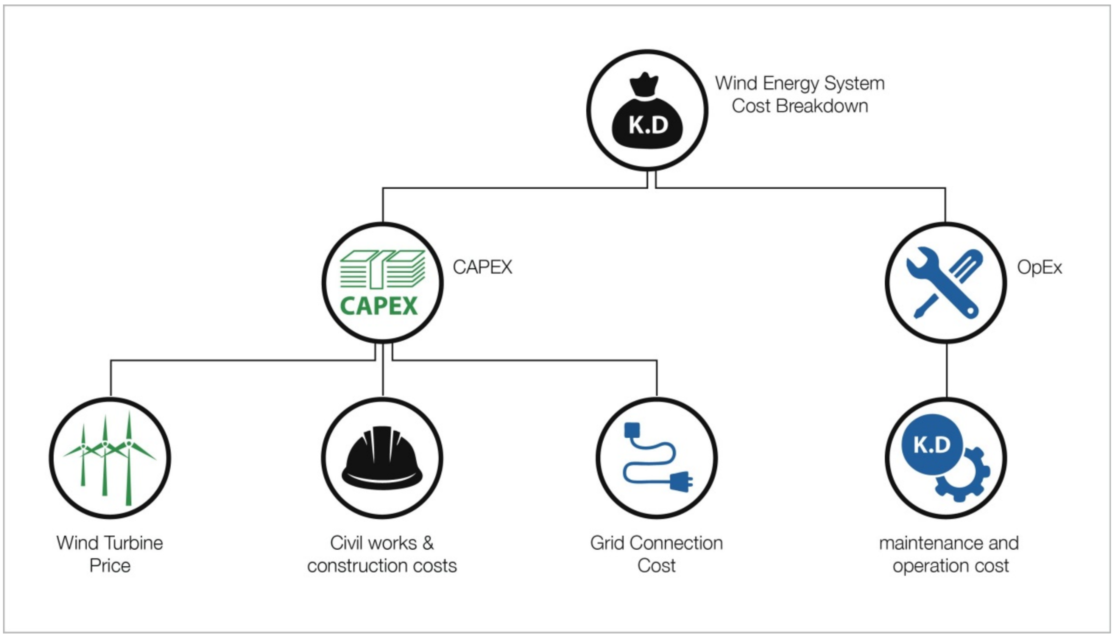


Figure 5.1 Breakdown of wind energy system cost components

Figure 5.2 shows the whole process of economic analysis of wind farms, including wind turbine installation and the resulting cost of energy per kWh:

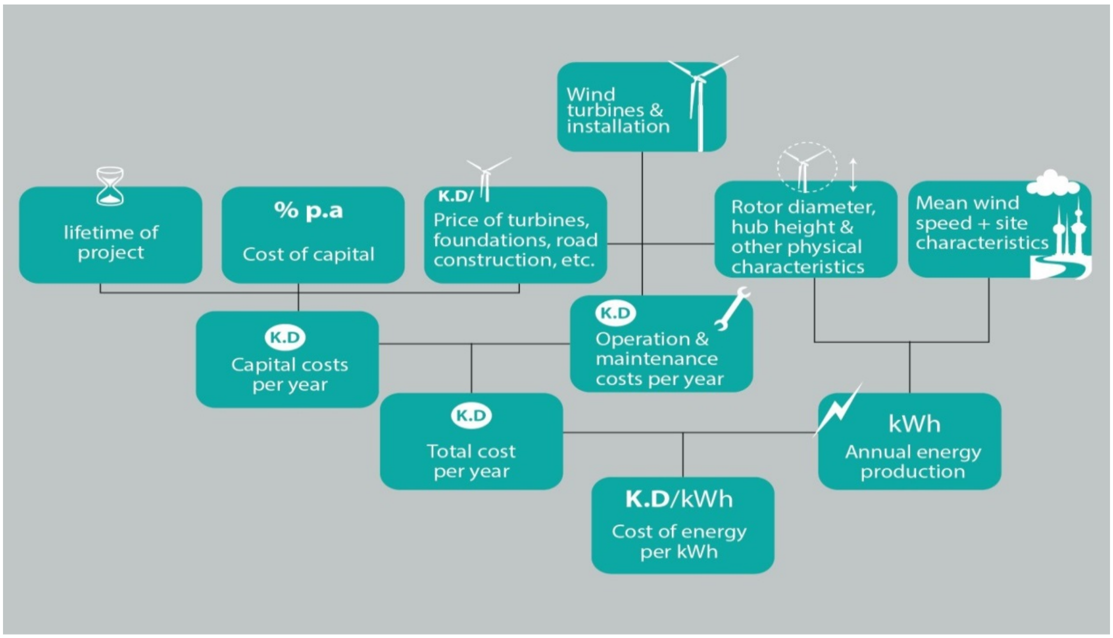


Figure 5.2 The cost of wind energy modified after (EWEA, 2009)

The International Renewable Energy Agency IRENA, 2012 represented the key findings of the cost of wind farm components as: initialled cost, capacity factor, operation and maintenance, and Levelised Cost of Energy (LCOE) in different regions shown in Table 5.3. As shown in section 3.2.3 the LCOE formula is:

$$LCOE = \frac{(\text{CapEx} \times \text{FCR}) + \text{OpEx}}{(AEPnet/1{,}000)} \quad \text{Equation 5-2}$$

Table 5.3 Typical new onshore wind farm costs and performance in 2010 (IRENA, 2012)

	Initialled cost **$/kWh/£/kWh/ KD/kWh**	**Capacity factor (%)**	**Operation and maintenance $/kWh/£/kWh/fils/kWh**	**LCOE $/kWh/£/kWh/fils/ kWh**
China/India	1300 to 1450 981 to 1094 393 to 438	20 to 30	N.A.	0.06 to 0.11 0.05 to 0.08 20 to 30
Europe	1850 to 2100 1396 to 1585 559 to 634	25 to 30	0.013 to 0.025 0.01 to 0.02 10	0.08 to 0.14 0.06 to 0.11 20 to 40
North America	2000 to 2200 1509 to 1660 604 to 656	30 to 45	0.005 to 0.015 0.01 10	0.07 to 0.11 0.05 to 0.8 20 to 30

5.2.1 The Installed Capital Cost of Wind Energy (CapEx)

Installed capital outlay, often referred to as CapEx (Capital Expenditure), for the wind turbines (including towers and installation) can be represented as between 64% as in, Figure 5.3 to as much as 84% of the total installed costs, with grid connection, civil works and other costs accounting for the rest (Blanco, 2009). Whereas, according to (EWEA, 2009), about 75% of the capital cost of the wind energy system is the cost of the wind turbine generator (blades, tower), transportation and installation. Table 5.4 shows the price structure of a typical 2 MW wind turbine in Europe in 2006. In comparison to similar renewable energies, the initial cost acts as a disincentive, even though it does not face problems related to availability and supply of fuel once it has been installed and commissioned. The capital costs of a wind power project can be broken down into the following major categories:

i. Cost of the turbine, which consists of blades, tower and transformer
ii. Construction costs for site preparation and the foundations for the towers;
iii. Cost of interface to the grid; this can include transformers and sub-stations, in addition to the connection to the local distribution or transmission network
iv. Other capital costs: such as construction of site access, control and instrumentation, etc.

Table 5.4 Cost structure of a typical 2 MW wind turbine installed in Europe (2006) (EWEA, 2009)

	INVESTMENT (€1,000/MW/£1,000/MW/KD1,000/MW)	SHARE OF TOTAL COST %
Turbine	928 /824/330	75.6
Grid connection	109 8.9/975.47/390.55	8.9
Steel pile foundation	80 6.5/715.91/286.63	6.5
Land rent	48 3.9/429.55/171.98	3.9
Electric installation	18 1.5/161.11/64.50	1.5
Consultancy	15 1.2/134.22/53.74	1.2
Financial costs	15 1.2/134.22/53.74	1.2
Road construction	11 0.9/98.44/39.41	0.9
Control systems	4 0.3/35.77/14.32	0.3
Total	1227/1089.18/436.07	100%

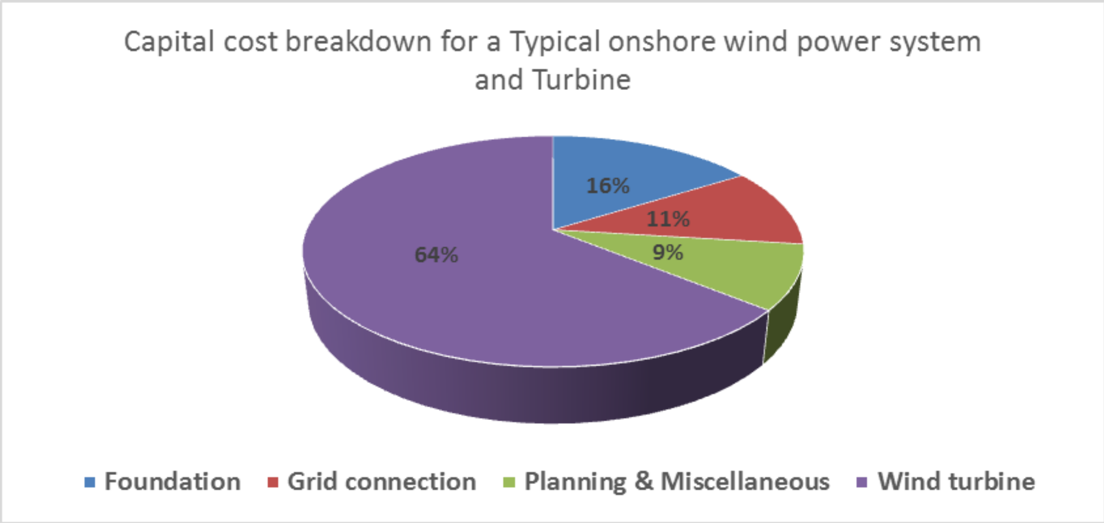


Figure 5.3 Breakdown of capital costs for a typical onshore wind farm and turbine (IRENA, 2012)

5.2.1.1 Cost of the Wind Turbine

The quoted prices for wind turbines in recent transactions in developed countries are in the range of ($1,100 to $1,400 / £831 to £1507 / 583KD to 742KD) per kW (Bloomberg NEF, 2011). This reduction could be attributed to increased competition among wind turbine manufacturers, as well as lower commodity prices for the key inputs of cement, steel and copper.

The turbine is the single most expensive item of a wind farm. In recent years, wind turbine prices have been on the increase, and reached their peak in 2009. The price of turbines has gone up from a figure of ($700 to $1,800 / £529 to £1359 / 211.5 KD/ to 544 KD) per kW within a decade. At its peak of ($1,800/ £1359/ 544KD) per kW for contracts with a 2009 delivery, wind turbine prices in Europe have fallen by about one fifth for contracts for delivery and commissioning scheduled in the first half of 2010. Global turbine contracts for delivery at the end of second quarter of 2010 and the second quarter of 2011 have averaged ($ 1,470/ £1110/ 444KD) per kW, down by about one tenth from peak values of US$ 1,730/kW. In the US market, prices of turbines have gone up more than two fold from a figure of around ($700/ £529/211.5 KD) per kW between 2000 and 2002, to ($1,500/ £1133 / 453KD) per kW about a decade later in 2008 and 2009 (Bloomberg NEF, 2011). Since then, turbine prices have dropped by 30% to 40%, initial estimations indicate that prices have reached between ($950 and $1,240/£ 717 and £936 / KD 287 and KD 375) per kW in 2016 (World Energy Council, 2016).

The US and Portugal appear to have the lowest prices for wind turbines. The reasons for this could be explained by the impact of lower wages and general manufacturing costs in some countries, and the degree of competition in a specific market, the bargaining power of market actors, the nature and structure of support policies for wind energy, as well as site specific factors. Furthermore, China could now be described as the most important wind market, yet it witnessed the highest reduction and had the lowest absolute wind turbine prices in 2010, at ($ 644/ £486/ 195KD)/kW. US turbine costs declined by 15% between 2008 and 2010, and data obtained in the first quarter of 2011 indicated a drop of 17%, which could translate into a full year reduction for 2001 of 20% to 25% compared to the highest figure seen in 2008 (EWEA, 2009). However, Chinese wind turbines fell by 37% from 2007 to 2016 (World Energy Council, 2016).

5.2.1.2 Civil Works and Construction Costs

This includes construction costs for site preparation and the foundations for the towers. Onshore wind farms generally have a poured concrete foundation. By contrast, offshore versions have driven/drilled steel monopiles. There are other types of foundation (e.g. suction, caisson, guyed towers, floating foundations, and self-installing concepts using telescopic towers) which would be deployed for offshore developments in deep water. Laying of foundations is capital intensive, with 45% to 50% of the cost of monopile foundations being directly linked to the steel required (Junginger, Faaij and Turkenburg, 2004). There would however be reductions in costs for foundations that can be made through economies of scale, reduced material consumption, and reduced material cost. Civil work cost is deferent in different region. Typical civil works can vary between 8% and 16% of total installed costs (IRENA, 2015). The levelized costs are affected by regional variations in construction labour rates and capital costs as well as material of construction availability (EIA, 2017).

5.2.1.3 Grid Connection Cost

It is feasible to interface wind farms with the transmission network or distribution network; transformers will be needed in order to step-up to the superior and higher voltages unlike if the wind farm were connected directly to the distribution network, and doing so would increase the cost.

In instances where a wind farm is in close proximity, the interface is typically a high voltage alternating current (HVAC) connection. By contrast, where the distances are relatively longer, a high voltage direct current (HVDC) link is used, as the reduced losses over this link will more than offset the losses in converting to direct current and back again to alternating current. It has been suggested that HVDC connections will be most appropriate for distances in excess of 50 km in the future (Douglas-Westwood, 2010).

There are significant disparities amongst countries in grid connection cost. In some instances the operator of the transmission system incurs the cost associated with the transmission system upgrade that is needed to connect to the wind farm; while in contrast, in some countries the wind farm owner is expected to pay for these costs.

Electricity and water utility are a state-owned and operated by the Ministry of Electricity and Water (MEW). MEW is responsible for producing, transmitting and distributing electricity and water in Kuwait. Low electricity tariff in Kuwait, which is subsidized the basis of a cost accounting approach and do not reflect the true cost incurred in generating, transmitting and distributing. Whereas, the production cost of electricity is ($0.073/£0.054/22fils)/kWh, the electricity tariff is ($0.016/£0.012/5fils) /kWh (Alray, 2017).

According to Douglas-Westwood (2010), grid connection costs (including electrical work, electricity lines, and the connection point) generally tend to be in the region of 11% to 14% of the total capital cost of onshore wind farms, and 15% to 30% of offshore wind farms. Table 5.5 illustrates a comparison breakdown of capital costs for typical onshore and offshore wind farms in European and North American countries in 2011.

Table 5.5 Comparison breakdown of capital cost for typical onshore and offshore wind farms in European and North American countries 2011 (IRENA, 2012)

	Onshore	**Offshore**
Capital investment costs (USD/kW)	1700-2450	3 300-5 000
Wind turbine cost share (%)[1]	65-84	30-50
Grid connection cost share (%)[2]	9-14	15-30
Connection cost share (%)[3]	4-16	15-25
Other capital cost share (%)[4]	4-16	8-30

1- Wind turbine costs include turbine production, transportation, and installation of the turbine.

2- Grid connection costs include cabling, substations, and buildings.

3- The construction costs include transportation and installation of wind turbines and towers, construction of wind turbine foundations (tower), and building roads and other related infrastructure required for installation of wind turbines.

4- Other capital costs here include development and engineering costs, licensing procedures, consultancy and permits, SCADA (Supervisory, Control and Data Acquisition), and monitoring systems.

5.2.2 Operations and Maintenance Costs (OpEx)

Another important factor that is essential to consider for wind energy, is the fact that operations and maintenance (O&M) costs are not uniformly spread over time. There is a tendency for these costs to increase as the duration of time from completion increases. This increase can be due to an increasing probability of component failures, and that when a failure does occur it will tend to be outside the manufacturer's warranty period. Wind turbines require operation and regular maintenance. The cost of wind power system maintenance and operation (O&M) is competitive compared to other power systems.

As shown in Table 5.6 O&M costs are considered to be fixed and variable. Fixed O&M costs typically include insurance, handling, and fixed grid access fees and service contracts for scheduled maintenance, whereas variable O&M costs typically comprise of scheduled and unscheduled maintenance not captured by fixed contracts, as well as replacement parts and materials and other labour costs.

In comparison with other countries, O&M costs appear to be the lowest in the US, at around ($10/MWh/ £7.5/kWh/ 3KD/MWh), this could perhaps be explained by the size and penetration of the market and the long experience with wind power in the

US. Other markets like those in Europe tend to have higher cost structures for operations and maintenance for onshore wind projects.

Operations and maintenance costs for offshore wind farms are generally higher in comparison to onshore wind farms given the higher costs incurred in accessing and conducting maintenance on the wind turbines, cabling and towers. Maintenance costs are also higher as a result of the harsh marine environment and the higher expected failure rate for some components. Overall, operations and maintenance costs are expected to be in the range of ($27 to $54 / £20 to £41 / 8KD to 16.4KD)/MWh (ECN, 2011).

The European Wind Energy Association EWEA (2009) presented that the cost of O&M in Germany, Spain, the UK and Denmark was estimated to be around (€0.012 to €0.015/ £0.01)/kWh of wind power produced over the total lifetime of a turbine. In addition, (IRENA, 2012) stated that for onshore wind farms in major wind markets, the cost of O&M is in the region of ($0.01/ £0.01)/kWh and ($0.025 / £0.02 / £0.01)/kWh, which are very similar values.

Table 5.6 Operation and maintenance costs for onshore wind projects (IEA, 2013a)(IEA Wind, 2011)

	Variable (USD/kWh £/kWh KD/kWh)	**Fixed (USD/kW/year £/kW/year KD/kWh/year)**
Austria	0.038/ 0.03/ 0.01	-
Denmark	(0.0144 to 0.018)/ 0.01/ 0.01	-
Finland	-	(35 to 38)/ (26.77 to 29.06)/ (10.57 to 11.5)
Germany	-	64/ 48.95/ 19
Italy	-	47/ 35.94/ 14
Japan	-	71/ 54.30/ 21.45
The Netherlands	(0.013 to 0.017)/ 0.01/ 0.01	35/ 26.77/ 10.57
Norway	(0.020 to 0.037)/ 0.02/ 0.01	-
Spain	0.027/ 0.02/ 0.01	-
Sweden	(0.010 to 0.033)/ (0.01 to .03)/ 0.01	-
Switzerland	0.043/ 0.03/ 0.01	-
United States	0.01/ 0.01/ 0.01	-

Wind turbines, like any other industrial equipment, require service and maintenance (known as operation and maintenance). However, compared to most other power generating costs, they are very low. Operational expenses are generally expressed in two categories:

(1) Fixed operation costs, which include discrete, known operations costs (e.g., regular maintenance, rent, land lease costs, taxes, utilities, and insurance payments) are typically do not change, and are dependent on how much electricity is generated, but it is possible to obtain standard contracts covering a considerable share of the wind turbine's total lifetime

(2) Variable operation expenses, which include unplanned maintenance of either the plant or turbine, planned turbine maintenance, and costs for repair and related spare parts are much more difficult to predict. O&M cost components tend to increase as the turbine gets older; costs for repair and spare parts are particularly influenced by turbine age, starting low and increasing over time (NREL, 2015; EWEA, 2009).

Given that the industry is relatively immature, there are a limited number of turbines that have reached their life expectancy of 20 years of continuous operation. These turbines have smaller capacity than those currently available on the market; furthermore, the design standards were more conservative in the beginning of industrial development, although less stringent than they are today. Operation and maintenance cost estimates are yet to be ascertained, particularly around the end of a turbine's productive lifetime. Nevertheless, some experience can be drawn from existing turbines in operation. Data obtained from Spain indicates that less than 60% of this amount goes solely to the operation and maintenance of the turbine and installations, with the rest equally distributed between labour costs and spare parts. The remaining 40% is split equally between insurance, land rental, and other overheads (EWEA, 2009).

Furthermore, for simplicity, annual operational expenses can be converted to a single term and expressed as either dollars per kilowatt per year ($/kW/year) or dollars per megawatt hour ($/MWh). An important consideration for wind energy is the fact that operation and maintenance costs are not evenly distributed over time. They tend to go up as the length of time from commissioning increases. This is due to an increasing probability of component failure, and that when a failure does occur it will tend to be outside the manufacturer's warranty period. There has been a lack of consistency in separating fixed and variable operations and maintenance costs, and it is not uncommon for operations and maintenance costs to be quoted as a total of US$/kW/year (NREL, 2015).

5.3 Levelised Cost of Energy (LCOE)

LCOE can be expressed as the anticipated electricity price for an energy project in terms of revenues which will be equal to costs, including making a return on the capital invested equal to the discount rate. This concept of LCOE is referred to as the anticipated electricity price for an energy project in terms of revenues which will be equal to costs, including making a return on the capital invested equal to the discount rate (IRENA, 2012; Myhr et al., 2014).

An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss. The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology. The approach used in the analysis presented here is based on a simple Discounted Cash Flow (DCF) analysis. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) to a common basis, taking into consideration the time value of money. Given the capital intensive nature of most renewable power generation technologies and the fact that fuel costs are low, or often zero, the weighted average cost of capital (WACC), also referred to as the discount rate in this research, used to evaluate the project has a critical impact on the LCOE. However, this has the additional advantage of making the analysis transparent, easy to understand, and allows clear comparisons of the LCOE of individual technologies across countries and regions, and between technologies. The differences in LCOE can be attributed to project and technology performance, not differing methodologies. More detailed LCOE analysis may result in more "accurate" absolute values, but result in a significantly higher overhead in terms of the granularity of assumptions required and risks reducing transparency. More detailed methodologies can often give the impression of greater accuracy, but when it is not possible to robustly populate the model with assumptions, or to differentiate assumptions based on real world data, then the supposed "accuracy" of the approach can be misleading.

Levelised Cost of Energy (LCOE) allows for a better analysis and evaluation of risk and total lifespan cost (Myhr et al., 2014). A similar reference value of money is obtained by discounting the costs to a given date by the annuity method. Once obtained, the LCOE may be interpreted as the minimum unit price of energy, and is a suitable variable for evaluating the performance of various concepts.

5.3.1 Capacity Factor

(Simmon, Yonk and Hansen, 2015) states that the capacity factor of a turbine can be calculated as a percentage of a wind farm's maximum energy capacity in terms of measuring how the wind farm can turn the wind into energy efficiently. The factor of capacity has an inverse effect on wind energy cost. There is a significant gap between studies on the figure of capacity factor; for example, the International Energy Agency (IEA) (2013a) and National Renewable Energy Laboratory NREL, (2015) use capacity factors at around 35 to 38%, on the other hand, Lazard (2014) use a 41% capacity factor. The National Renewable Energy Laboratory NREL (2015) described the value of capacity factor equal to 38% as reasonable for a high wind speed location. The market average capacity factor in 2008 was from 31.1% to 33.5% (Wiser and Bolinger, 2015).

In the case of Shagaya and the Gamesa G90 2MW, 29.2% has been estimated based on discount of losses. Related to the rated power, the Gamesa G90 turbine capacity factor has been estimated of 29.2%, which indicates greater efficiency of this turbine type. The high tower versions (100 m) result in a 5% increase of energy. The height of the tower and the swept area of the wind turbine will affect the LCOE value.

Simmon et al. (2015), states that the capacity factor of a turbine is a measurement of how efficiently a wind plant can turn wind into energy. This is calculated as shown in section 5.1 (equation 5-1). A high capacity factor can drastically lower the cost of wind energy, and vice versa. The capacity factor is a significant part of calculating the cost of wind, yet estimates of the average market capacity factor vary widely from report to report. While moderate studies such as those of the International Energy Agency (IEA) (2013a) and the National Renewable Energy Laboratory NREL (2015) use capacity factors at around 35 to 38%, more generous reports, like that from Lazard (2014), use a 41% capacity factor.

The selection of a capacity factor for analysis is important because the results are very sensitive to the values assumed. At the highest (53%) and lowest (18%) capacity factors, NREL is used to examine the sensitivity of the results to the assumption that

average installed cost of capital ranged from near $43/MWh to about $126/MWh. Obviously, the choice of capacity factor matters a great deal to the LCOE.
Historically, the net capacity factor has ranged from 18%–51% (Wiser and Bolinger, 2015), meaning that the NREL estimate for the representative wind plant is within range.

5.4 System Advisor Model (SAM)

This package simulates the performance of wind energy and various other renewable energy projects. The economic model can represent financial structures for projects that either buy or sell electricity at marketing rates (National Renewable Energy Laboratory NREL, 2014). This document describes the capabilities of the US Department of Energy and National Renewable Energy Laboratory's System Advisor Model (SAM), Version 2014.1.14, released on January 14th, 2014, for potential users wanting to learn about the model's capabilities. SAM is a computer model that calculates performance and financial metrics of renewable energy systems. Project developers, policymakers, equipment manufacturers, and researchers use SAM results to evaluate financial, technology, and incentive options for renewable energy projects. SAM simulates the performance of photovoltaic, concentrating solar power, solar water heating, wind, geothermal, biomass, and conventional power systems. The financial model can represent financial structures for projects that either buy or sell electricity at retail rates (residential and commercial), or sell electricity at a price determined in a power purchase agreement (utility). SAM's advanced simulation options facilitate parametric and sensitivity analyses, and statistical analysis capabilities are available for Monte Carlo simulation and weather variability (P50/P90) studies. SAM can also read input variables from Microsoft Excel worksheets.

5.5 Economic Analysis in Kuwait

In the study, the wind farm was initially analysed economically in relation to its Levelised Cost of Energy (LCOE). As a second step, a financial analysis was conducted. This analysis examined the financial profitability of the construction and operation of the wind farm. Financial indicators were calculated for the two institutional setups of public financing and financing within commercial conditions. This section consists of three parts: firstly capital cost (CapEx), followed by operation and maintenance costs, and finally Levelised Cost of Energy (LCOE).

5.5.1 Energy of Wind Farm Output

In Kuwait, the Shagaya wind farm consists of five wind turbines of 2MW each. Table 5.7 shows the characteristics of the selected wind turbine (Gamesa G90).

Table 5.7 Characteristics of the selected wind turbine

Characteristics	Turbine
Turbine model	GamesaG90
Rated power (Pr) (kW)	2000
Hub height (m)	100
Rotor diameter (m)	90
Swept area (m2)	6,362
Number of blades	3
Cut-in wind speed (Vci) (m/s)	3.0
Rated wind speed (Vr) (m/s)	9.0 - 19.0 rpm
Cut-off wind speed (Vco) (m/s)	25
Price/(KD/£/$)	831,067KD £2,106,384 $2,789,484

Due to high daytime temperatures, it could be assumed that turbines would operate with reduced power above 40°C and shut down at above 45°C with using the cooling system of generator. Temperatures between 40°C and 45°C can be expected for 10.5% of the year, and temperatures above 45°C at 4.5%. A further assumption would be that the real full load hours (approximately 10-13% of the year), where the turbines operate with rated power, can be expected simultaneously to the hours of highest temperature. Hence, the energy losses due to temperatures between 40°C and 45°C were estimated at 5%, which means an overall loss in terms of temperatures above 40°C of approximately 10%. Other technical losses include unavailability due to turbine shutdown for reasons of repair and maintenance of approximately 5%, and electrical losses of approximately 1.0 % as the grid access is 1km away. In addition, blade degradation and grid failure account for about 1.5%.

Technical losses due to turbine downtime caused by repair, maintenance, electrical losses, extreme weather conditions, grid failures, as well as insufficient turbine performance due to blade degradation, and high temperature are considered in Table 5.8.

Table 5.8 Estimated technical losses (KISR)

Technical losses	Value (%)	Comments
Technical non-availability	5.0	Repair, maintenance
Electrical losses	1.0	Grid access < 1km
Other losses	1.5	Blade degradation, Grid failures
High temperature losses	10.0	>40°C: reduced power:>45°C:no operation

Table 5.9 shows the annual energy output value with the percentage of total losses deducted from the annual energy output, resulting in the net annual energy output value of 25.5 MWh/year.

Table 5.9 Net annual energy output and net capacity factor of a wind farm

Wind turbine generator	Rated capacity (MW)	Annual energy output (MWh/year)	Capacity factor (%)	Losses (%)	Net annual energy output (MWh/year)	Net capacity factor (%)
5XG90	10	30.6	35.0	18.0	25.5	29.2

5.5.2 Capital Cost

The estimation of investment costs was based on the findings of European Wind Energy Association (EWEA, 2009) because this study took place in a European country (UK), and as in Section 4.3 the selected wind turbine was from European suppliers which are based on European market specifications.

In this analysis, the investment costs for various wind farm projects per MW in recent years has been analysed, taking into account recent cost developments.

The investment cost breakdown for the 10 MW farm is shown in Table 5.10. Accordingly, the largest proportion could be due to the purchase of WTG. The second largest cost item represents the transportation of the WTGs to the site. For the connection of the wind farm with the Shagaya substation, $2,446,755 (KD739, 104) has been allocated.

Table 5.10 Breakdown of investment costs of wind farm components

	Component	Cost (KD)	Cost ($)	Cost (£)
81.4%*	Wind turbine (WTG) cost			
	Purchase of 10 MW (5WTG)	4,150,246	13,756,200	10,388,682
	WTG transportation	984,248	3,262,340	2,463,719
	Electrical works	447,013	1,481,646	1,118,939
	Engineering	164,041	543,722	410,619
10.5%*	Grid connection cost			
	Connection cost	738,186	2,446,755	1,847,789
8.1%*	Civil works and construction costs			
	Civil works	574,144	1,903,029	1,437,167
	CapEx plant	7,057,877	23,393,692	17,666,916
	Construction insurance	336,735	1,116,126	842,898
	Contingencies 15%	1,058,682	3,509,054	2,650,038
	CapEx	8,450,880	28,010,872	21,153,811

*Percentage of CapEx cost

Annual costs for land lease of ($72,200/ £54,525/KD20, 000) (approximately 50,000 m²) have been considered in accordance with land lease prices as given by the Kuwaiti Chamber of Commerce, 2016.

5.5.2.1 Wind Turbine Cost

The cost of a wind turbine includes several major categories such as the purchase of the wind turbine, plus its transportation, engineering, and electrical works, which will be described in the following sections:

5.5.2.1.1 Purchase of Wind Turbine

The price of the Gamesa G90-2MW turbine is ($2,751,240 / £2,077,736 / KD 830,049), which is within the range of global price. In addition, Dr. A. Al-Qattan (2016) stated that Gamesa wind turbines have specifications that suit Kuwait's desert environment. According to Gamesa, the total purchase cost of five Gamesa90 wind turbine generators is ($13,756,200/ £10,388,682/ KD 4,150,246), which is equivalent to (KD 830,049 / $ 2,751,240/ £626,853).

5.5.2.1.2 Wind Turbine Transportation

Transportation is a critical part of the cost structure of a wind project, and can be a deciding factor in the scheduling and costing of a project. The movement of equipment from ports and factories to wind farm sites has become an increasing challenge as the industry moves to larger, multi-megawatt turbines. Transportation has been estimated to be 10% of the capital cost of a wind farm project. The prices of shipping of the wind turbines depend on the geography, which can vary between manufacturers, influencing the choice of developers. For example, a developer with late-stage projects may be liable to a turbine manufacturer located close to its sites (Aswathanarayana, 2010; AWEA, 2016; Wind Power Monthly, 2015)

Similarly, the transportation and installation of the wind turbines and towers also constitute a significant cost component. The absolute cost per wind turbine, as well as transport and installation costs, has not grown proportionately to turbine size, helping to reduce the relative importance of these costs to onshore wind farms. With regards to offshore cost components, these costs are considerably higher than the onshore equivalent, and the relative scarcity of purpose-built vessels and cranes has resulted in these costs being unlikely to decrease until this constraint is mitigated. It is clear from Table 5.10 that transportation value is high, which is not surprising, because the manufacturer (Gamesa) has a factory in China, from which components are shipped to Kuwait.

Based on Port.com, (2014), the transfer of wind turbine equipment from China to Shuwaikh Port in Kuwait covers an estimated distance of 7447 nautical miles (8569.855miles), which takes approximately one month, then wind turbine equipment will be transferred from the Shuwaikh port to the Shagaya renewable energy farm by road truck of 100 km (62 miles). (Guezuraga, Zauner and Pölz, 2012) stated that a typical 2MW wind turbine is transport as the following parts:

- 1x complete nacelle
- 3x extendible trailer for blade transport
- 4x trailers for towers
- 1x trailer loaded with cables and controllers
- 1x trailer with blade hub
- 1x trailer loaded with an approx. 12.2 m (40 ft) container with tools and generation for erection

Based on the above assumption of transporting five wind turbines to the Shagaya farm, eleven trailers would be required for each turbine; Figure 5.4 shows the truck used for each blade. KISR estimated the cost of transportation to be (KD 984,248 / $3,262,340/ £2,463,719).

Figure 5.4 Trailers used to transport blades

5.5.2.1.3 Electrical Works

Wind turbines require an electrical connection between wind turbine components preparing it for connection with the power substation, and also require engineers and electricians from Gamesa. The cost of this is approximately (KD 89,403/ $296, 329/ £223,788) for each wind turbine (see Figure 5.5).

Figure 5.5 Electrical work for wind turbine tower connection

5.5.2.1.4 Engineering

Engineering works include the installation of all engineering parts of each wind turbine and the local transportation of the equipment, as well as on-the-job training (OJT), which comes to about (KD 32,808/ $108, 744/ £82,123).

5.5.2.2 Grid Connection

The direct transmission line of 132-kV to the main Shagaya substation covers a distance of approximately 600 m (0.4 miles) from the wind farm substation. Including a medium voltage/ high voltage (MV/HV) transformer would be an effective solution for the Shagaya wind farm, as shown in Figure 5.6 and Figure 5.7. As stated by an expert from the Public Authority of Housing Welfare, director of the electrical section (PAHW)(Alsharaah, 2017) ,the cost of grid connection is arund (KD 738,186 / $2,446,755/ £1,847,789).

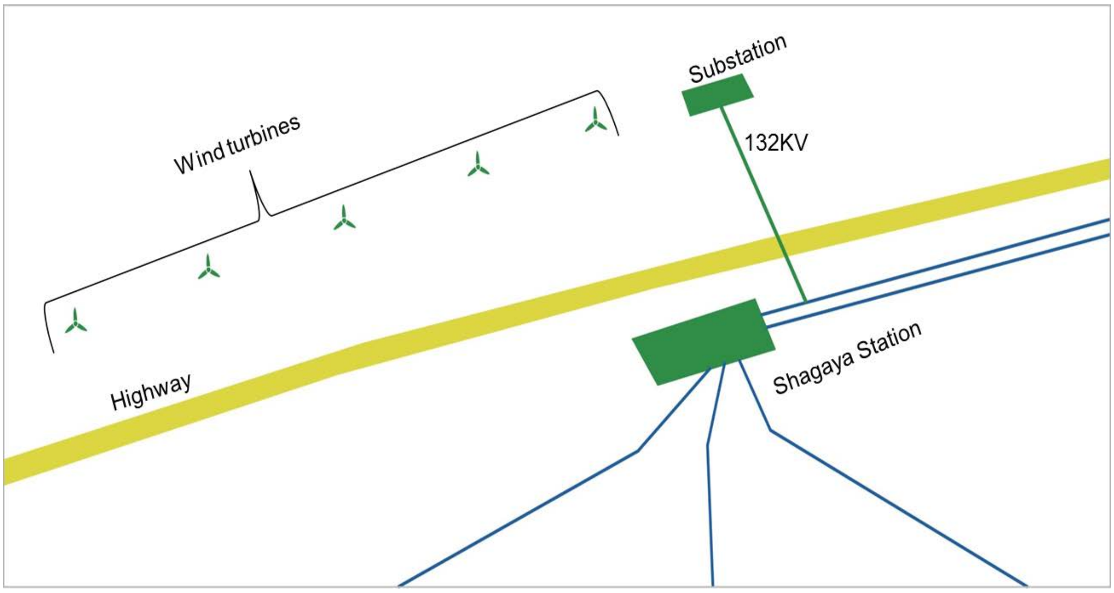


Figure 5.6 Grid connections at Shagaya farm

Figure 5.7 Electrical tower to connect electricity from Shagaya farm to the main station

5.5.2.3 Civil Works

(Al-Qattan, 2016) has assessed the civil works for the Shagaya wind farm to be approximately (KD 574,144/ $1,903,029/ £1,437,168).

5.5.3 Operation and Maintenance Costs

Operational expenditures for the wind farm include the following:

- Fees for O&M service contract
- Spare parts
- Insurances
- Administration

Blanco, (2009) stated that for the first two years of its lifetime, a turbine is usually covered by the manufacturer's warranty. In the German study, O&M costs made up a small percentage of about 2% of total investment costs for these two years, corresponding to approximately (0.3 to 0.4 c€ / 0.27 to 0.35 pence) /kWh It is clear from Table 5.11 that between the third year and the tenth year, the total O&M costs increased by between 2.5-3% of total investment costs, which is equivalent to around (0.6 to 0.7 c€/ 0.53 to 0.62 pence) /kWh, and for more than ten years the total O&M costs have been approximately 5% annually. The fixed and variable operations and maintenance (O&M) costs are a significant part of the overall LCOE of wind power.

O&M costs typically account for 20% to 25% of the total LCOE of current wind power systems (EWEA, 2009), Based on that the average value 22.5% has been assumed as OpEx cost of LCOE, which has been calculated to be ($0.01312 / £0.01) kWh/year.

5.5.4 Levelised Cost of Energy (LCOE)

In order to obtain the LCOE for the Shagaya wind farm, it is essential to use the equation in Section 2.4. Assumptions included on the calculation are as follows:

• Calculations related to the selected onshore wind turbine (2 MW).

• Investment costs that reflect the range given in Table 5.10 that is, a cost per kW is approximate ($2801/ £2115 / 846KD)/kW.

• O&M costs are assumed to be 22.5% of the levelised cost of energy.

• The lifetime of the turbine is set at 20 years (COMSOL, 2017).

• The discount rate is assumed to range from 5 to 10% per annum. The calculation in this study uses a discount rate of 8.0 % per annum.

• Economic analyses are carried out on a simple national economic basis. Taxes are not taken into account, as taxes are not implemented in the county.

Table 5.11 Summary Results of Levelised Cost of Energy

Project capacity (MW)	10
Number of turbines	5
Turbine capacity (MW)	2
Site	
Location	Shagaya, Kuwait
Wind speed (m/s at a 100-m height above ground)	8.5
Net capacity factor	29.2
Net annual energy (AEP) (MWh/MW/yr.)	(25579.2) (10 MW X8760 hX0.292)
Technology	
Rotor diameter (m)	90
Hub height (m)	100
Foundation	Spread foundation, pile foundation
Cost	
Capital cost (millions)	$28,010,872/ £21,153,811/ 8,462,925KD
Contingency (15%; millions)	$3,509,054/ £2,650,038/ 1,060,190KD
OpEx ($/MWh)	$1.19/MWh/ £0.9/MWh/ 0.36KD/MWh
Discount rate	8%
Economic operating life (years)	20
FCR	10%
LCOE $ / MWh (fils/kWh)	$0.058/kWh/ £0.04/kWh/17.6fils/kWh

5.5.5 System Advisor Model (SAM)

To estimate the cost benefit of a wind farm in Kuwait, a SAM model was used to simulate the financial aspects for the 2MW project. In SAM, the assumption of the wind turbine price is based on NERL database, including the size and power of the turbine. Default data assume also, such as capacity factor of 40.8% and percentage of contingencies of 3%. These default data have a significant part in calculating the cost of wind, high capacity factor can decrease the cost of wind energy, and the percentage of contingencies which can vary from location to another, can be added to the capital cost. The effect of SAM default data on the result will show later in section 8.1. Table 5.12 shows the result of the SAM simulation.

Table 5.12 SAM simulation results per 2MW

Metric	Value
Annual energy (year 1)	7,148,399 kWh
Capacity factor (year 1)	40.8%
Levelised COE	2.2¢/kWh/ £1.95/kWh 10 fils/kWh
Net capital cost	$2,767,302/£2,089,866/ KD 836,084

5.6 Summary

This chapter discussed the economic analysis demonstrating the structure of wind turbine cost, which can be broken down into two main components: Capital Expenditures **(**CapEx), and Operation Expenditures (OpEx). The capital costs of a wind power project have been broken down into several categories, such as cost of the turbine, construction, and cost of interface to the grid. Operation and maintenance costs appear to be the lowest in the US, whereas other markets such as Europe tend to have higher cost structures for onshore wind projects. In Egypt cost of operation and maintenance are taken as 25% of the annual cost of the turbine (machine price/life time)(Ahmed, 2010). In GCC and Kuwait, (Alnaser and Alnaser, 2011) estimated that the O&M cost of 20 MW wind farm is ($0.5/£0.38/ KD0.15) million/year.

Levelised Cost of Energy (LCOE) is varies by technology, country and project. It was obtained by applying the LCOE equation for wind energy to assess the economic benefits of wind farm implementation in Kuwait. The financial profitability of the construction, operation of the wind farm and financial indicators were calculated, including technical losses. The investment costs for various wind farm projects per MW in recent years were analysed, taking into account recent cost developments. The differences in LCOE was attributed to project and technology performance, but resulted in a significantly higher overhead in terms of the granularity of assumptions required and risks reducing transparency.

The International Renewable Energy Agency IRENA, 2012 presented the key findings of the cost of wind farm components as: initialled cost, capacity factor, operation and maintenance (O&M), and Levelised Cost of Energy (LCOE) in different regions. O&M costs were found to be fixed and variable. When compared with other countries, O&M costs appear to be the lowest in the US, at around ($10/MWh/ £7.73/MWh/ 3 KD/MWh) due to the size and penetration of the market and the long experience with wind power in the US. Other markets like those in Europe tend to have higher cost structures for operations and maintenance for onshore wind projects. Operations and maintenance costs for offshore wind farms were higher in comparison to onshore wind farms given the higher costs incurred in accessing and conducting maintenance on the wind turbines, cabling and towers. Maintenance costs were also higher as a result of the harsh marine environment and the higher expected failure rate for some components. Overall, operations and maintenance costs are expected to be in the range of ($0.03 to $0.05/kWh/ £0.02 to £0.04/kWh/ 0.01 to 0.02 KD/kWh). In Kuwait as it is clear above it was calculated to be ($1.19/MWh/ £0.9/MWh/ 0.36KD/MWh).

This analysis examined the financial profitability of the construction and operation of the wind farm. With regards to the factor of capacity, it had an inverse effect on wind energy cost. There was a significant gap between studies on the figure of capacity factor, in the case of Shagaya and the Gamesa G90 2MW, 29.2% had been estimated based on discount of losses. Related to the rated power, the Gamesa G90 turbine capacity factor had been estimated to be 29.2%, which indicates greater efficiency of this turbine type. Therefore, the selection of a capacity factor for analysis is important because the results are very sensitive to the values assumed.

Transportation had been estimated to be 10% of the capital cost of a wind farm project. The absolute cost per wind turbine, as well as transport and installation costs, had not grown proportionately to turbine size and helped to reduce the relative importance of these costs to onshore wind farms. Transportation value was high, which is not surprising, because the manufacturer (Gamesa) has a factory in China, from which components are shipped to Kuwait.

The turbine was found to be the single most expensive item of a wind farm; there are five wind turbines at the Shagaya farm; eleven trailers would be required for each turbine. KISR estimated the cost of transportation to be ($3,262,340/£2520738.7/KD 984,248).The cost of electrical works found to be approximately ($296,329/ £2,289,667/ KD 89,403) for each wind turbine. Furthermore, engineering works came to about ($108,744/ £84,024 / KD 32,808) including a medium voltage/high voltage (MV/HV) transformer which would be an effective solution for the Shagaya wind farm which will be a cost of grid connection of about ($2,446,755/ £1,890,554/ KD 738,186); the civil works for the Shagaya wind farm to be approximately ($1,903,029/ £1,470,429 KD 574,144). It has been found that the final value of levelised cost of energy is ($58.34/MWh/ £44/MWh/17.6fils/kWh) whereas the LCOE obtained from SAM simulation was (2.2¢/kWh/£1.95/kWh /10 fils/kWh) which is lower than the manual calculation of levelised cost of energy by 43 percent.

As shown in Figure 5.8, the graph clearly shows a high economic viability against the other source of electricity generation. As can been seen in comparison to solar, wind energy sits lower (£0.043/kWh) than solar energy (see yellow block). The blue block shows the cost of wind energy at global level, clearly the wind energy in Kuwait in among the lowest part of the cost. Wind energy in Kuwait is compares with the highest cost of the global wave energy as shown in the light blue block. If compared to biomass it appears in the average area of the global cost.

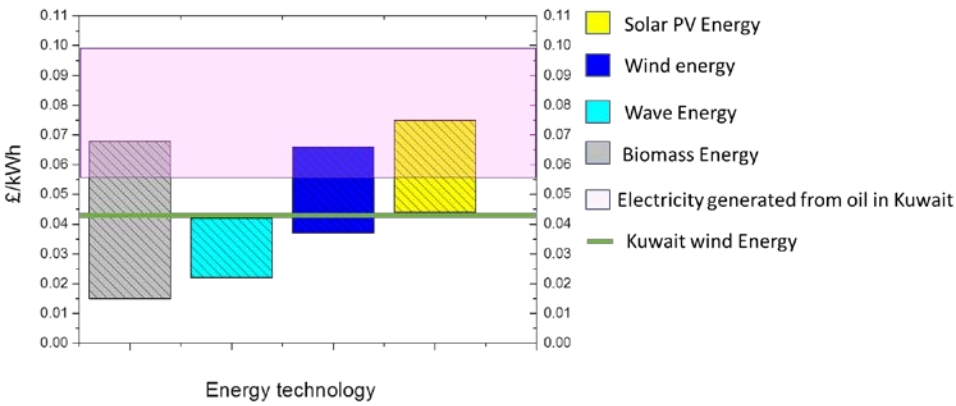


Figure 5.8 LCOE comparison between different renewable energy, Kuwait Shagaya wind energy and the LCOE electricity generated in Kuwait

6 Life Cycle Assessment

6.1 Introduction

In ISO 14040, Life Cycle Assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle". Thus, LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle, from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal 'from cradle to grave' (Guinée, 2001). Life Cycle Assessment is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to disposal as well as recycling ISO (14040, 2006). The term 'product' includes both goods and services ISO (14040, 2006). LCA is a comprehensive assessment and considers all attributes or aspects of the natural environment, human health, and resources (Finnveden et al., 2009).

The application of the ISO (14044, 2006) and ISO (14040, 2006) standard allows us to make an LCA study quantifying the overall impact of a wind turbine and each of its components, and then the whole wind farm. Applying this methodology, the wind turbine is analysed during all phases of its life cycle, from cradle to grave. Most of the literature uses the ISO 14040 standard (Martínez et al., 2009b; Guezuraga, Zauner and Pölz, 2012; Martínez et al., 2010; Al-Behadili and El-Osta, 2015; Ardente et al., 2008; Bonou, Laurent and Olsen, 2016; Crawford, 2009; Davidsson, Höök and Wall, 2012; Ekvall and Weidema, 2004; Garrett and Rønde, 2013; Kabir et al., 2012; Klöpffer and Grahl, 2014; Martı´nez et al., 2015; Oebels and Pacca, 2013; Tremeac and Meunier, 2009). ISO 14040 is to report the principals and framework. On the other hand, ISO 14044 is to report the process complementation, work to driving and background the environmental impacts.

(Tremeac and Meunier, 2009) use of the LCA methodology consists of four major steps. The first one is the definition of the goal and scope of the analysis. This includes the definition of a reference unit; all the inputs and outputs are related to this reference. This is called the functional unit, which provides a clear, full and definitive description of the product or service being investigated, enabling subsequent results to be interpreted correctly. The second step is the inventory analysis, also called the life cycle inventory (LCI), which is based primarily on systems analysis, treating the process chain as a sequence of sub-systems that exchange inputs and outputs.

(Dolan and Heath, 2012) stated that because life cycle assessment (LCA) measures GHG emissions, it will be helpful for decision makers to be informed of attributable environmental impacts of energy technologies, as (LCA) is particularly suitable for comparing conventional power generation systems to renewables.

Rajaei and Tinjum (2013) included the four major steps of LCA. The first is the definition of the goal and scope of the analysis. This includes the definition of a reference unit; all the inputs and outputs are related to this reference. The second step is the inventory analysis, also called the life cycle inventory (LCI). The following step is the impact assessment. This includes impacts in terms of emissions and raw material depletion. The final step is to compare with other processes offering a similar utility, and to form a critical view of the previous steps.

In order to assess the environmental impact of the entire life cycle of a wind turbine, a life cycle assessment (LCA) is carried out. The objective of a LCA of a product or process is to capture a range of environmental liabilities or impacts that accumulate over the entire life cycle, from the cradle to the grave.According to ISO 14040 and 14044 standards, a LCA is carried out over four stages, as shown in Figure 6.1 (Tremeac and Meunier, 2009; Pereg and Fernandez de la Hoz, 2013).

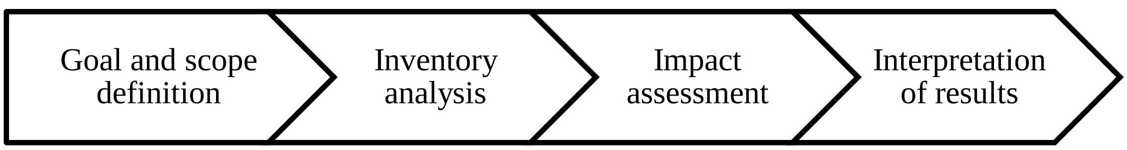


Figure 6.1 Stander four stages of Life Cycle Assessment

1. Goal and scope definition (context and purpose of the study).

2. Inventory analysis (collecting all inputs and outputs of materials and energy in all processes and operations along the value chain of the product throughout its life cycle).

3. Impact assessment (evaluating the potential environmental impacts associated with those inputs and outputs).

4. Interpretation of results (evaluating the significance of the potential environmental impact of the system).

Al-Behadili and El-Osta (2015) analysed and evaluated the LCA of the Dernah (Libya) wind farm. They applied the LCA outlined in ISO 14044, since it allows quantifying of the overall impact of a wind turbine, each of its components, and then the whole wind farm, where the wind turbine is analysed during all phases of its life cycle.

6.2 Goal and Scope

The initial phase defines the objective and scope, which sets the criteria of the study, the intended use of the results, conditions, data requirements, and the assumptions made to analyse the product system in question. The scope of the study defines the envelope of the system in terms of technology coverage, geographic, and temporal study, the product system attributes, and the level of detail and complexity.

6.2.1 Goal of the Study

The developed LCA model seeks to identify the impact on the environment throughout the life cycle of a wind turbine, such as the emission of CO_2 and the energy payback. The study has specifically focussed on the Gamesa onshore wind turbine model G90 with 2MW rated power installed in the Shagaya wind farm in a flat desert area. The general dimensions of this wind turbine are a 90m rotor blade, 6,362m^2 swept areas, and a height of 100m. To achieve the third objective of this study, the wind turbine was analysed throughout the various stages of its life cycle, from cradle to grave, taking into consideration the following: the manufacture of each of its component parts, transport to the wind farm, construction, operation and maintenance, and final decommissioning with subsequent disposal of waste residues.

6.2.2 Functional Unit

Producing electricity is the function of the wind turbine; kWh is the measuring unit of electricity which is used as the functional unit for the system. In this study, for simplicity, the electricity produced by one unit of a wind turbine during its life time is chosen. The Gamesa G90 2MW onshore wind turbine generates a net energy of 5,115,840 kWh /year (5116 MWh/year), due to the losses at Shagaya farm, as mentioned in Section 5.4.1. The capacity factor of 29.2 % is considered. The total electricity generated over a lifetime of 20 years is 102,316,800 kWh (102,320MWh). Therefore, the functional unit in this study is 102,316,800 kWh of electricity.

6.2.3 System Boundaries

In this study, the system boundaries are considered as the following:

6.2.3.1 Boundaries in Relation to Nature

In this study of the life cycle of a wind turbine, the boundary begins from the first phase of manufacturing up to the operation in order to keep the plant functioning, such as oil changes and gearbox replacement, until the final phase which is sending the wind turbine to landfill or recycling.

6.2.3.2 Geographical Boundaries

- The location of manufacture of the wind turbine (Europe-Spain) will be influenced by the carbon intensity of materials.
- The future situation for manufacturing of the wind turbine is expected to remain the same, thus wind turbines installed in Kuwait are currently manufactured in Europe.
- In Kuwait, where the wind turbines are installed will affect life cycle emissions.
- A location like Kuwait with low wind speed will lower the capacity factor and increase life cycle emissions (Dolan and Heath, 2012).
- The Kuwaiti Ministry of Environment, (2017) confirmed that the only materials to be recycled are wood and steel; any other materials will be sent to the landfill at Shuaiba.

6.2.3.3 Time Horizon

The lifetime of the wind turbine is 20 years.

6.2.3.4 Assumptions and Limitations

Martínez et al. (2009), stated that the limits to data collection do not represent a significant weakening of the final results, rather they allow for adjustment of the LCA study to make it more flexible.

The wind turbine itself defines the boundary limit of the system, whereas transformers and substations are not included since it is considered that the transmission of electricity from any energy source would be the same. The paint used in the rotor, nacelle and tower is also excluded from the scope of this analysis, as it was impossible to obtain data from the manufacturers and it is of little relevance to the final result (Guezuraga, Zauner and Pölz, 2012).

The LCA model developed includes both the turbine and the foundations which support it, leaving aside the system for connection to the grid (medium voltage lines and transformer substation).

Due to limitations of time and cost, this LCA was performed under the following conditions:

- It has been taken into account that for all these sub-components, which make up 100% of the foundation, 100% of the tower, approximately 84% of the rotor, and 88% of the nacelle, the reduction of the percentage of the rotor and nacelle is due to lack of information from the manufacturer. Table 6.1 below shows the estimated weight percentage of the wind turbine components.

Table 6.1 The estimated weight of the wind turbine components (Pereg and de la Hoz, 2013)

<table>
<tr><th colspan="3"></th><th>Weight (Kg)</th><th>Estimated weight (Kg)</th><th>% of the estimated weight</th></tr>
<tr><td rowspan="5">Wind turbine</td><td colspan="2">Rotor</td><td>38 070.16</td><td>32 068</td><td>84</td></tr>
<tr><td colspan="2">Tower</td><td>250000</td><td>250 000</td><td>100</td></tr>
<tr><td colspan="2">Nacelle</td><td>68 266.72</td><td>59825</td><td>88</td></tr>
<tr><td rowspan="2">Foundation</td><td>Concrete</td><td>1174537</td><td>1174537</td><td>100</td></tr>
<tr><td>Steel</td><td>172700</td><td>172700</td><td>100</td></tr>
<tr><td rowspan="3" colspan="2">Total</td><td>Wind turbine (WT)</td><td>356336.88</td><td>337993</td><td>95%</td></tr>
<tr><td>WT/concrete foundation</td><td>1530873.88</td><td>1512530</td><td>99%</td></tr>
<tr><td>WT/steel pile foundation</td><td>529036.88</td><td>510693</td><td>97%</td></tr>
</table>

- The current recycling rate of the waste wind turbine was obtained and estimated by Gamesa (see Table 6.2 below).

Table 6.2 Type of material and disposal method (Pereg and de la Hoz, 2013)

Material type	**Disposal method recycling**
Iron and steel	Recycling (98%)
Fibreglass and carbon fibre	Landfill (100%)
Lubricants, greases and oils	Combusted (100%)
Plastic	Recycling (90%)
Copper	Recycling (95%)
Paints and adhesives	Landfill (100%)
Cable	Recycling (99%)
Electric / electronic components	Recycling (50%)

- A production of 5 GWh/wind turbines per year
- One replacement generator has been provided for during the complete lifetime of the wind turbine

6.2.4 Manual Method

As discussed previously in Section 3.3, upon reviewing the software available, all calculations will be performed manually, as described below.

6.3 Life Cycle Inventory

Inventory analysis is the second phase of inventory, and generally is the longest. This stage involves the collection of all data on inputs and outputs and performing the appropriate calculations to quantify the inputs, such as raw materials and energy, and outputs such as emissions, effluents and waste. Within each stage, this data is to refer to each of the processes involved in it. In other words, the inventory analysis is a material and energy balance of the system, but may include other parameters, such as land use, radiation, noise, vibration, and biodiversity affected. It also includes data collection and performing the appropriate calculations to quantify the inputs and outputs of the system studied (Pereg and Fernandez de la Hoz, 2013). ISO 14040:2006 defines the analysis life cycle inventory (LCI) and LCA phase as the compilation and quantification of inputs and outputs for a given production system throughout its life cycle.

However, the overall inventory will be a large list of data on fuel consumption and emissions of a large number of substances, from cradle to grave, from which their environmental impact will be interpreted and evaluated (Pereg and Fernandez de la Hoz, 2013).

6.3.1 Process Flow Chart

In this LCA, the entire life cycle of the wind turbine is considered; from manufacture of the components until the turbine is decommissioned. Turbine transport to site and assembly as well as operation and decommissioning are included, since these phases are also part of the lifetime of the wind turbine. A flow chart of the wind turbine life cycle is represented in Figure 6.2 , which shows an outline of the model used for assessing the environmental impact of a wind turbine during its entire life cycle. A wind turbine consists of many electrical, electronic and mechanical parts and components. The components of a wind turbine, such as the nacelle, also comprise many sub-components and/or electrical parts. It is difficult to gather all the information on all the parts and components from suppliers. The focus was on compiling the LCI data on important components such as the base, the tower, the nacelle, and the rotor. However, in the few cases in which the data found was not sufficiently reliable and proven, was used quasi-process information from commercial SimaPro software. The materials and energy used in the various components were incorporated into the model using data provided by Gamesa and the commercial databases of SimaPro. During the operational phase, all maintenance operations have been taken into account. These maintenance operations are performed by the owner company of the wind farm and recorded in its environmental management system according to the ISO 14001 standard. Among the maintenance tasks programmed we can check quantities of oil and grease used replacement of filters and transport, amongst other procedures.

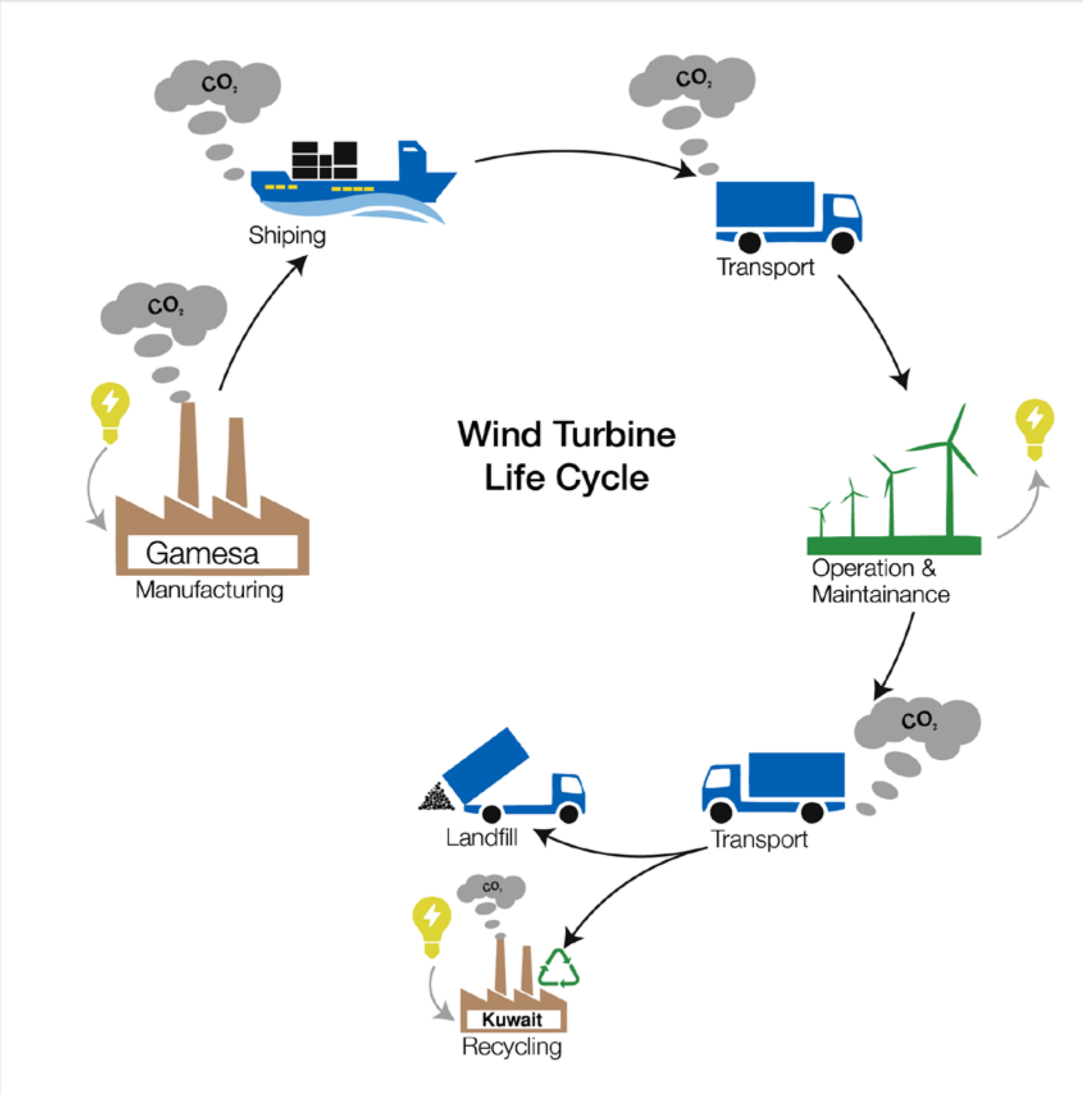


Figure 6.2 LCA process flow chart

6.3.2 Wind Turbine Manufacture

The wind turbine manufacturing phase includes upstream processes such as mining, refining, processing, and construction of the main components of the wind turbine (Nalukowe et al., 2006; Guezuraga, Zauner and Pölz, 2012). Below we briefly describe each of the components analysed:

- **Rotor**

The rotor consists of the hub, nose cone, and 3 blades. The blades are made of a material consisting of approximately 64% glass fibre and 15% carbon fibre, whereas the hub and nose cone are generally made of cast iron and glass-reinforced plastic GRP (Gamesa, 2010). The whole unit weighs approximately 38.5 tonnes. Each blade is 43.9 m long, and weighs 6.33 tonnes. The nose cone weighs 310 kg. The blade hub is made of cast iron and weighs 8.366 tonnes (Appendix E). In the decommissioning process at the end of the turbine's life, the blades will be sent to the dump.

- **Nacelle**

The nacelle is normally comprised of the nacelle frame, which is made of about 56% steel and 42% cast iron, and covers the generator, which is made of steel, cast iron and copper. The gearbox is made of cast iron and steel, and the yaw system and transformer are made of steel and aluminium (Gamesa, 2010). The structure of the nacelle consists of a frame and a nacelle cover. The main components of the turbine inside the nacelle are responsible for converting the mechanical rotational energy of the rotor into electrical power, and the main components are the main shaft, the gearbox, the generator, transformer, and the yaw system; the total weight of these components is around 70 tonnes. During its use and maintenance phase, a complete oil change for the gearbox and cooling system is necessary. Regular lubrication of the gears and other mechanical parts of the system is also provided for.

- **Tower**

The tower is made of steel, which is delivered to the turbine manufacturer in steel plates; therefore they do not need to process any further. Welding, sandblasting and surface treatment are performed at the manufacturing location (Burton et al., 2011). Once the whole tower is erected, it measures 100m and weighs 250 tonnes (Appendix E). (Martínez et al., 2009b) stated that as there is no maintenance work on the tower during the operation of the wind turbine. The average material losses are estimated at 10% for the recycling process during the decommissioning process of the tower.

- **Foundation**

There are two types of foundation: steel pile, and reinforced concrete. The reinforced concrete foundation is generally concreted in situ, and after excavation the hole is filled with concrete and reinforced steel (Burton et al., 2011). According to Gamesa, the foundation has a volume of 15x15x20, 450m^3 of concrete, a total weight of around 1175 tonnes, and uses about 14.5 tonnes of iron for the reinforcing bars, and the steel ferrule used to connect and support the turbine tower weighs 15 tonnes. Steel pile foundation was assumed by the researcher to have a shell thickness of 0.075m and 22m length constructed of 100 percent steel with a total weight of around 173 tonnes.

During the lifetime of the wind turbine, the possible emissions from the concrete foundation and steel pile foundation into the environment have been considered. In the decommissioning process, the concrete foundation has been assumed to be sent to the landfill and covered with a layer of 20–30 cm of organic soil, whereas a steel pile foundation will be 100% recycled.

Figure 6.3 shows the wind turbine sub-components. It is clear that steel is the largest element, with 85% of the total wind turbine components, followed by iron and fibre glass, with 10% and 4% respectively. 1% of the total materials of the turbine include copper, aluminium, and GRP.

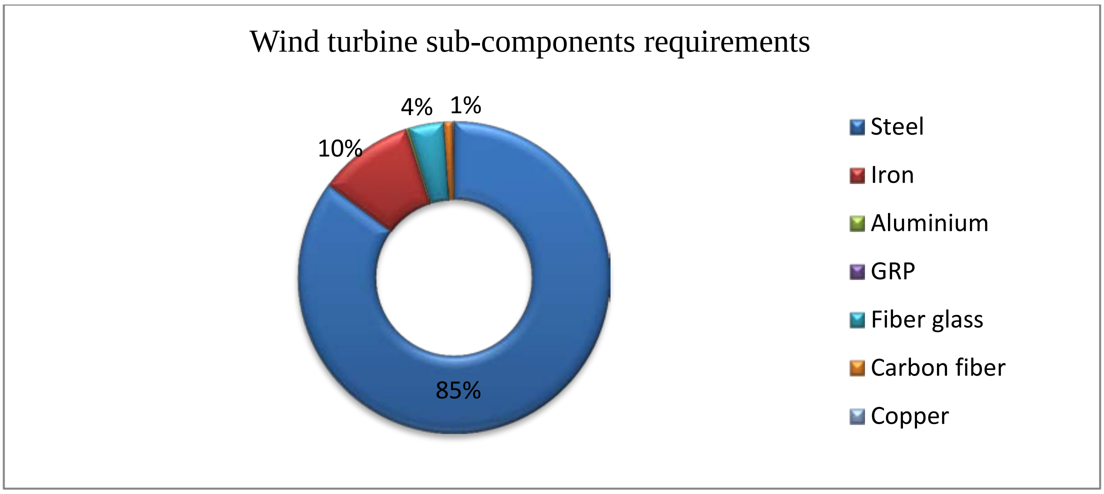


Figure 6.3 Wind turbine sub-component requirements

6.3.3 Transport and On-site Assembly

Transport and on-site assembly includes the transport of the turbine components to the wind farm and the insulation. It has been assumed in Section 5.4.2.1.2 that the components will be transported from the manufacturer in Spain to the port in Kuwait, and will then be transported from the port to the site by road. The transported components are as follows:

- All wind turbine components.
- 1x complete nacelle shipping
- 3x extendable trailer for blade transport
- 4x trailers for towers
- 1x trailer loaded with cables and controllers

- 1x trailer with blade hub
- 1x trailer loaded with an approximate 12.2 m (40 ft.) container with tools required for erection.

6.3.4 Operation and Maintenance

Operation and maintenance are routine actions to keep the farm in order and fix any devices that may become out of order. The scheduled maintenance covers oil changes, lubricants, and also the transfer of workers during service operations. Some spare part replacement is required for the gearbox of the turbine. Dismantling and recycling includes dismantling of turbines, transportation by truck to the disposal site, and in some cases recycling of components (Guezuraga, Zauner and Pölz, 2012).

(Guezuraga, Zauner and Pölz, 2012) estimated that the required maintenance for the 2MW geared turbine over a 20-year lifetime is one gearbox replacement every 7 years. Whereas (Puigcorbe and De-Beaumont, 2010) stated that only one or two gearbox replacements would be expected over the 20-year lifetime of the turbine. On the other hand, (Nalukowe et al., 2006) have assumed that the gear and the gearbox must be replaced once during the 20-year lifetime of the Gamesa wind turbine. In this study, one gearbox replacement over 20 years is assumed. Turbine service is assumed to be carried out three times a year in the form of oil and lubricant changes, and the distance covered is assumed to be 100 km per trip (Guezuraga, Zauner and Pölz, 2012).

6.3.5 Inventory Analysis

The inventory analysis covers the inputs of metals, concrete, fibreglass and transportation details of the turbines to site, to the disposal area, and during the operational phase. Components, sub-components, materials of the sub-components, and the mass of material in kg are obtained from Gamesa and the embodied carbon dioxide and energy from the material were obtained from Bath University (ICE) as mentioned in section 4.6.3 as shown in Table 6.3.

Table 6.3 The Inventory of Carbon and Energy (ICE) data of the assembly material for the Gamesa 90-2MW (Hammond and Jones, 2008; Pereg and de la Hoz, 2013; Gamesa, 2017)

Components and sub-components		Material weight (kg)	Embodied energy (MJ/kg)	Embodied carbon dioxide ($kgCO_2/kg$)	Total energy (MJ)	Total embodied carbon dioxide ($kg\ CO_2$)
Rotor (32068kg)	Three blades	Fibreglass=12 153	28	1.54	340 284	18 716
		Steel= 899	25.3	1.95	22 745	1 753
		Copper=53	42	2.71	2 226	144
	Blade hub	Cast iron=8 360	25	2.03	209 000	16 971
	Nose cone	GRP=183	97.5	8.1	17 843	1 482
		Steel=8 643	25.3	1.95	218 668	16 854
		Cast iron=228	25	2.03	5 700	463
	Pitch system	Cast iron=858	25	2.03	21 450	1 742
		Steel=691	25.3	1.95	17 482	1 347
		32068			**855 398**	**59 472**
Nacelle (55 925 kg)	Frame	Steel=3000	25.3	1.95	75 900	5 850
		Cast iron=10 900	25	2.03	272 500	22 127
	Main shaft	Steel= 8 341	25.3	1.95	211 027	16 265
		Cast iron =3 135	25	2.03	78 375	6 364
	Generator	Steel=5 456	25.3	1.95	138	10 639
		Cast iron=123	25	2.03	3 075	250
		Copper=352	42	2.71	14 784	954
	Gearbox	Steel=8 159	25.3	1.95	206 423	15 910
		Cast iron=8 008	25	2.03	200 200	16 256
	Yaw system	Steel=3 082	25.3	1.95	77 975	6 010
		Cast iron=1 229	25	2.03	30 725	2 495
		Aluminium =240	155	9.16	37 200	2 198
	Transformer	Steel=3 225	25.3	1.95	81 592	6 547
		Aluminium=675	155	9.16	104 625	6 183
		55 925			**1 394 539**	**118 048**
Tower (250 000kg)	Steel Tower	Steel=250 000	25.3	1.95	6 325 000	487 500
		250 000			**6 325 000**	**487 500**
Total		**337 993 (338 t)**			**8 574 937**	**665 020**
Steel pile Foundation (172 700 kg)	Steel pile foundation	Steel=172 700	25.3	1.95	4 369 310	336 765
		172 700			**4 369 310**	**336 765**

Concrete Foundation (1 174 537kg)	Steel	Steel bars=14 537	13.1	0.72	190 435	10 467
	Concrete	Concrete=1 116 000	0.75	0.107	837 000	119 412
		1 174 537			**1 027 435**	**129 879**
TOTAL Turbine A		**510 693**			**12 944 247**	**1 001 785**
TOTAL Turbine B		**1 512 530**			**9 602 372**	**794 899**

It has been assumed that turbine components have been shipped from the location of the manufacturer in Spain to the port in Kuwait, and then transported from the port to the site by road. The distance travelled by the 2 MW turbines is estimated to be 7447 nautical miles (13791.84km) by sea, and 100 km by road. The transportation is divided to three phases: to the site, decommission, and empty truck return. The load transport by tonne over the distance is counted as CO_2 emissions in tCO_2 after taking into account the conversion emission factors for each type of transportation. Table 6.4 shows the three phases of transportation and the CO_2 emissions. Ramadan (2016) , who is a research scientist at the Environmental Pollution and Climate Program, KISR, stated that data for CO_2 emission from transportation in Kuwait is not available. Due to this lack of information, data from a country with similar environmental conditions to Kuwait has been used. All conversion factors for CO_2 emissions and fuel consumption in transportation is based on data from Brazil (Oebels and Pacca, 2013).

Table 6.4 The transportation data and factors of CO_2 emissions for different types of transportation

Component		Transportation	Load capacity (tonne)	Distance (Km)	CO_2 emission factor (gCO_2/tonne-km)	Total CO_2 emissions (tCO_2)
To the site	All components	sea shipping	511	7447 nautical miles =13791.84km	8.4	59
	Blades	3 trucks	13.1	100	37	0.0485
	Blade hub	1 truck	8.4	100	37	0.031
	Nacelle	1 truck	56	100	37	0.207
	Tower	4 trucks	250	100	37	0.925
	Cables and controllers	1 truck	6.2	100	37	0.0229
	Tools and generation for erection	1 truck	2	100	37	0.0074
	Steel pile foundation	1 truck	173	100	37	0.64
	Concrete foundation	21 mixing truck	56	100	37	4.35
TOTAL	**Turbine A**					**61**
	Turbine B					**65**
Empty return		Consumption (l/100km)		Distance (km)	CO_2 emission factor ($kgCO_2$/l)	Total CO2 emissions (tCO2)
	Turbine A	35		1200	2.9	1.22
	Turbine B	35		3200	2.9	3.25
O&M	Gearbox	Sea shipping	16.2	13791.84	8.4	1.9
	Gearbox	Truck	16.2	100	37	0.06
	Oil change	Truck	Consumption (l/100k)35	600	2.9	0.609
TOTAL						**2.57**
Decommission	Blades	3 trucks	13.1	143	37	0.069
	Blade hub	1 truck	8.4	143	37	0.044
	Nacelle	1 truck	56	143	37	0.296
	Tower	4 truck	250	143	37	1.32
	Cables and controllers	1 truck	6.2	143	37	0.033
	Tools and generation for erection	1 truck	2	143	37	0.010
	Steel pile foundation	1 truck	173	143	37	0.915
	Concrete foundation	4 truck	1175.5	143	37	6.22
TOTAL	**Turbine A**					**2.7**
	Turbine B					**8**
TOTAL Turbine A						**67.5**
TOTAL Turbine B						**79**

6.4 Evaluation of the Impact of the Lifecycle

The third phase proceeds to the impact assessment in terms of emissions and raw material depletion, with a classification and evaluation of the results of the inventory, and a relation of the results with observable environmental effects. (Pereg and Fernandez de la Hoz, 2013). In order to compare environmental impacts, it is necessary to select the following impact categories: climate change, cumulative energy requirements, and energy payback time, as shown below.

6.4.1 Climate Change

As shown in Section 1.1, global CO_2 emissions from fuel in 2016 amounted to 32.4 Gt. Kuwait is in fourth position with 30.3 tonnes of CO_2 annual emissions. Kuwait has signed the Kyoto protocol with a long-term goal of reducing global greenhouse emissions by 50% before 2050. To measure how much a given mass of CO_2 is estimated to contribute to global warming, the emission of Green House Gas (GHG) can be estimated by the mass of GHG gas on a relative scale compared to that of the same mass of carbon dioxide by unit of $kgCO_2/kWh$. The main GHG's are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Guezuraga, Zauner and Pölz, 2012). This study will take carbon dioxide (CO_2) emissions as the main GHG's.

6.4.2 Cumulative Energy Requirements

This is the basic term for assessing the energy related part of a life cycle analysis for energy systems. The total cumulative energy requirement contains the energy requirements needed to deliver a product or a service evaluated as primary energy measured in kWh.

6.4.3 Energy Payback Time

This is a term used to measure the net energy value of a wind turbine, and how long the plant has to operate to generate the amount of energy that is required during its entire life. This is calculated as:

$$\boldsymbol{EPBT(year) = \frac{E_{input}}{E_{annual}}} \qquad \textbf{Equation 6-1}$$

Where the E_{input} is the total primary energy requirements of the system throughout its life cycle and the E_{annual} is the annual electricity generated by a system.

Therefore, it is defined as the total cumulative energy requirements divided by the total annual energy generated by the turbine, where the total cumulative energy requirements comprise energy for production, transport, maintenance, and decommissioning.

6.5 Interpretation of Results

The interpretation phase is a systematic technique to identify, quantify, review, and evaluate information from the results of the Inventory and Evaluation, and communicate them effectively. The results of the previous phases are evaluated together in a manner consistent with the objectives set for the study, in order to establish findings and recommendations for decision-making. The main objective of the study is to calculate a number of relevant parameters related to energy consumption, such as CO_2 emissions and the energy payback time of the wind turbine. These results are compared with other sources of energy based on fossil fuels to assess the potential of wind plants. The assessment of life cycle impacts is essential to improving understanding of the results of the inventory phase ISO (14040, 2006; 14044, 2006). The first category returns inventory results on a number of environmental issues, the second type models the damage inventory results.

Figures 6.4 and 6.5 show two different types of wind turbine of the same Gamesa 90-2 MW generator with different foundations of either steel pile (Turbine A) or concrete (Turbine B).

In the case of Turbine A (Figure 6.4), the tower is the largest component, with 49 % of the total weight, which is not surprising because the tower is usually wholly constructed of heavy steel, followed by the steel pile foundation at 33%, which is also made of steel, but is smaller. This followed by the nacelle with 12 %, and finally the rotor, which is the lowest at 6 %. The nacelle and rotor are a lower weight because they consist of light materials.

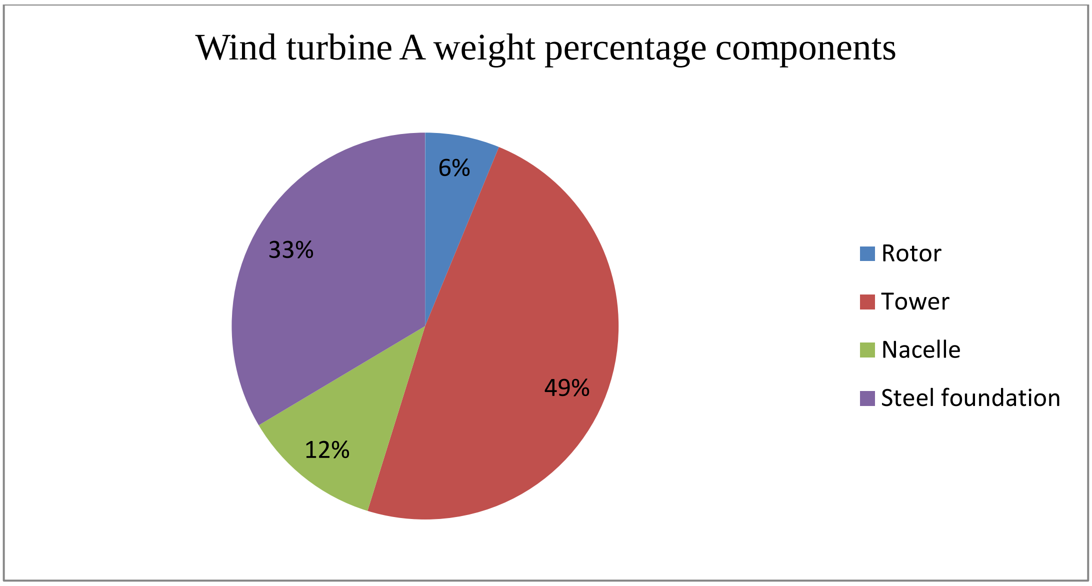


Figure 6.4 Wind turbine weight percentage components with a steel pile foundation (Turbine A)

Figure 6.5 shows Turbine B. The largest percentage of weight is the concrete foundation at 77 %of the total weight of the wind turbine (1,174,537 kg). It consists of 14,537 kg of steel (engineering steel) and 1,116,000 kg of concrete with a low embodied energy factor of 0.75 MJ/kg. It is more than four times the weight of tower and consists of two heavy materials: steel, and concrete. The tower comes next, at 17%, followed by the nacelle at 4 %, and finally the rotor at 2%of the total weight. The tower, nacelle and rotor use the same materials as Turbine A.

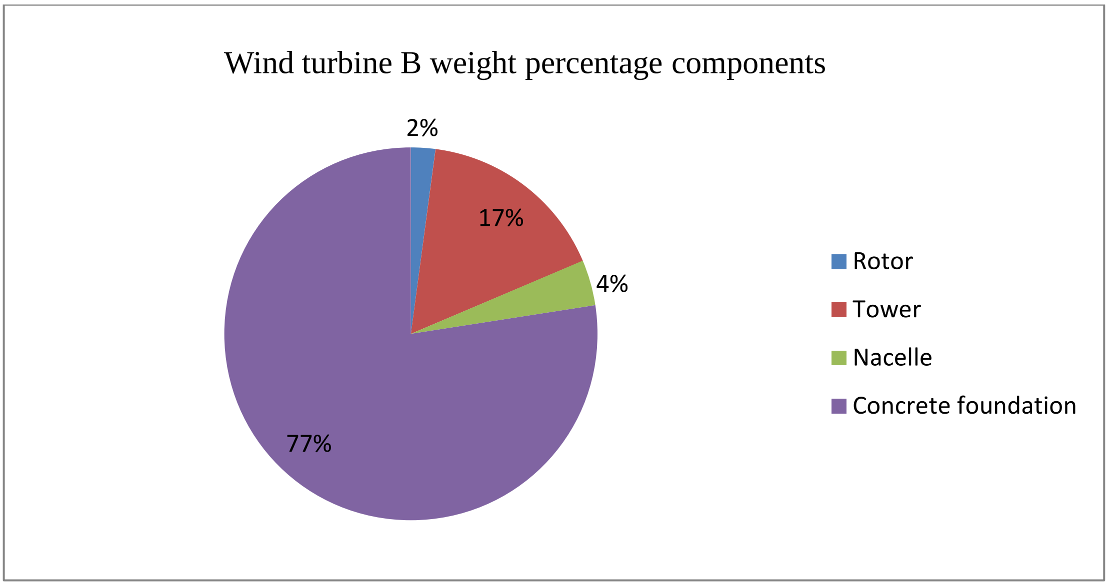


Figure 6.5 Wind turbine weight percentage of components with concrete foundation (Turbine B)

The impact of each component on the wind turbine life cycle at different stages is as follows:

a) **Manufacturing stage:**

In this stage, the two main impacts are from the carbon dioxide impact and embodied energy for the components of the wind turbine. As shown in Table 6.3, each component and sub-component in the manufacturing phase has been looked at individually.

Figure 6.6 shows that the wind turbine tower has the greatest CO_2 emissions at the manufacturing stage, as it is composed of 100% steel and weighs 250,000kg, followed by the steel pile foundation with a weight of 172,700kg. The nacelle comes next, which consists of 31,263 kg of steel and 23,395kg of iron, and finally the component with the smallest CO_2 emissions is the rotor, as fibreglass takes up 40% of its weight.

Figure 6.7 shows the embodied energy in MJ for each component of the wind turbine. Similar to the manufacturing stage, the tower of the wind turbine shows the highest embodied energy of 6,325,000 MJ compared to other components. This is because the factor of the embodied energy for steel is 25.3 MJ/kg, and the weight of the steel tower is 250,000kg. The other component of embodied energy is the steel pile foundation, which has energy of 4369310 MJ, and a high factor of embodied energy of 25.3 MJ/kg, followed by the nacelle, with 1,394,539 MJ, whereas the rotor has the lowest energy.

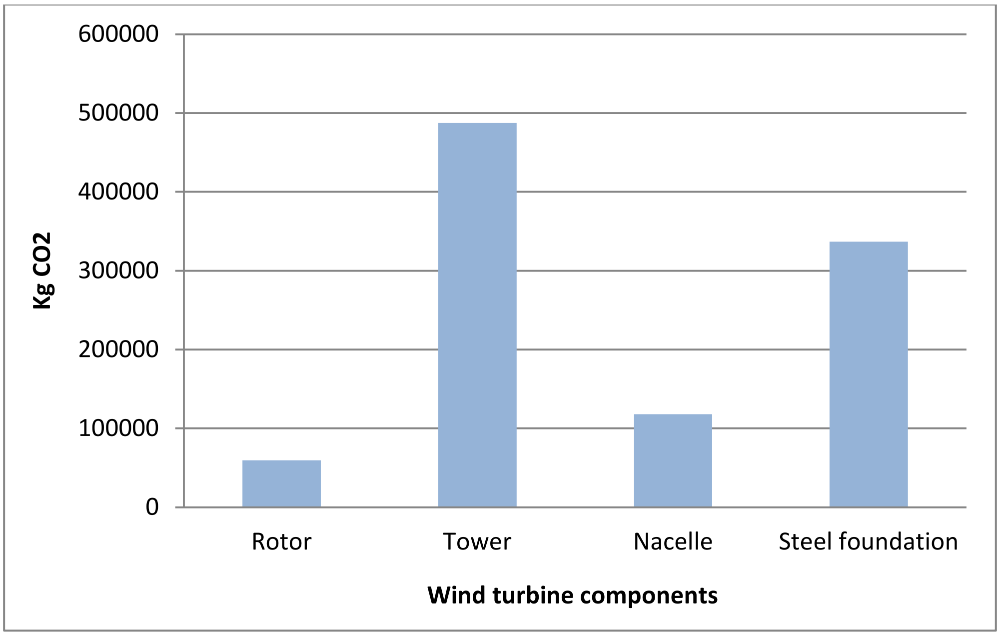


Figure 6.6 Carbon dioxide emissions from the manufacturing stage ($KgCO_2$)

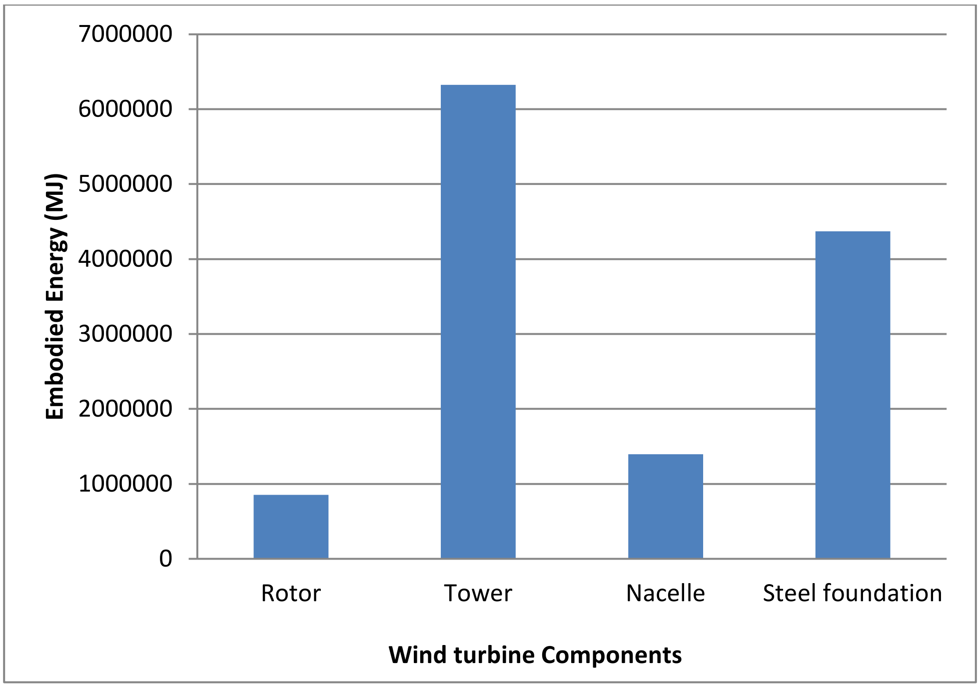


Figure 6.7 Embodied energy from manufacturing stage (MJ)

In the manufacturing stage, it is clear that the weight of the sub-component material and the embodied carbon dioxide ($kgCO_2/kg$) are the two main factors that control the contrast between the CO_2 emission impacts of the wind turbine components. The factor of embodied carbon dioxide is different for each sub-component. The highest carbon dioxide factor is for aluminium, at 9.16 $kgCO_2/kg$, and the second highest factor is for GRP, at 8.1$kgCO_2/kg$ (see Table 6.3). However, the percentage of their weights is small compared to the total weight of the wind turbines, at 0.05% and 0.27% respectively; therefore they have a limited effect on the total embodied carbon dioxide. On the other hand, steel and cast iron which are 86% and 10% respectively of the total weight of the wind turbines, and have a huge effect on the results of the manufacture stage. According to Figure 6.9, with regard to the manufacturing stage, the total CO_2 emission of Turbine A is higher than Turbine B by 33.6%, as a result of the steel pile foundation for the turbine being constructed by the manufacturer, whereas the concrete foundation in Turbine B is cast in situ.

b) Transportation stage:

This stage is divided into four phases for the two types of turbines (Turbine A and Turbine B). The four phases are: 1) transport of the wind turbine from manufacturer to site, 2) operation and maintenance, 3) empty return, and 4) decommission. Each phase, with a level of CO_2 emission, is shown in Figure 6.8.

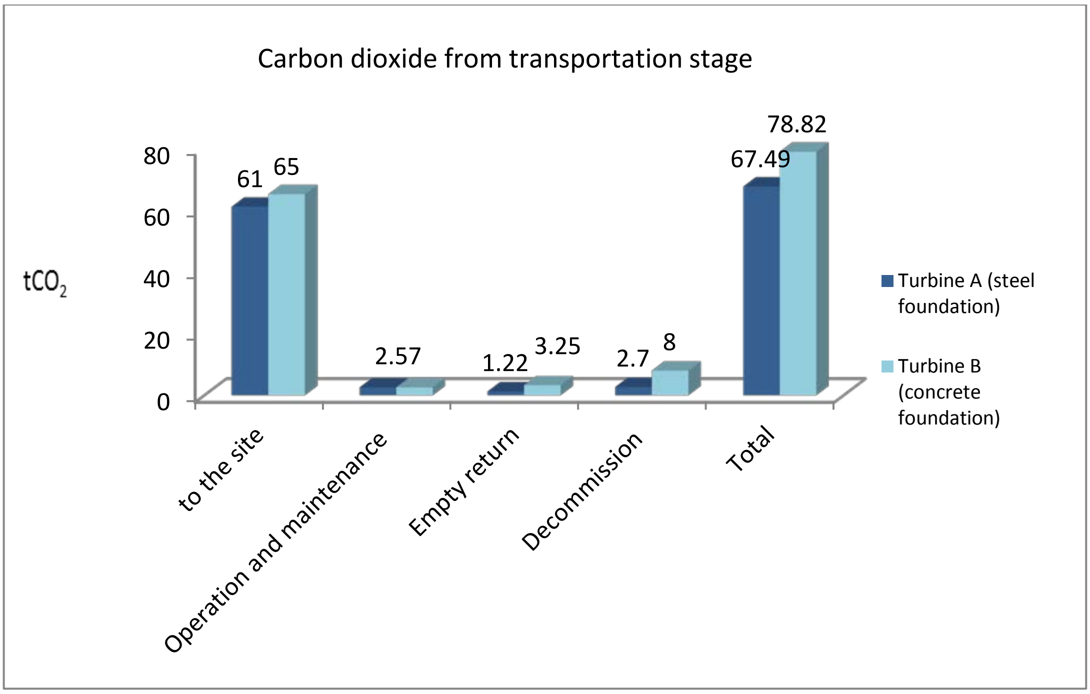


Figure 6.8 Carbon dioxide emissions from the transportation stage

Figure 6.8 shows that the transportation stage of the total CO_2 emissions in Turbine B is slightly higher than that of Turbine A, as the number of truck trips due to weight in the concrete foundation is greater than that of the steel pile foundation. It is clear from the above that carbon dioxide emissions from transportation to the site for both turbine A and B are much higher than other stages, due to the large distance that the wind turbine must travel from Spain to Kuwait. Carbon dioxide emissions from Turbine B at the site stage are slightly higher than Turbine A because road transportation of the pile steel foundation and wind turbine components was necessary, whereas the concrete foundation is cast at the farm site. In decommission and the empty return stages, Turbine B's carbon dioxide emissions are higher than those of Turbine A. Generally, Turbine B has greater carbon dioxide emissions than A, and this may be due to its weight and volume, which requires a greater number of trucks to transport it, whereas they have similar emissions at the operation and maintenance stage, as both have the same source of emissions from replacing the gearbox and changing the oils of the wind turbine generators, and not from the foundations. However, the share of transportation is between 4%-6.5% of the cumulative energy requirements of wind turbines. Furthermore, all of the LCAs processed by VESTAS showed that the environmental impacts of transportation were insignificant (Dirk Giirzenich, Jyotirmay Mathur, Narendra Kumar Bansal, 1999; Lenzeu, M. and Wachsmann, 2004).

c) Operation and maintenance stage:

This includes construction for Turbine B, the CO_2 emissions in the construction process obtained from the main construction work when the concrete foundation is casted in situ. The concrete foundation weighs 1,174,537 kg and consists of 14,537 kg of steel (engineering steel) and 1,116,000 kg of concrete, with total CO_2 emissions of approximately 130 tCO_2, as shown in Table 6.5. Therefore, the CO_2 emissions of Turbine B are greater than Turbine A at 130 tCO_2, as shown in Figure 6.9, which is the value of the total embodied carbon at the construction.

Table 6.5 Inventory of carbon data of the concrete foundation at the construction stage (Gamesa, 2010; Hammond and Jones, 2008)

Component	**Subcomponent**	**Weight kg**	**Material**	**Embodied carbon dioxide factor $kgCO_2/kg$**	**Embodied carbon $kgCO_2$**	**Total embodied carbon tCO_2**
Foundation	Concrete Foundation	1174537	Steel =14537kg Concrete= 1116000kg	0.72 0.107	10467 119412	130

d) Decommission stage

In this stage materials such as concrete were taken directly to landfill. It is shown in Figure 6.9 that Turbine B has three times the CO_2 emissions of Turbine A due to the high volume of concrete it uses.

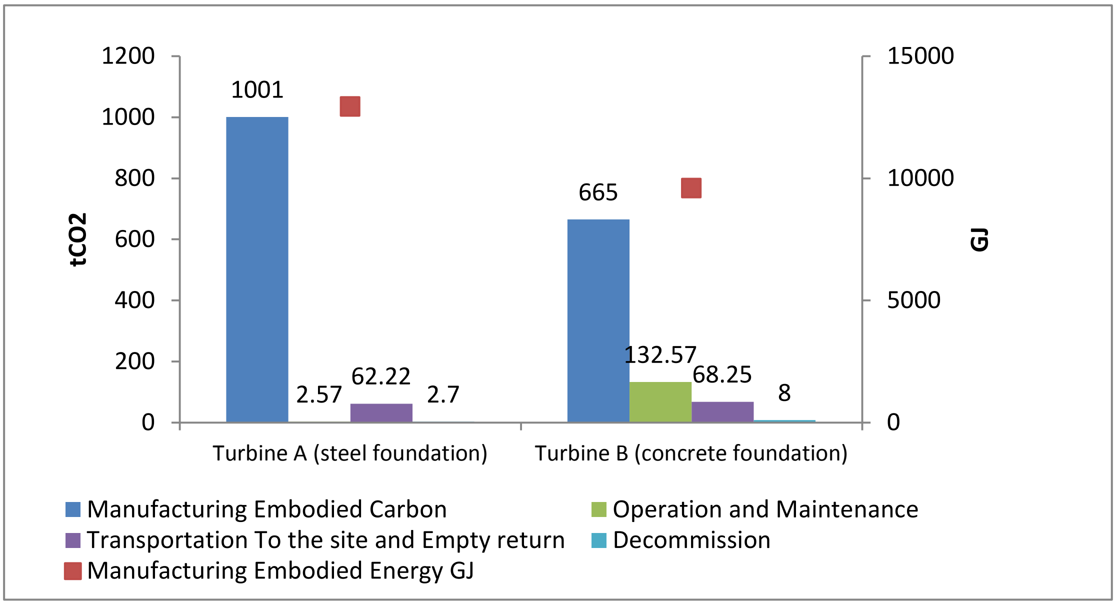


Figure 6.9 Embodied carbon and energy of Turbine A and Turbine B at different stages

6.6 Summary

LCA is a tool for the analysis of the environmental burden of products at all stages in their lifecycle. The objective of LCA of a process is to capture a range of environmental impacts that accumulate over the entire lifecycle, from the cradle to the grave. The LCA outlined was applied in ISO 14044 as four stages were carried out: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. The boundary of the analysis covered the manufacture of each of its component parts, transport to the wind farm, construction, operation and maintenance, and decommissioning. The impacts of the lifecycle were evaluated, including climate change, cumulative energy requirements, and energy payback time, which are the most important parameters in LCA and vary depending on the assumptions made. The most sensitive scenario is the manufacturing phase.

Due to the lack of information, some data of a country with environmental conditions similar to Kuwait has been used. All conversion factors for CO_2 emissions and fuel consumption in transportation are based on data from Brazil (Oebels and Pacca, 2013). Both embodied energy MJ/kg, which is defined as the energy required to produce a material from its raw form, per unit mass of material produced (Deshmukh and More, 2014), and embodied carbon dioxide $kgCO_2/kg$ are obtained from the Inventory of Carbon and Energy (ICE) at Bath University.

Table 6.6 Summary of the literature review of carbon footprint

Author	Onshore turbine model	gCO_2/kWh
(Martínez et al., 2009a)	2MW-Gamesa	6.6 g CO_2/kWh
(Tremeac and Meunier, 2009)	4.5MW and 250W wind turbines	15.8and 46.4 g CO_2/kWh
(Guezuraga, Zauner and Pölz, 2012)	1.8MW-gearless turbine and 2.0MWturbine with gearbox	8.82 gCO_2/kWh 9.73gCO_2/kWh
(Garrett and Rønde, 2013)	V80 2.0MW	7 to 10 g CO_2/kWh

The results presented in Table 6.6 of CO_2 per generated power vary according to the difference in turbine model and the difference in assumptions and limitations stated in the research. The values for the 2 MW wind turbines in of the literature range between 6.6 g/kWh and 10 g/kWh .

Table 6.7 Values of lifecycle for both turbines

	Units	Turbine A: steel pile foundation	Turbine B: concrete foundation
Total CO_{2e}	tonne	1069	874
Total cumulative energy requirements	GWh	3.6	2.7
Annual energy generated	GWh	5.116	5.116
Energy payback time	Year	0.7	0.5
CO_2	g/kWh	10.4	8.5

As shown in Table 6.7, the carbon footprint per functional unit is 10.4 gCO_2/kWh and 8.5 gCO_2/kWh for Turbine A and Turbine B respectively, According to IRENA, (2015), the average CO_2 emissions from Kuwait electricity using crude oil is high, at 645gCO_2/kWh (IEA, 2015). The difference between the average CO_2 emissions from electricity generated from oil and the carbon footprint per functional unit for Turbine A and Turbine B respectively is very high, at approx 98%.Iit is clear from the above that there is an environmental benefit to implementation of a wind farm in Kuwait. It is clear from Table 6.7 that CO_2 emissions per kWh in Kuwait conform with the literature findings in Table 6.6. It must be taken into account that the stage which most significantly affects the results is the manufacturing stage, which is almost the same for the 2MW wind turbine. On the other hand, any other difference in geographical boundaries, such as the manufacturers location for transportation, turbine model and size, and foundation type have minor affect on the results. The table also shows that the total carbon dioxide for Turbine A is greater than the emissions of Turbine B, at about 18%. Accordingly, the carbon footprint per unit generated in Turbine A is higher than Turbine B, which is consistent with the literature (shown in Table 6.6).

Table 6.7 shows that the total annual energy generated for both turbines is the identical because they use the same Gamesa 90-2MW wind turbine. However, the results in this table show a different value for the total cumulative energy for Turbine A and Turbine B, which is 3.6 GWh and 2.7 GWh respectively, because of the difference in the type of foundation. The payback time shows a slight difference of approxmate two months between both turbines due to the total cumulative energy requirements in GWh, which means that Turbine A will require about 8.4 months of operation to return the amount of energy used in manufacture, operation and decommission, whereas Turbine B requires approxmate 6 months. From reviewing literature the CO_2 emissions from wind energy (15g/kWh) is the lowest among other sources of renewable energy: solar, biomass and wave energies. In this study it has been found that the wind energy CO_2 emissions are (10.4 and 8.5) g/kWh which are lower than the average literature value of CO_2 emission from wind energy, because of the variation of the wind turbines farm location, the material of wind turbine, the material of foundation, size, and weight of wind turbine. Figure 6.10 shows the comparison of CO_2 emission between different sources of renewable energy, electricity used crude oil and wind energy.

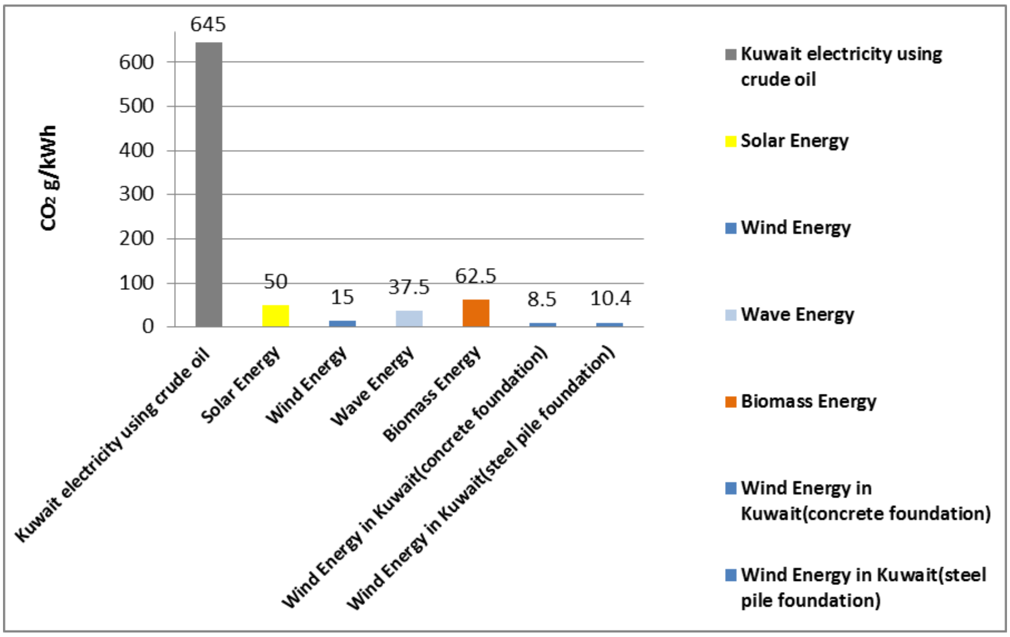


Figure 6.10 The comparison of CO_2 emission of different sources of energy

7 Finite Element Modelling

7.1 Introduction

In order to prevent instability and failure of the structure, an appropriate connection between the turbine tower and the ground must be provided. The foundation, which is the main part of a wind turbine structure, combines with the tower to transfer the load from the turbine to the soil. The size and the material of the foundation have significant effect on selecting the most economical and environmentally friendly foundation, without affecting the structure integrity which is more important. According to the findings in chapters 5 and 6 concrete foundation is lower cost and environmentally friendly than the steel foundation. However, in this study steel pile foundation was used.

The numerical modelling of the whole system will be presented in this chapter as follows:

- Validation model with available data, which is a necessary step for acceptance of the results and effectiveness of a model. The model can then be used as a tool for investigating the effect of the parameters on wind turbine and soil behaviour. Two validation models were modelled. First, steel wind turbine tower was modelled to investigate the tower deflection and stress. Second, wind turbine tower with its steel pile foundation surrounded by soil which is similar to my real model to understand the soil behaviour and steel tower displacement and stress.

- Identify any areas of the model requiring modification and improvement based on the validation.

- Implement the improvements into COMSOL with the identified modifications.

- Run analyses to determine the stability of the problem and understand the soil-structure interaction.

- Identify critical parameters within the model that control behaviour and stability.

This chapter will present the numerical model used in the present study. The equations governing the soil response and the pile behaviour are described, and the boundary conditions presented. The assumptions and the limitations of the numerical model are then discussed and finally the implementation of the equations in the commercial software package COMSOL is presented. COMSOL is a commercial FEM (Finite Element Method) tool that allows the users to design their own governing equations and boundary conditions for specific physical problems (Chang and Jeng, 2014).

To model a wind turbine in the environment and soil of Kuwait, different stages should be taken into account, as shown in Figure 7.1. The approach is based on FEM analysis by using COMSOL software. In the first stage, soil modelling only to check geostatic equilibrium which is defined before the pile is installed (Kellezi and Hansen, 2003; Pitilakis et al., 2014; Ahmed and Hawlader, 2016). This will be validated later in sections 7.5 by using fundamental soil mechanics for linear solutions. The second stage will be soil with pile foundation modelling to check the behaviour of soil and pile. Finally, the steel wind turbine tower has been inserted into the 3D model to conduct the soil-structure interaction which will be validated against the literature (previous modelling studies for wind turbine tower). The combined static loads are applied as the vertical load of the tower weight and then the lateral loads of wind load and load from rotor torque are applied on the top of the wind turbine tower head.

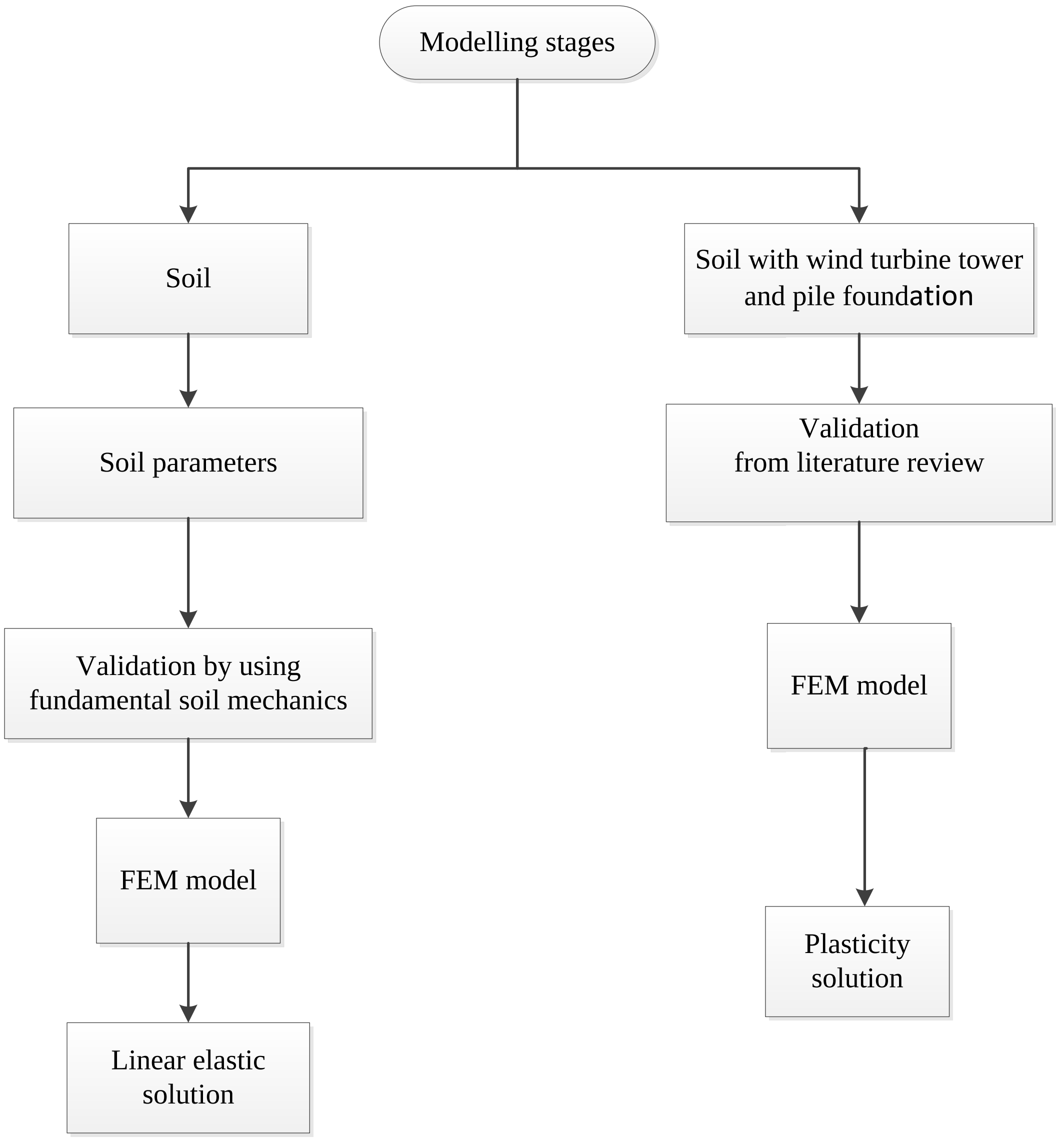


Figure 7.1 Stages of modelling by COMSOL

For FE analysis; a number of assumptions are made:

1. The soil is an isotropic material,

2. Reversibility of stress-strain relations under final equilibrium conditions,

3. Small strains,

4. The pore-water pressures are zero due to drained condition for sand under static loads.

Similar studies have investigated different solutions for the support of wind turbine in general locations. Literature were identified and reviewed to compare the top tower total displacement and maximum Von Mises stress values, as shown in Table 7.1.In the process of validation and verification of the model (see section 7.2), a case study from the literature has been utilised. The author studied the soil-structure interaction for onshore wind turbine which is similar to the research interest.

Table 7.1 Summary of wind turbine FE analysis literature

Reference	Description	Maximum displacement (m)	Maximum Von Mises stress (MPa)
(Lozano-Minguez, Kolios and Brennan, 2011)	-5.5 MW Offshore wind turbine (90 m length, 6 m base diameter, 3.87 m top diameter and 0.02 m thickness). - Submerged Dense Sand (75 MPa Young's modulus and Poisson's coefficient 0.3). -monopile (35m in water+40m in soil 7m diameter, and 0.04m thickness) - Software :Abaqus	2.37	177.6
(Chien and Jang, 2009)	-Steel tubular tower of V47-660kW onshore-wind turbine(50m height, 3m diameter,15mm thickness) -No information about dimension of pile foundation or soil type. Software: SAP2000	0.5059	-
(Hsu, Wu and Chang, 2014)	-5MW wind turbine tower subjected to static loads (100 m height, 3. Top diameter 3.87m, bottom diameter 6m, top thickness 0.019and bottom thickness 0.027) -Wind turbine (Modulus of Elasticity 210GPa, Poisson's Ratio 0.29,Density 7.7 g/cm3 and Tensile Strength Steel 460MPa) - No information about soil and foundation	2.401	300
(Xie, Tseng and Chang, 2010)	-5MW wind turbine tower subjected to static loads (100 m height, 3. Top diameter 3.87m, bottom diameter 6m, top thickness 0.019and bottom thickness 0.027) - No information about soil and foundation	2.781	402.5
(Papanastasiou, 2011)	- V90 – 3MW onshore-wind turbine (90m height, bottom base diameter 4.15m and top base diameter 2.3m, thickness 75mm)(Modulus of Elasticity 250GPa, Poisson's Ratio 0.33,Density 7.85 g/cm3 and Tensile Strength Steel 200MPa) -pile foundation (4.15m diameter, 22m length, 75mm thickness) -Clay Soil (Young's Modulus 300MPa, Cohesion 140 kPa, Poisson's Ratio 0.33, Bulk Density 2000 kg/m^3) -Software: COMSOL v3.5	2.03	200

7.2 Finite Element Model

In this study COMSOL software was used to perform the FE analyses. Wind turbine tower with a pile foundation was installed in drained dense sand and then simulated.

The wind turbine tower is laterally loaded for different loads which are wind pressure along the tower length and the aerodynamic loads from the rotor of the wind turbine generator. Investigation by FE analyses to find the displacement and stress was obtained. The soil was modelled as a 40mx40mx40m cube; this was considered to be large enough to ensure that the boundary conditions imposed on the model had no influence on behaviour of the wind turbine and the soil in close vicinity.

7.2.1 Linear elastic model

Linear elastic model to use as a first analysis of the problem as the calculation tends to be fast for simplicity, frequently it has been characterized the real soil behaviour of using idealized of linear elastic model. The results have been obtained from this model is reasonable and far away from failure (Potts and Zdravkovic, 1999) . Linear elastic model was conducted for the soil.

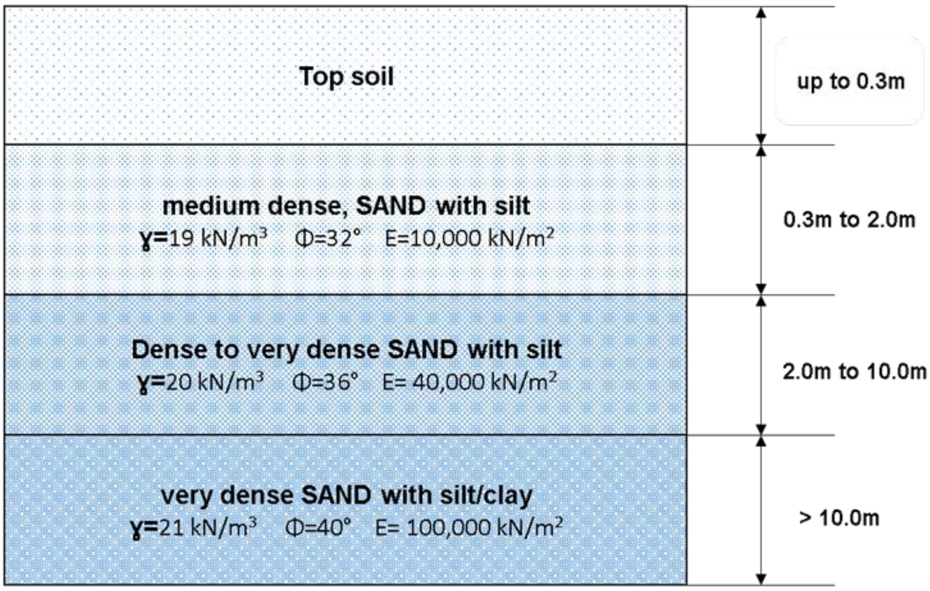
7.2.1.1 Soil Simulation

COMSOL represents real soil behaviour; a simulation of the soil consists of 3 layers ranging from medium dense to very dense sand as shown in the soil profile in Figure 7.2.

The input parameters for the simulations are summarised in Table 7.2. The effective body force of the soil was adopted to find out the initial behaviour to be able to initiate the second step whiles the pile was installed.

Table 7.2 Soil material properties for the three layers

Description	Value
Layer 1	
Young's Modulus (E)	1.00E+08 (Pa)
Poisson's Ratio (ν)	0.33
Bulk density (Ɣ)	2100 (Kg/m^3)
Friction angle (Ø)	40°
Layer 2	
Young's Modulus (E)	4.00E+07 (Pa)
Bulk density (Ɣ)	2000 (Kg/m^3)
Friction angle(Ø)	36°
Layer 3	
Young's Modulus (E)	1.00E+07 (Pa)
Bulk density (Ɣ)	1900 (Kg/m^3)
Friction angle (Ø)	32°



Where, γ is the bulk unit weight of soil (kN/m^3)
Ø is angle of internal friction and
E average modulus of elasticity (kN/m^2)

Figure 7.2 Schematic representation of the boundary conditions applied to the soil (repeated)

7.2.1.2 Geometry

A 40m x 40m x 40m soil block was drawn in COMSOL and boundary conditions were set as shown in Figure7.3

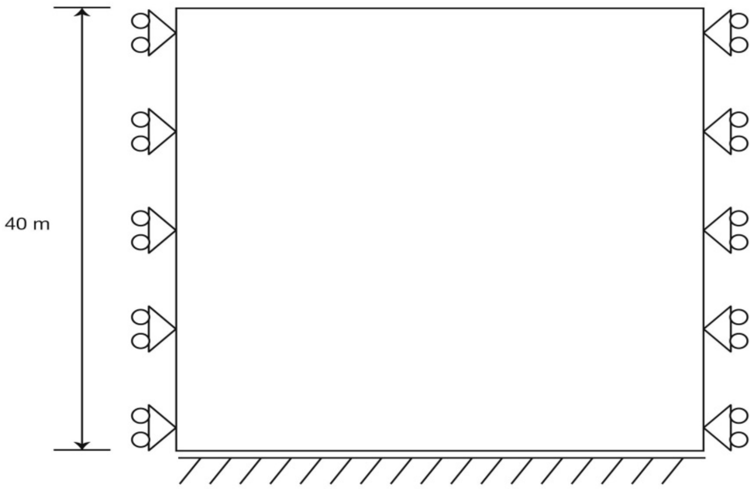


Figure 7.3 Vertical section in the soil with boundary condition set

7.2.1.3 Results

The COMSOL model simulated the effects on the sand by showing the stress and deformation. The region of soil that experienced deformation in the simulation is shown in Figure 7.6. The vertical and horizontal stresses for the soil using COMSOL are equal to the vertical and horizontal stresses calculated using the fundamental soil mechanics equation as illustrated in Figures 7.4 and 7.5. The soil's vertical and horizontal stresses can be calculated using basic soil mechanics (Barnes, 2010; Das, 1999; Sivakugan and Das, 2010); the equations for determining the vertical and horizontal stress of the soil are shown below:

$$\sigma_v = \gamma * h$$ **Equation 7-1**

$$K_o = 1 - sin\emptyset$$ **Equation 7-2**

$$\sigma_h = \sigma_v * K_o$$ **Equation 7-3**

In Equation 7-1, the vertical stress of the soil is equal to multiplying the density of the soil; hence a 21kPa by 40m depth will equal 840kPa, which is almost the similar to number attained by the COMSOL simulation which is 812 kPa (Figure 7.4). In addition, the horizontal stress of the soil based on equation 7-3 is 437 kPa as shown in Figure7.5.

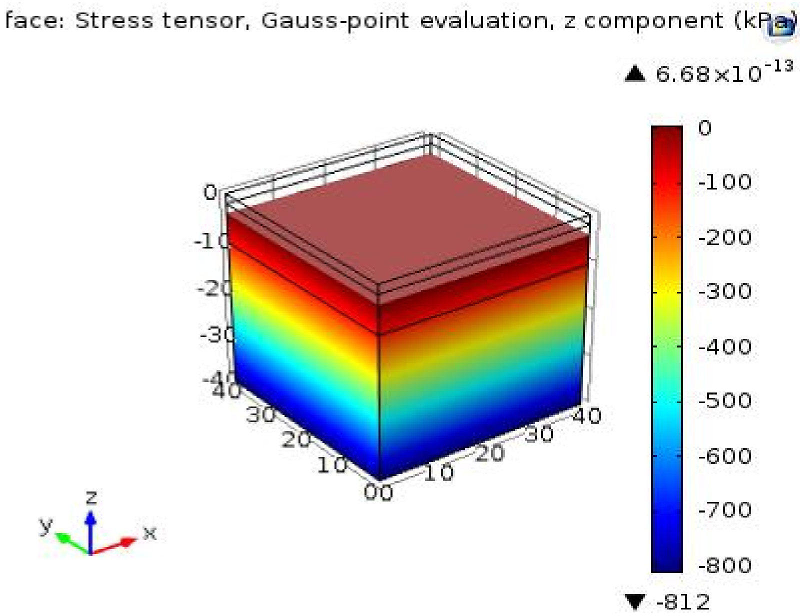


Figure 7.4 Vertical stress of the soil (kPa)

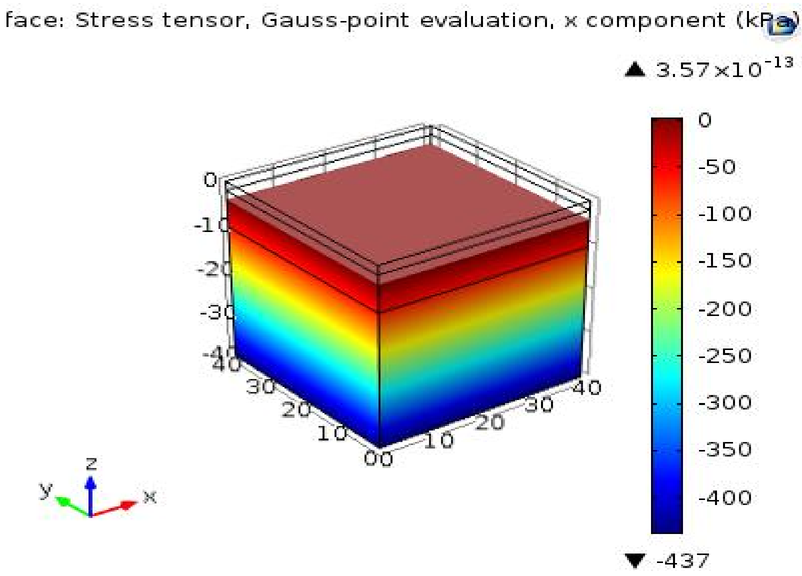


Figure 7.5 horizontal stress of the soil (kPa)

The initial displacement of the soil due to self-weight in z direction is 11cm as shown in Figure 7.9:

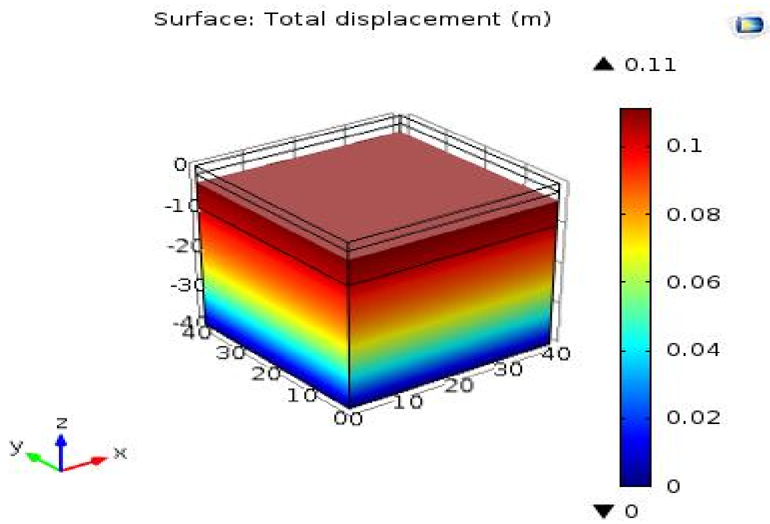


Figure 7.6 Vertical displacement of the soil due to gravity load (m)

7.3 Case Study for Validation: (Papanastasiou, 2011)

Papanastasiou (2011) developed numerical models of a 3MW Vestas V90 wind turbine using COMSOL v3.5. The researchers calculated the loads for the wind turbine based on the stander of (DNV GL, 2015). The static model created by (Papanastasiou, 2011) has been reconstructed and modelled in COMSOL v5.0. The model was a 3MW Vestas V90 wind turbine was implemented in a clay soil layer. Soil –structure interaction was considered, soil plasticity with Mohr-Coulomb model for the soil and Von-Mises constitutive model for the steel structure were used. The boundary condition has been considered, Fixed the soil layer at the base of the deepest soil layer; roller in the vertical direction on the four external edges of the soil block. The total horizontal displacement experienced by the tip tower was 2.05m and the maximum Von Mises stress was 236 MPa.

7.3.1 Static Model

In order to validate the COMSOL Multiphysics v5 software and the constitutive models, the static model created by (Papanastasiou, 2011) was reconstructed and modelled within COMSOL 5. Both material properties and boundary conditions have been applied identically to the validation study. The modelling was carried out in 3D using the structural mechanics module-static analysis elasto-plastic material. First the geometry was drawn and then the material properties, constrains and loads were specified. Under the elasto-plastic material settings, Mohr-Coulomb model and Von-Mises constitutive models were chosen. The mesh was initialised, refined.

7.3.2 Geometry

A wind turbine with 3MW rated power has a 90m tower height, conical tower is with a base and top diameter of 4.15m and 2.3m respectively. The thickness of the tower wall was assumed constant along the tower height which is 75mm. The mass on the top of the tower was weighted 152,000kg. The mono-pile foundations, has a base diameter of the tower (4.15m) deep to the soil of 22m length and thickness of 75mm. The soil has been modelled as a 40 x 40 x 40m cube.

7.3.3 Material properties

The V90 – 3MW turbine tower and foundation have both been modelled as structural steel as shown in Table 7.4. The Von Mises yield criterion was chosen as to produce good results for materials such as metals where hydrostatic pressure does not influence the behaviour of the material (de Souza Neto, Peric and Owen, 2008).

Table 7.3 Tubular tower and foundation material properties

Material Parameter	Unit
Young's Modulus	200 (GPa)
Poisson's Ratio	0.33
Density	7850 (kg/m^3)
Yield Level	200 (MPa)

The soil was modelled utilising the Mohr-Coulomb yield criterion. The material parameters presented in Table 7.5.

Table 7.4 Soil material properties

Material Parameter	Unit
Young's Modulus	300 (MPa)
Cohesion	140 (kPa)
Poisson's Ratio	0.33
Bulk Density	2000 (kg/m^3)

7.3.4 Loading

Analysis is divided into wind condition load and structural load. The wind pressure along the tower of wind turbine length was applied as uniformly distributed load (udl) with the tower height. The remaining loads were applied at the top of the tower at the nacelle level and are summarised in Table 7.6; these represent the loads transferred from the turbine and rotor to the tower. The values of load presented here have been calculated via the simplified method (DNV, 2002).

Table 7.5 Loading from wind turbine and rotor

Loading Type	Magnitude
Moment about horizontal axis in rotor plane (Mx) (kNm)	14314
Horizontal force along rotor axis (Fy) (kN)	1909
Moment about Vertical Axis (Mz) (kNm)	14314

7.3.5 Boundary Conditions

The soil layer at the base of the deepest soil layer was fully fixed; roller in the vertical direction on the four external edges of the soil blocks to constrain the horizontal movement.

7.3.6 Meshing

Tetrahedral mesh elements were used. Mesh density was 108 368 elements. The number of degrees of freedom solved was 28 552.

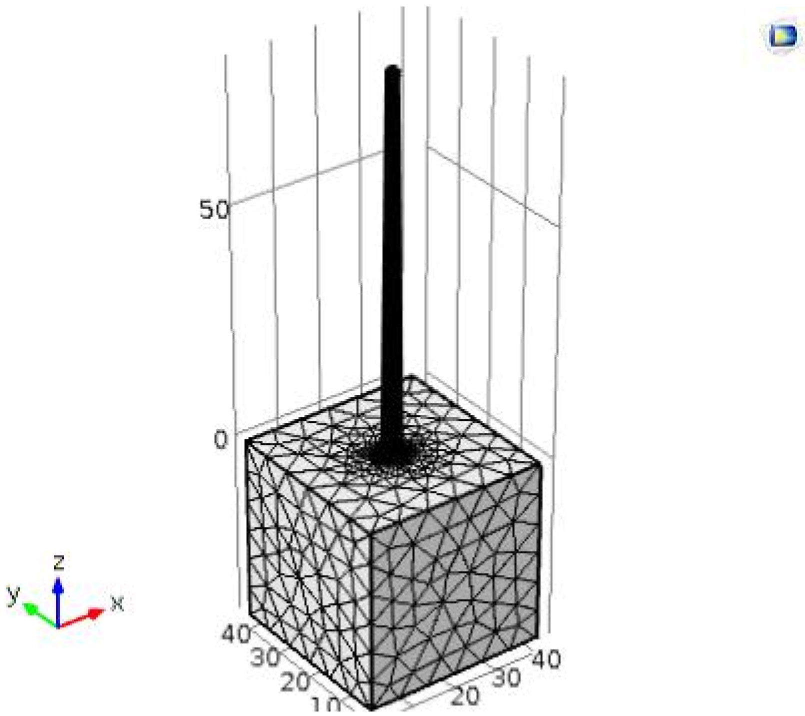


Figure 7.7 Mesh of the validation model

7.3.7 Results

The total horizontal displacement experienced by the tip tower was 2.05m as shown in Figure 7.9, and the maximum Von Mises stress at the base of the tower was as displayed in Figure 7.10. Soil vertical displacement at Z direction was 0.03m as shown in Figure 7.11. Table 7.7 compares the results obtained in the validation study to the numerical model created for validation.

Table 7.6 Comparison of maximum displacement in x-direction between validation study and numerical models created for validation.

	Case study	**Numerical model created for validation**	**Deviation from validation study**
Maximum displacement in x-direction(m)	2.03	2.05	0.97%
Von Mises	2.003e8Pa	2.36e8Pa	15%
Soil displacement	0.023	0.03	23.3%

As displayed in Table 7.7 there are acceptable different between the result, that's due to in the case study Papanastasiou (2011) he used COMSOLv3.5 which is old version and implement the Von Mises model in the software which can give less accurate of the built in Von Mises model in COMCOL v5.0. Otherwise, for the purposes of this investigation, the comparison of the results to the validation study is considered sufficiently accurate.

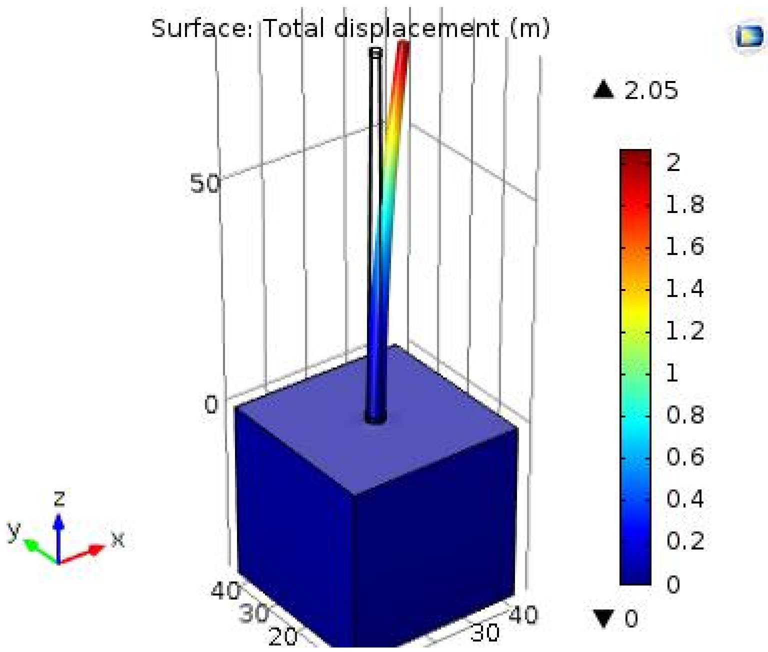


Figure 7.8 Total displacement of the wind turbine tower

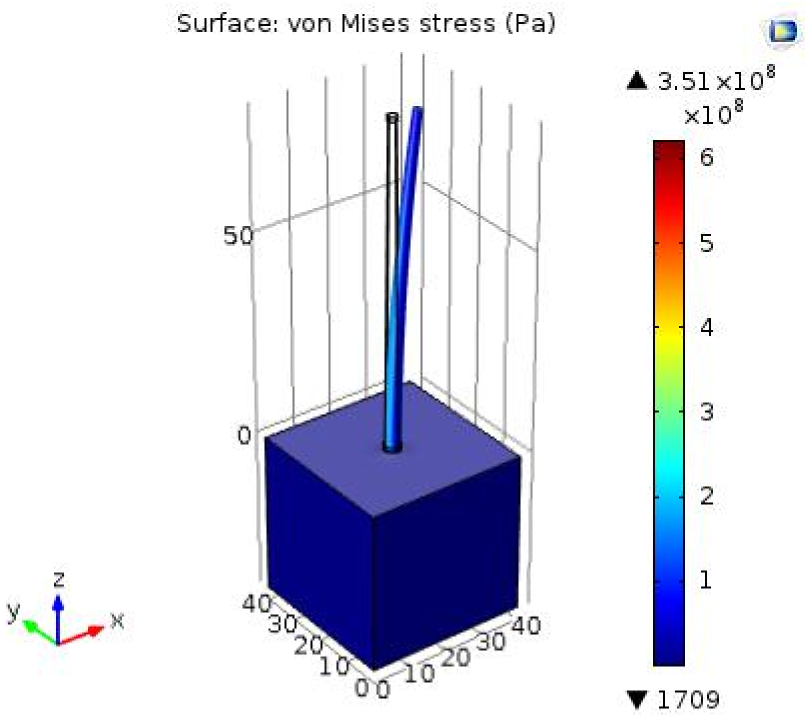


Figure 7.9 Von Mises stress of the wind turbine tower

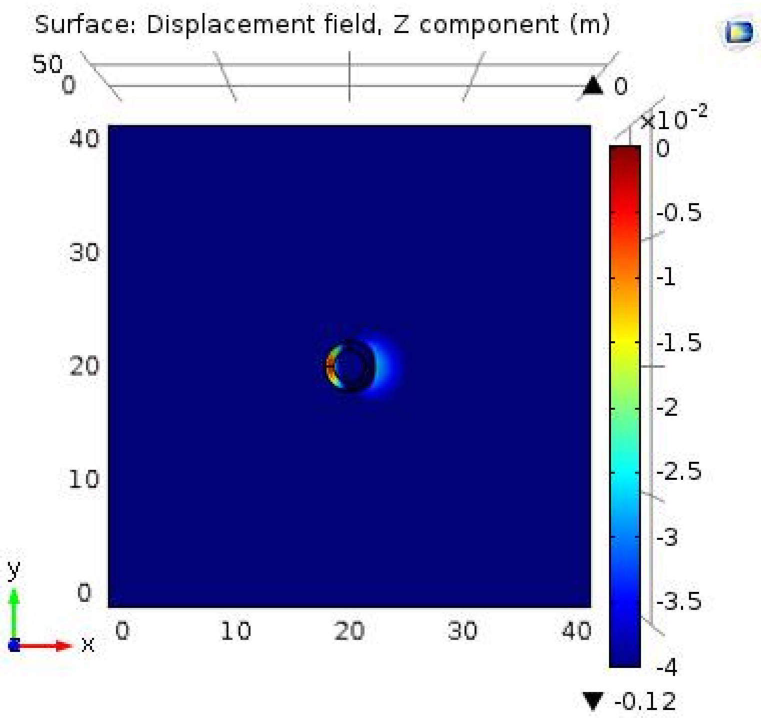


Figure 7.10 Soil displacement at Z direction

7.4 The Final Numerical Model

The static model was divided into three geometric groups: the soil, the foundation and the tower; the thickness of the wall of the tower is 75mm; the tubular tower is conical with an assumed base and top diameter of 4.15m and 2.3m respectively; and the standard specification of the wind turbine within the software was provided by Gamesa for its G90-2.0 MW turbine model. The material properties for the soil are assigned based on the KISR investigation and the geometry and material properties for the pile are based on a preliminary pile design done by which consists of a 4.15m diameter and 22m pile length (Papanastasiou, 2011). The entire system geometry was drown by using COMSOL is shown in Figure7.12. The results came within the range of the total displacement. The total top tower displacement of 2.35m was acceptable compared to the literature in Table 7.1

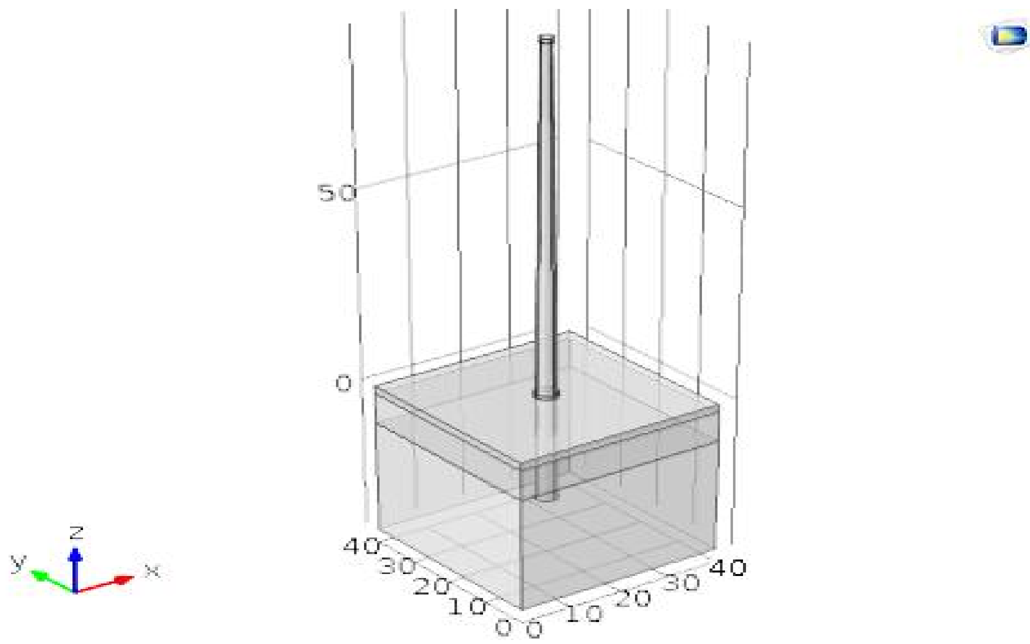


Figure 7.11 the entire system drown by using COMSOL

7.4.1 Geometry

In this analysis a conical steel tower with base diameter 4.15m, 2.3m top diameter and thickness wall of 0.075m was modelled as shown in Figure 7.13.

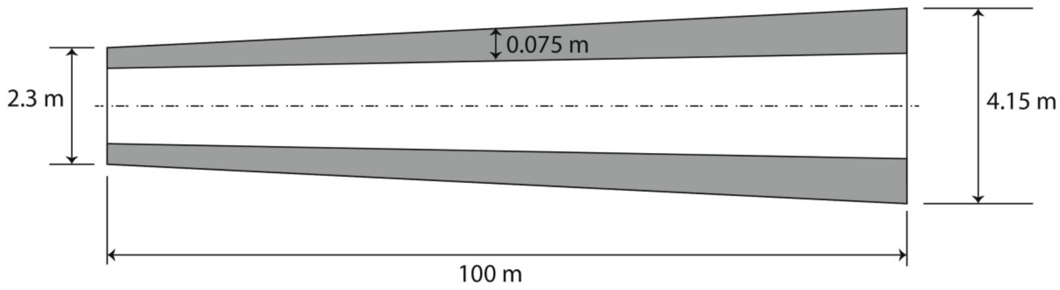


Figure 7.12 Sectional dimensions of the tower

The soil was modelled as a 40m x40m x 40m cube; with different layer due to field study by KISR proposed 5B metre distant from the face of the pile foundation on both sides (where B is the diameter of the pile) (EL-Hamalawi, 2011) as started with this size of the soil which is examined for the stress and strain adjust to the boundary, it was found that the tower-induced strain and stress around the boundaries are neglectable. Accordingly, the proposed dimension of the model was considered as suitable (Figure 7.14). The same rule applies for the model depth in the z-direction, since the pile –imposed stresses and strain have no effect (5B metre) where B is the diameter of the pile below the tip of the pile (Figure 7.15).

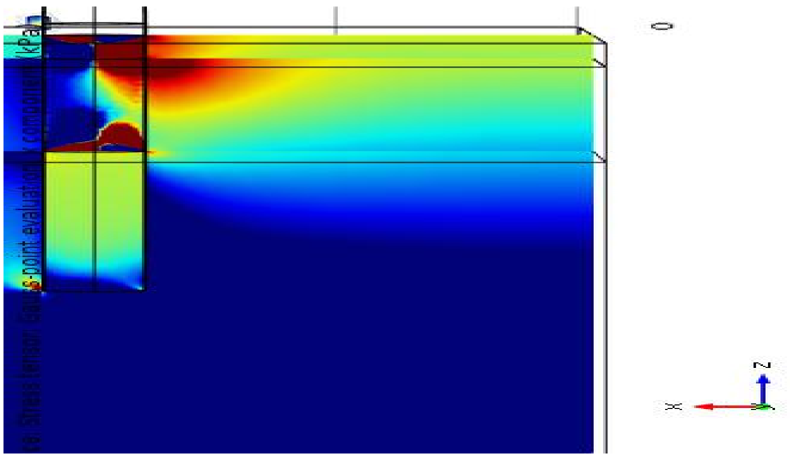


Figure 7.13 Effect of the soil stress around the pile on the ground surface

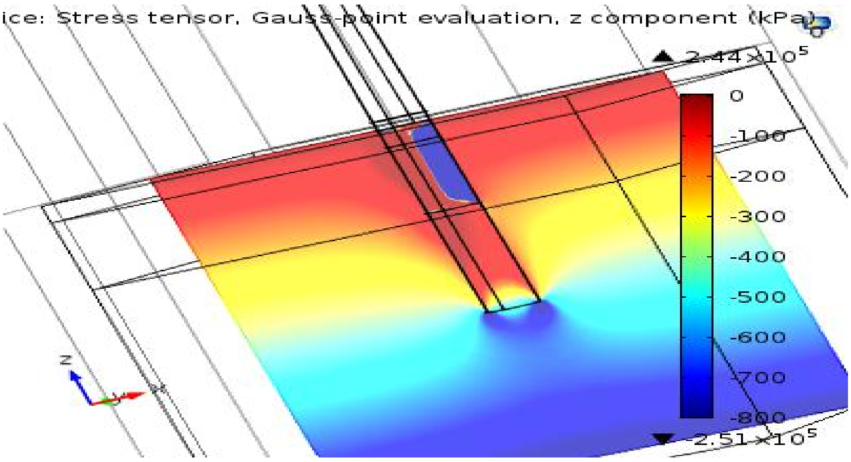


Figure 7.14 Effect of the soil stress below the tip of the pile (kPa)

As shown on Figure 7.16 below, the soil displacement vanishes 8 metres off the centre of the pile at the ground surface at maximum lateral deformation. Due to this consideration, the soil size is large enough to ensure that the boundary conditions imposed on the model had no influence on the behaviour of the turbine and the soil in the close vicinity.

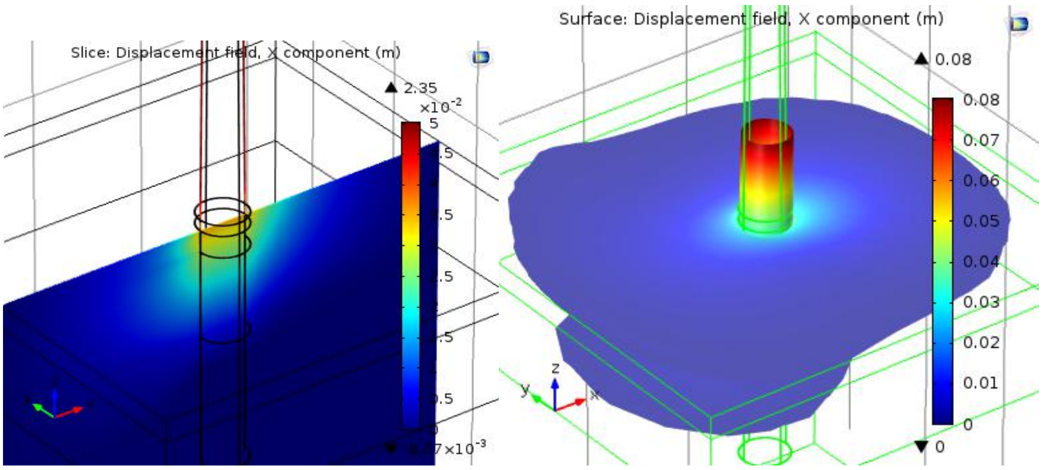


Figure 7.15 Vertical section on the (xz plane)left and top veiw (right) of the effect of the displacement around the pile on the ground surface

7.4.2 Material Properties

Table 7.2 shows the soil material properties which have three different layers. The tower and tubular pile foundation have both been modelled as structural steel in accordance with the material properties provided for the Gamesa 90-2MW wind turbine (Pereg and Fernandez de la Hoz, 2013) and are detailed in Table 7.3 as the tower and pile have the same properties.

7.4.3 Material Models

In this research, various constitutive models including linear elastic and elasto-plastic constitutive models have been used. The pile is modelled linear elastically using Von Mises yield criteria; the soil has been modelled using an elastoplastic perfectly plastic constitutive model adopting Mohr-Coulomb yield criterion. Due to absence of plastic region in the model, soil hardening or softening has been considered to be out of the scope of this research.

7.4.4 Loading

Wind loads are the main loads in the design of parabolic collector structures. There are also external loads which are taken into account during the design of the structure, including dead load, resulting from the self-weight of the structure, and loads due to exposed wind (Figure 7.17) (Schweitzer, 2012).

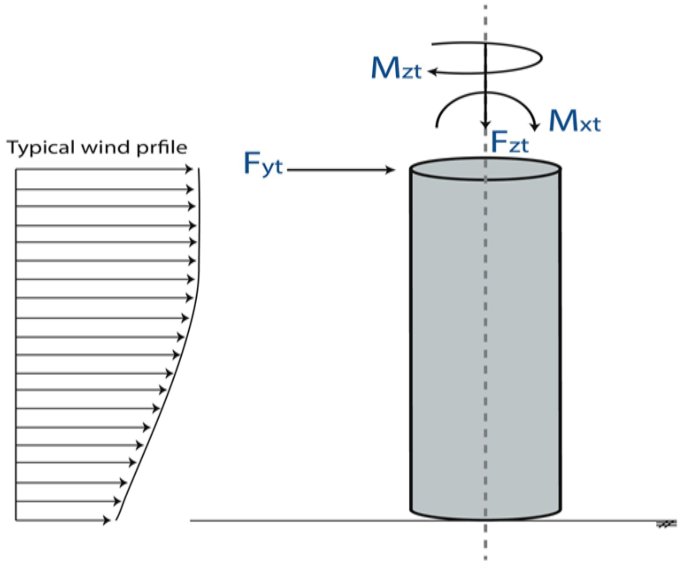


Figure 7.16 loads acting on a wind turbine supported on a pile foundation (Lombardi, Bhattacharya and Muir Wood, 2013)

The fundamental basic wind velocity was taken to be 8.5m/s (See Appendix G Wind Force calculation).

The remaining loads were applied at the top of the tower at the nacelle level and are summarised below in Tables 7.8 and 7.9 which show specifications of the wind turbine and loading from wind turbine and rotor respectively; these represent the loads transferred from the turbine and rotor to the tower. Figures 7.18 demonstrate the loading arrangement at the tower top. The tower top has a diameter of 2.3m, therefore both Mx and My have been simulated by two equal and opposite point loads in the denoted directions of magnitude 7791.3kN, i.e. Fy has been applied as a horizontal point of magnitude 2217kN.

The values of load presented here have been calculated via the simplified method (DNV, 2014) and as described below:

- Design rotor loads by simplified method (static load)

$$\boldsymbol{F0 = 300A\ where\ A\ is\ the\ swept\ area\ of\ the\ wind\ turbine}$$ **Equation 7-5**

Where:

$F0$ is the airflow load

A= πR^2 , R is the radius of the rotor

$$\boldsymbol{Me, nom = \frac{Pnom}{2\pi \times nr \times \zeta}}$$ **Equation 7-6**

Where:

Me, nom is a driving torque

$Pnom$: Nominal power of wind turbine

$\zeta: nominal\ frequency \leq 0.9$

$nr: rotor\ efficiency$

Horizontal force in rotor plane (F_x =0)

Moment about horizontal axis on rotor plane (M_x= e $F0$) where: e = R/6.

Horizontal force along rotor axis (F_y =$F0$)

Moment about rotor axis M_y =1.3 Me, nom

Vertical force (self-weight) $F_z = -mg$, where m is mass and g=9.81 kg/m^3

Table 7.7 Specification of wind turbine

Specification	Value
Rotor diameter	97m
Swept area	7390m^2
Nominal power	2000000W
Rotor frequency	0.27
Rotor efficiency	0.8
Total mass of wind turbine	335 tonnes
Mass of blades & nacelle	72+47 = 119 tonnes = 119,000kg

Table 7.8 Loading from wind turbine and rotor

Loading Type	Magnitude
Moment about horizontal axis on rotor plane (M_x) (kNm)	17920
Horizontal force along rotor axis (F_y) (kN)	2217
Moment about vertical axis (M_z) (kNm)	17920
Vertical force on the tower F_z (kNm)	11674
Moment about rotor axis (M_y)(KNm)	1916

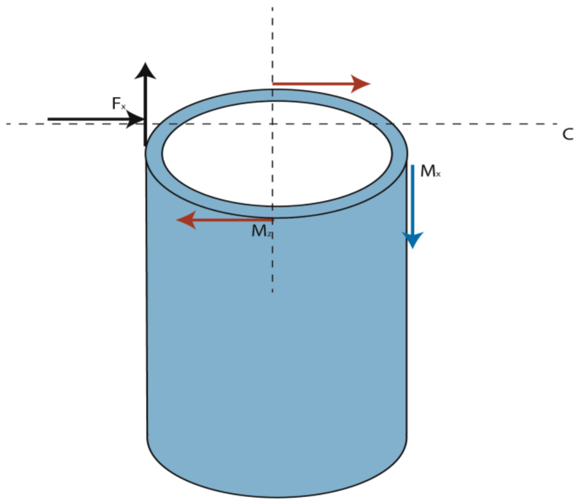


Figure 7.17 Turbine and rotor loading arrangement

7.4.5 Boundary Conditions

The boundary conditions have been applied to the present model such that they do not influence the behaviour of the turbine, foundation and the soil in the close vicinity. The soil was fully fixed at its base and in the horizontal direction only on all four vertical sides of the cube; a Horizontal and Vertical sections representation of this is presented in Figure 7.19 and 7.20.

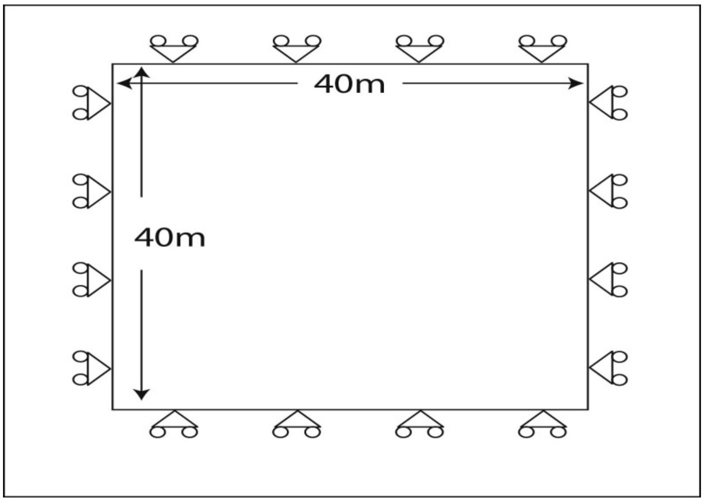


Figure 7.18 Horizontal section of the boundary condition of the soil

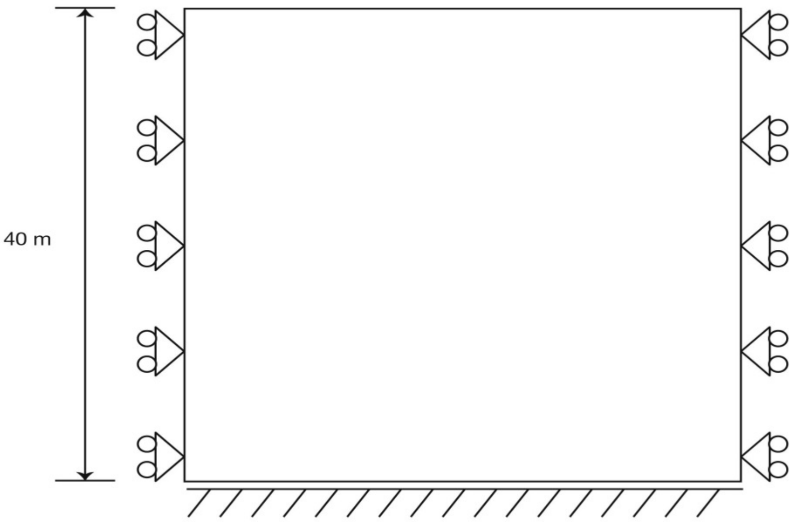


Figure 7.19 Vertical section of the boundary condition of the soil

7.4.6 Interactions

The pile and tower were fully connected with the boundary between the top of the pile and the tower. The Soil/pile interaction was setup such that the pile and the soil deform in-phase, and that the amount of deformation of both the soil/pile is equal at the interface.

7.4.7 Meshing

Owing to the different combined geometries of the model (cylindrical, cubical) free tetrahedron stress/solid elements have been chosen to discretise the model. Due to the high expected stresses and displacement in this model, mesh refinement was incorporated through which the top layer and the area surrounding the pile were meshed with smaller elements (finer mesh).Mesh density was 115560 elements. The number of freedom solved was 31468, as shown below in Figure 7.21

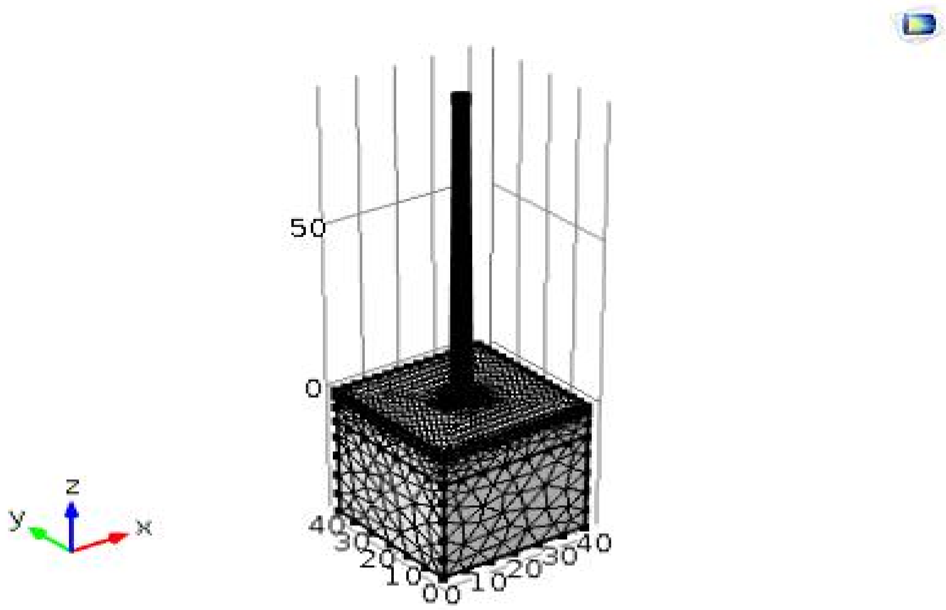


Figure 7.20 The Mesh of the model

The nominal element size in the coarse part of the mesh is 19.7 m and the nominal element size in the finer part of the mesh is 7.21m. The number of elements within the model totalled 164418, including 132704 tetrahedral, 28895 triangular, 2739 edge, and 80 vertex elements.

7.4.8 Results

The results are within the range of the total displacements shown in the summary of the literature review in Table 7.1. The total displacement of the tower tip of the wind turbine was 2.35m, on the loads direction X axis (Figure 7.22).

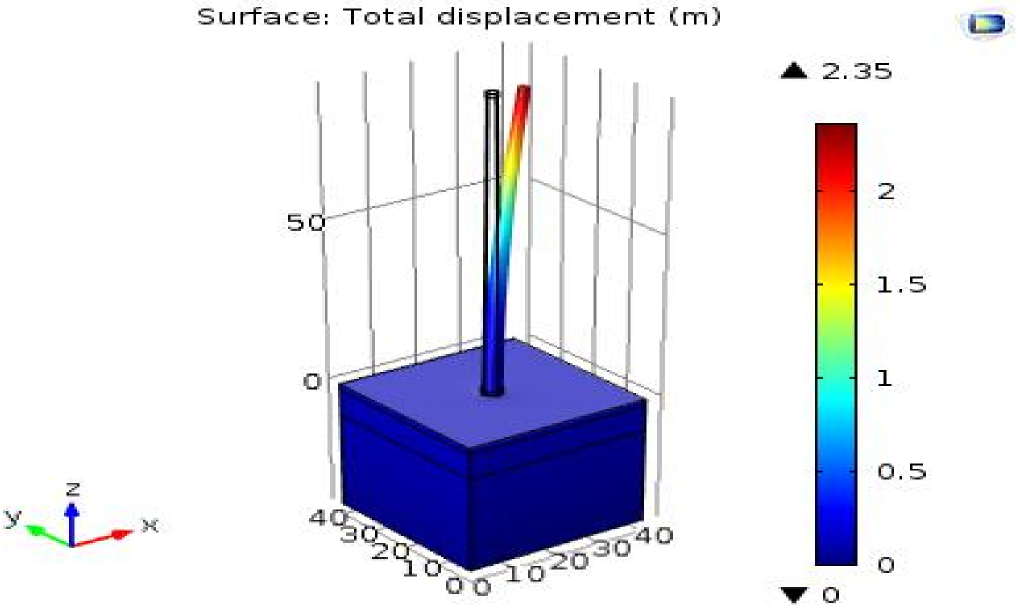


Figure 7.21 The total displacement in meter of the wind turbine tip tower (m)

The maximum Von Mises stress at the base of the tower is 230MPa as shown in Figure 7.23 which is engaged within the results in the Table 7.1 of the summary of literature review.

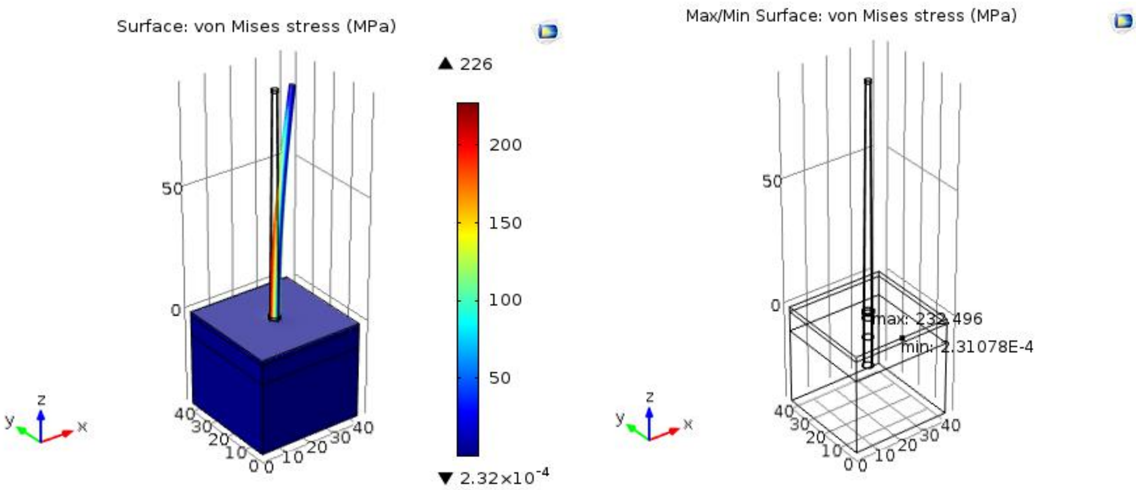


Figure 7.22 Von Mises stress on the base of the tower and the maximum stress point (MPa)

Figures 7.24 and 7.25 show that the vertical displacement in the Z direction under the pile was (8cm) while the lateral displacement in X direction on the pile head is 3.5cm.

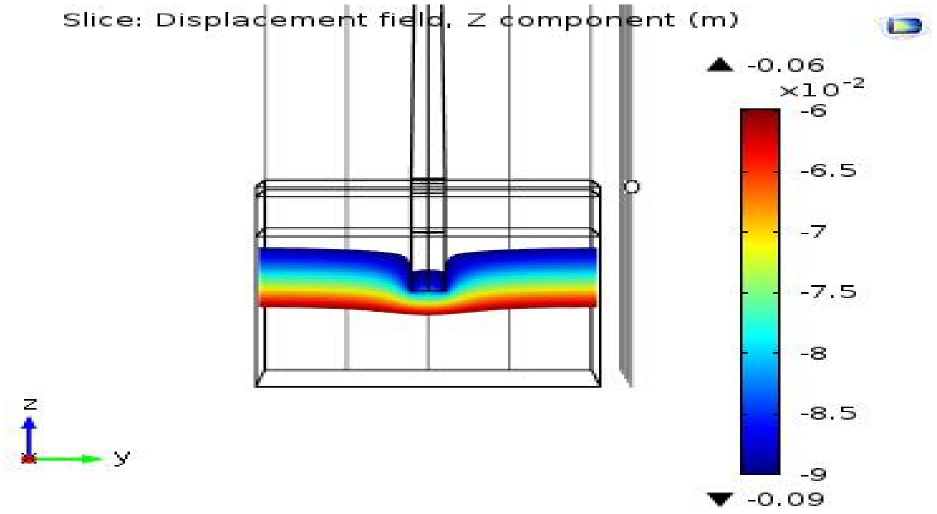


Figure 7.23 Vertical displacements at Z direction under the pile (m)

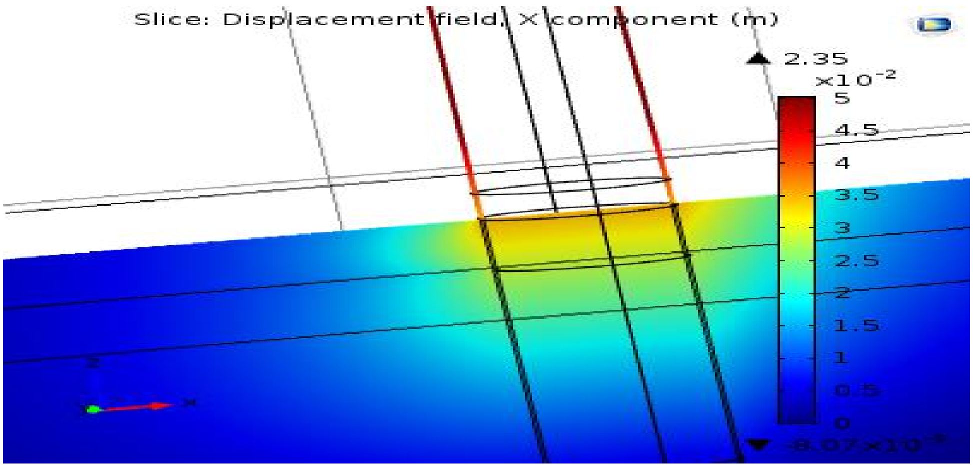


Figure 7.24 Lateral displacement on the pile head (m)

The stress on the pile was also reasonable at the head of the pile; Figure 7.26 below shows the tension (in blue colour) is negative value of -100MPa and the compression sides (in red colour) is positive value of 80MPa.

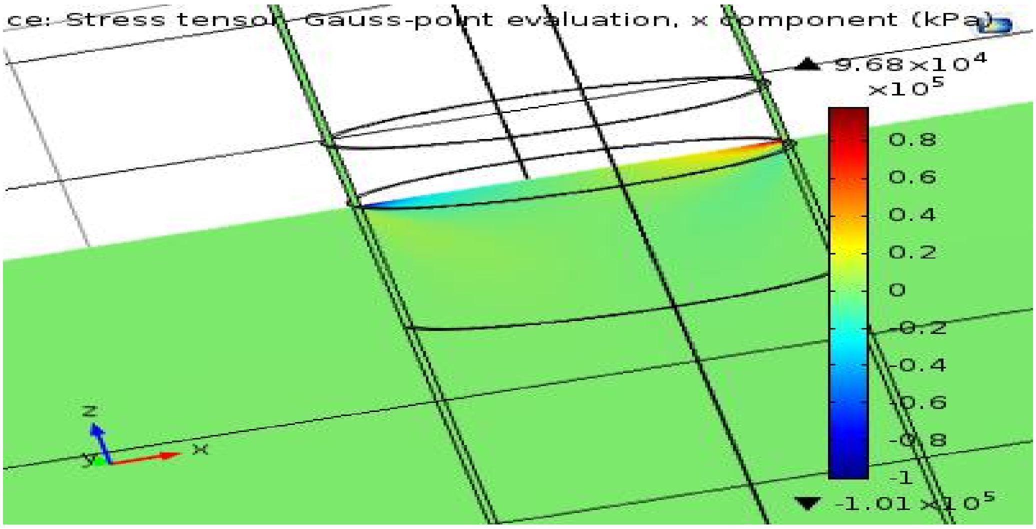


Figure 7.25 lateral stress on the head of the pile (kPa)

The vertical displacement of the soil in the Z direction including the pile was 14cm as shown in Figure 7.27 compared with the initial displacement of the soil without the pile was 11cm which is due to its self-weight (Figure 7.28). The soil acutal vertical displacement due to the pile is therfor 3cm, which is reasonable as the soil at lower cohesions, deformation is occurring within the soil, subsequently inducing larger deformations within the structure. Which is the deformation in the soil of the literature is less due to high cohesion of the soil like clay or rock.

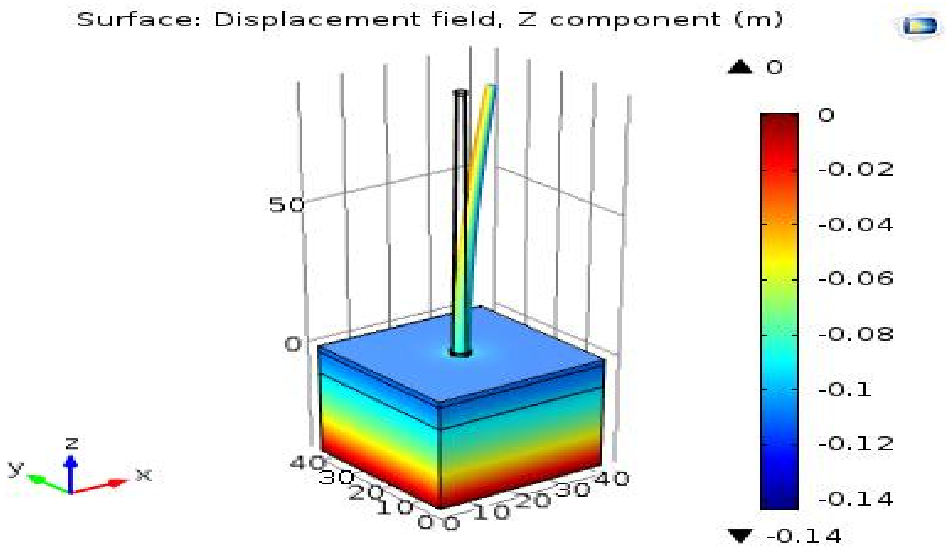


Figure 7.26 Vertical displacement of the soil in Z direction (m)

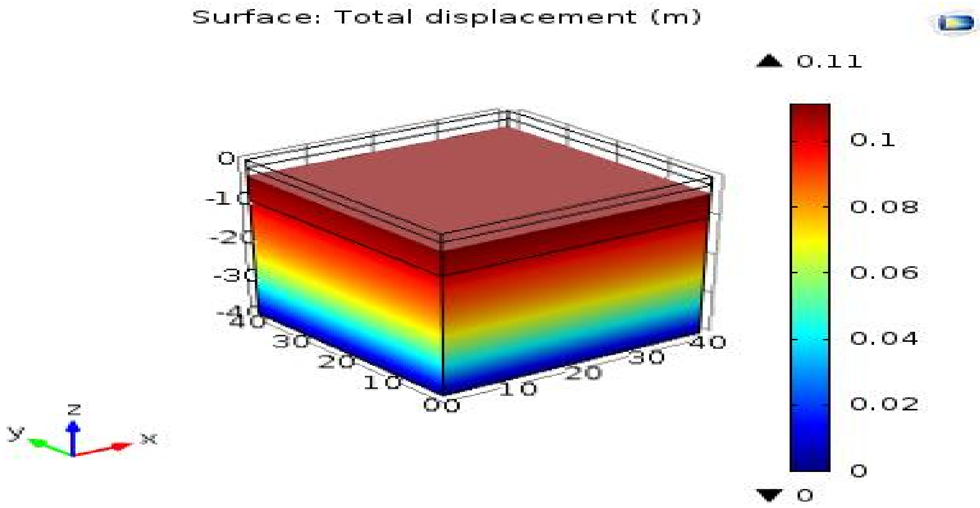


Figure 7.27 Initial vertical displacement of the soil in Z direction (m)

Figure 7.28 shows that the displacement of the soil in the X direction which is on the ground surface is 3cm whereas the soil displacement in the Y direction was 7mm which is very small and reasonable due to the effect of the load on the X direction (Figur7.29).

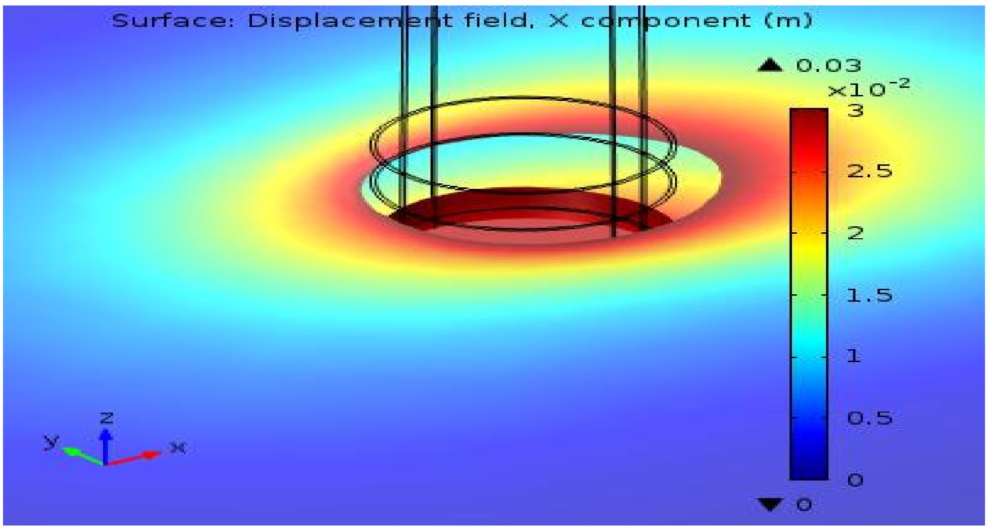


Figure 7.28 lateral displacement of the soil in X direction (m)

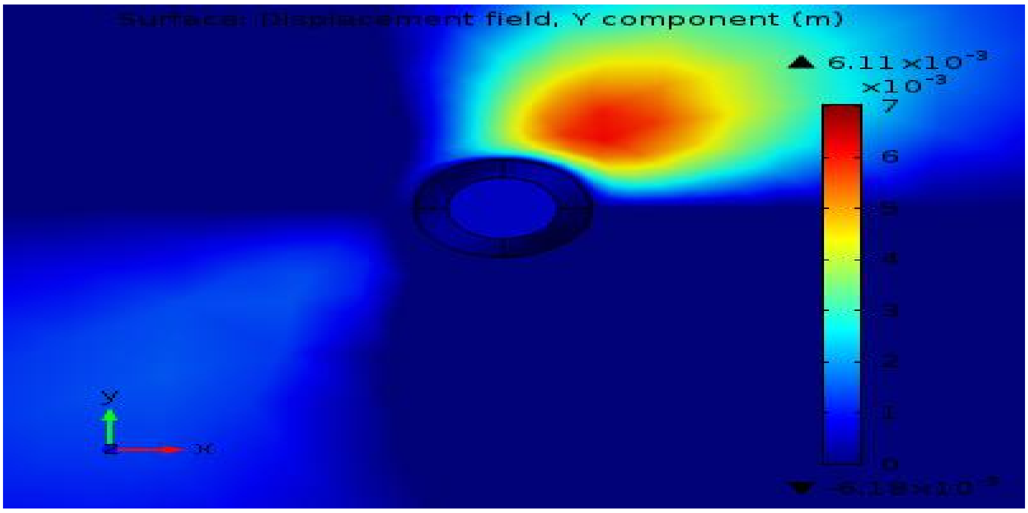


Figure 7.29 lateral displacement of the soil in Y direction (m)

As shown in Figure 7.31, the vertical section in the soil including the pile, the stress of the soil in the Y direction ranged from zero to 500 kPa which is comparable to the natural stress and means that there is no risk of failure.

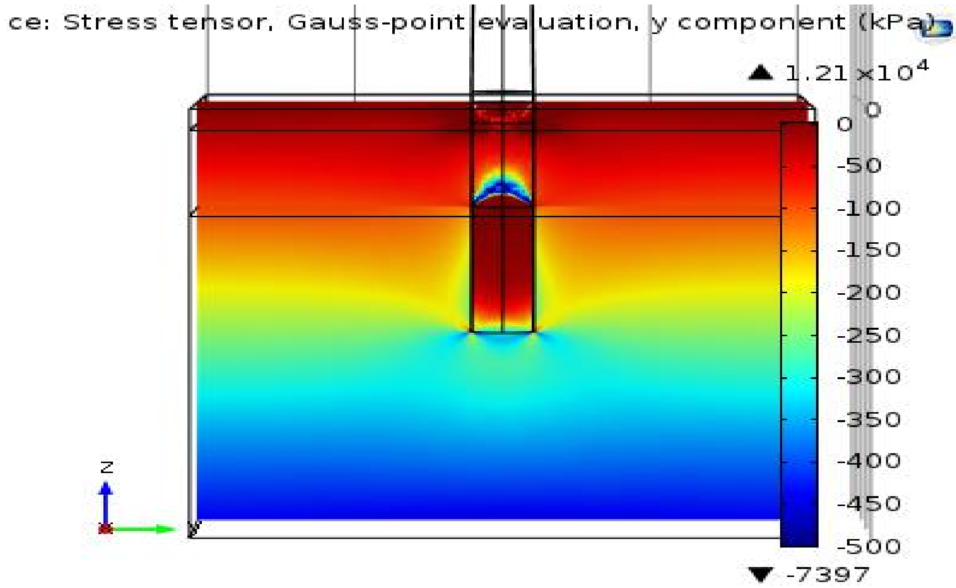


Figure 7.30 Vertical sections in the soil including the pile (ZY plane) (kPa)

7.5 Summary

Representing the exact behaviour of a structure or soil in a numerical model is practically impossible. It is therefore expected that some degree of error will be apparent within the results presented above. Therefore, it is important to detail any factors that could contribute to any significant error such as typical of geotechnical engineering and soil mechanics applications; the soil has been treated as a homogeneous and isotropic medium. The properties of the soil are the same everywhere in the medium and the same in all directions. In reality, this is not a true representation of a real soil, but it does provide close estimations in practice when combined with adequate safety factors (Das, 2008). The assumption that properties such as Young's Modulus of the Soil (Es) and cohesion (C) are the same everywhere is an idealisation, and will have an effect on the results obtained. Significantly, layered soils have not been included which has been shown to have significant effects on soil and structural behaviour. For example, Das (2008) reports that studies by Burmister (1958) proved that for a given loading condition, the presence of a stiffer soil layer on top of a softer one will reduce the propagation of stresses into the lower layers of the soil. The HAWT tower has been modelled as a conical tube of constant thickness in order to minimise meshing difficulties. In modern wind turbines, thickness is varied with tower height especially in soft designs (Kuhn, 1997). Additionally stiffeners are commonly located at specified spacing (Lavassas et al., 2003). Both of these could have significant implications on wind turbine behaviour, especially tower tip displacement and dynamic response of the structure. The wind loading on the tower has been applied as a uniform distributed load (udl) line load varying with height. In reality, this is an oversimplification. A more accurate representation would be to apply the load as a pressure perpendicular to the tower varying with both height and tower*)* circumference (EN1991-1-4(2005), 2010).

Despite the fact that the tower load is dynamic in nature, pseudo static load is justifiable since the taken loads will be taken at maximum amplitude and applied to the tower as a static load. The pile and the tower made of steel failure in compression or under tensile stresses and below that level of stress it behaves as elasticity; (Von Mises) was used. Owing to the granular nature of soil, this material demonstrates a tendency to develop a shear surface between the particles and to fail in shear mode. Therefore, such material is best described by the Mohr-Coulomb (MC) constitutive model. Soil/pile interface was modelled as continues such simulation is not perfect indeed, but to address the realistic interaction properties at the soil/pile interface is complicated and time consuming and usually associated with numerical convergence problems. The continuity type has been proven by several authors (Jeng, Luo and Zhang, 2010; Hansen, 2012; Chang and Jeng, 2014; Chang et al., 2014; Holzbecher, 2014; Loria and Laloui, 2016) to be reasonable close. The structure stability of the entire system (soil, pile, tower, turbine loads and wind loads) where examined for the whole model, indicating no plastic region was formed (i.e. no failure points and the system structure is stable and all of the components of the structure are stable).

In Table 7.1, some of the studies used SAP2000 and GH bladed software from analysis of onshore wind turbine with fixed base without including the soil and foundation. Others used (ABAQUS) software to analysis the soil-structure interaction of offshore wind turbine depth in water of 20m to 40m, including wave load. Quilligan, O’Connor and Pakrashi (2012) reported that the investigations into the structural performance of towers taller than 90 m are unavailable. In this research 100m wind turbine was analysed. The displacement of the wind turbine tower increase by increasing the height. In comparison with the literature the maximum displacement of 100m tower was 2.35m which is compatible with the total displacement of 2.03m for 90m height tower in the validation study in a clay soil (cohesion,140MPa) which is more cohesive than the dense sand in Kuwait.

8 Conclusions, Recommendations and Future Work

8.1 Conclusions

Regions as in Kuwait where wind speeds are expressive, it was necessary to consider other factors, such as potential exposure from this source in the energy world whereas in other parts of the world where wind speeds are low, factors such as wind energy production, economic optimisation and environment impact are key determinants in the evaluation of renewable energy projects. It can be concluded that wind energy is not only climate-friendly and free from GHG emission but also has cost-effective and less negative social and environmental impacts compared to other sources of energy as technology is getting more efficient and cost-effective. It has the potential to reduce the energy-crisis worldwide and create employment opportunities. Wind energy is now a mature technology and there is enough evidence in favour of large-scale wind energy. Research has been undertaken to minimise potential negative impacts of integrating large-scale wind energy into the grid for a sustainable power system for the future. Findings of this study are expected to be used as guidelines by the policy makers, manufacturers, industrialists and utilities for deployment of large-scale wind energy into the energy mix. Different types of renewable energy were discussed and found to be unavailable or unfavourable in Kuwait. At present, solar energy is more expensive than wind energy and requires a large amount of land.

The results obtained from applying the (LCOE) equation for wind energy was compared the (LCOE) of the electricity generated in Kuwait; this comparison lead to an assessment of the economic benefit of wind farm implementation in Kuwait. Compare the LCOE for wind energy in Kuwait with other renewable energy such as solar energy, wave energy and biomass energy will support the choice of wind energy as favourable renewable energy for Kuwait.

To conclude, Table 8.1, Figures 8.1and 8.2, make clear the differences in wind energy cost from several sources such as SAM (2014), IRENA (2012), EWEA (2009) and Fraunhofer (2014) compared with the analysis conducted by the researcher. SAM seems to be the lowest wind turbine cost. There is a consistency between the different sources of the cost of wind energy, whereas SAM has the lowest price because SAM is using the estimated cost values using NREL wind cost and scaling model, (LCOE) values shown on the table are different. The highest value is found in IRENA, followed by Fraunhofer, and the lowest in SAM, because IRENA and Fraunhofer have the highest wind turbine generator price and civil works and construction costs, which leads to high capital cost, whereas SAM has low capital cost due to low wind price and relatively low cost of civil works. This cost estimation is based on multiple factors, such as the price of the wind turbine generator, and SAM also includes the percentage of contingencies, which at 3% are considered to be low which also lead to make the capital cost low compared to other figures shown in table 8.1. Kuwait has the highest capital cost due to the high cost of transportation, as components are imported from overseas, and the labour of operation cost is high compared to Europe since workers are recruited from abroad. The percentage of contingencies which was added to the CapEx is 15%, as shown in Table 5.1 which shows the investment cost for the 10 MW farm. The LCOE cost of EWEA is higher than Kuwait due to the high price of wind turbine generators. In addition, the LCOE of wind energy for a 2MW wind turbine in Kuwait is 17.6 fils/kWh (0.04 £/kWh), which is lower than the LCOE electricity generated in Kuwait at (22 fils/kW/0.06 £/kWh) and lower than LCOE of the PV solar system in the GCC which is range between ($0.0585 and $0.1/£0.04 and £0.08 / 17.7 and 30 fils) per kWh after a collapse of the cost of PV solar system in 2016(IRENA, 2016) from ($0.27/£0.2/80fils) per kWh in 2011(Alnaser and Alnaser, 2011).

Table 8.1 Summary of the cost of wind energy for a 2MW wind turbine from several sources

	Analysis results	(NREL, 2014) **SAM**	(IRENA, 2012) **IRENA**	(EWEA, 2009) **EWEA**	(Fraunhofer IWES, 2014) **Fraunhofer**
2MW Wind turbine price ($/£/KD)	$ 2,751,240 £2,075,528 KD831,426	$2,077,302 £1,567,116 KD627,761	$3,163,000 £2,386,292 KD955,855	$2,940,000 £2,218,052 KD888,465	$ 2,621,576 £1,977,820 KD792,238
Grid connection cost ($/£/KD)	$489,351 £369,205 KD147,881	$550,000 £414,964 KD166,209	$496,000 £374,379 KD149,890	$218,000 £164,546 KD65,879	$172,472 £130,181 KD52,121
Civil works and construction costs ($/£/KD)	$380,606 £287,218 KD115,018	$422,881 £319,052 KD127,794	$460,000 £347,058 KD139,011	$338,000 £255,012 KD102,143	$655,394 £494,477 KD198,058
Capital cost ($/£/KD)	$5,602,174 £4,226,583 KD1,692,963	$2,767,302 £2,087,802 KD836,271	$3,950,000 £2,980,094 KD1,193,67 9	$3,496,000 £2,638,091 KD1,056,481	$3,449,443 £2,602,959 KD1,042,849
Capacity factor (%)	29.2	40.8	25 to 35	35	-
Operation and maintenance ($/£/KD/kWh)/ year	$0.013 £0.01 KD0.004	$0.026 £0.02 KD0.008	$0.013 £0.01 KD0.004	$0.026 £0.02 KD 0.008	$0.026 £0.02 KD0.008
LCOE ($/£/fils)/kWh	$0.053 £0.04 **Fils 17.6**	$0.026 £0.02 **Fils 10**	$0.106 £0.08 **Fils 33**	$0.08 £0.06 **Fils 23.3**	$0.093 £0.07 **Fils 28.5**

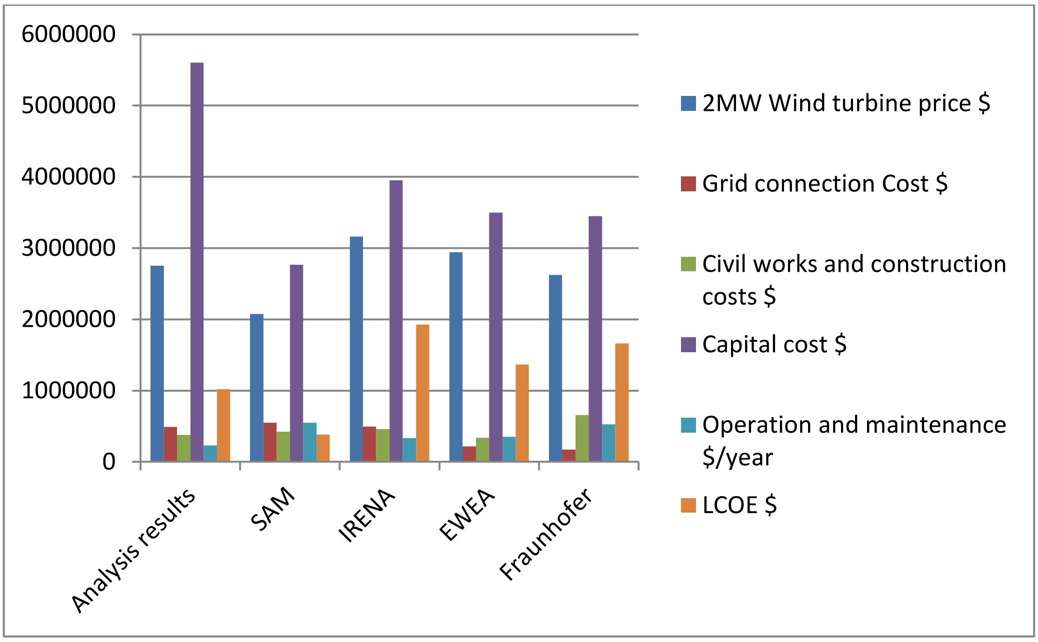


Figure 8.1 Comparison between different sources of the cost of implementation of a 2MW wind turbine

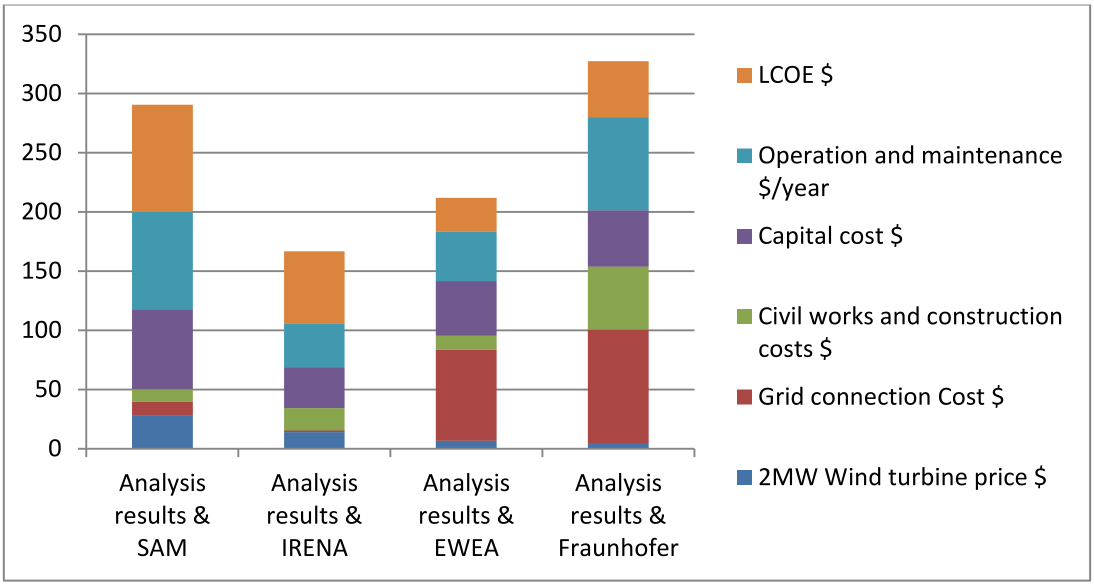


Figure 8.2 The percentage difference between the analysis result and SAM, IRENA, EWEA and Fraunhofer

The finding of the LCOE wind energy in Kuwait is ($0.0583/kWh/£0.043/kWh/ 17.6fils/kWh) which is competitiveness with the LCOE of electricity generation from oil priced at ($0.07/kWh/£0.06 /kWh /22 fils/kW) and with the PV solar system LCOE in the GCC which is range between ($0.0585 and $0.1/£0.044 and £0.08 / 17.7 and 30 fils) per kW.

An LCA was conducted and finding indicated that the average CO_2 emission from Kuwait electricity using crude oil is high, at 645gCO_2/kWh (IEA, 2015). The carbon footprint per functional unit is 10.4 gCO_2/kWh and 8.5 gCO_2/kWh for steel pile foundation turbine (Turbine A) and concrete foundation turbine (Turbine B) respectively. The values of lifecycle for both turbines are online with the literature review values ranging between 6.6 g/kWh and 10 g/kWh. It has been concluded that the total annual energy generated for both turbines is identical because they use the same Gamesa 90-2MW wind turbine and the results showed a different value for the total cumulative energy for Turbines A and B, which is 3.6 GWh and 2.7 GWh respectively, because of the difference in the type of foundation. The payback time showed a slight difference of approximately two months between both turbines due to the total cumulative energy requirements in GWh.

Soil-structure-interaction was considered, facilitated through the use of the elasto-plastic Mohr-Coulomb (MC) constitutive model. Modelling a wind turbine in the environment and soil of Kuwait has followed a different stages based on 3D FEM analysis by using COMSOL software included the soil, pile-soil interaction and steel wind turbine tower. The results of the total displacement of the tip tower was 2.85m and maximum Von-Mises stress at the base of the tower was 230 MPa which is similar to the literature (Xie, Tseng and Chang, 2010; Papanastasiou, 2011) and confirmed that the structure stability of the entire system (soil, pile, tower, turbine loads and wind loads). No failure points occurred and the system was found to be stable. With regard to the stress in the Z direction under the pile; it was compression 500Kpa which is comparable to the natural stress which means that there is no risk to failure.

Overall, for Kuwait, wind energy is a promise alternative to generate electricity instead to the oil cured which is clean, environmental friendly based on life cycle assessment with low CO_2 and cheaper compared to other sources of renewable energy. As such this source of energy will protect the earth from the atmospheric contamination. It was also found that wind energy has minimal environmental impacts compared to other sources of energy.

8.2 Contribution to knowledge

The majority of this work has contributed to the knowledge for both the scientific and industrial communities. Previous work had within wind energy feasibility studies in the MENA region had normally involved selecting appropriate location sites based on available space, or wind availability within the various locations. However these assumptions, although in theory were valid assumptions, in practice were not feasible, due to issues related to land ownership/control, or wind data being inaccurate/unavailable. This is the first time these tow main factors have been investigated properly and in an academically rigorous manner. Specifically for Kuwait, relevant data was gathered from the sources on site, and land ownership was investigated and checked, upon which several suggested locations, including ones previously suggested by other researchers (REF the paper of potential wind), were shown to be either owned privately or restricted areas by the oil company and MOD. Thus the locations chosen in this thesis are optimum from a view of space, availability, soil suitability, ownership, and wind velocities and its potential.

Another significant contribution to knowledge is the process of examining several interconnected factors when selecting wind turbine generators, which are different from the usual factors and methods used during this process, especially within the MENA area. This is especially significant as for instance, a life cycle assessment has never been used in the MENA region for wind turbines, thus accounting for the environment in a region where environment is normally considered as a very low priority. This involved contacting wind turbine suppliers, and obtaining data for various processes/materials, etc, and then analysing these. The stability of the structure has also always been looked at either from a structures viewpoint, with underlying soils not accounted for properly, or a geotechnical approach, with the structure's weight being applied as a load. The finite element modelling in this thesis looks at the soil-structure interaction that occurs; displacements occurring in the structure due to the various loads results in the soil moving, which in turn results in the structure adjusting its movement/stresses accordingly. This is in addition to the soil in question being silty dense sand, when previous cases were mainly on clay soils, which are inappropriate for the MENA region. Atmospheric conditions of dust, high temperature and medium wind speed available in MENA were also accounted for when calculating the estimated technical losses to calculate the capacity factors. The latter are not normally factors looked at within the literature as most of the literature looks at wind turbines within European/North American/Australasian countries, where dust and extremely high temperatures are uncommon. The holistic methodology used here can therefore be generalised to the MENA region, or any other arid areas in the world.

8.3 Recommendations and Future Work

The recommendations and future work are presented as following:

8.3.1 Industry Recommendations

- The use of renewable energy needs political support as laws governing power generation regulation should give more flexibility to the use of renewable energies in Kuwait. Moreover, the government needs to develop policies to support investors in a large scale of wind turbine farm.
- Develop a strong collaboration between different Kuwaiti parties: academia, industry and government to join together to support renewable energy as an alternative to oil and reduce its consumption.

- Establish urgently efficient local, regional and international networking to benefit from others' best practices and acquire expertise.
- People in Kuwait should be encouraged by the government to generate energy in their houses using wind energy and there must be social awareness. As example of this in Kuwait is shown in Figure 8.3

Figure 8.3 A house in Kuwait using wind turbine to generate energy for the house

- Put a high priority in terms of technological support into wind resources assessment in Kuwait, which can greatly enhance citing and evaluation of the appropriateness of these technologies by introducing Geographical Information System (GIS) showing the spatial distribution and the best location of wind turbines.
- As the countries of the GCC are sharing the electrical network, as a vision of 2020 of GCC countries (GCCIA, 2001) it would help to develop a Global Atlas which covers some of the GCC countries including Kuwait, to provide an online (GIS) system linked to a number of data centres located around the world. All the information can be accessed directly from the Global Atlas GIS interface.
- At the national level, renewable energy can also attract investment, provide energy security through diversification, encourage the technological innovation and improve stable economic growth.

- National and regional policies can play a key role in supporting RE development and implementation, helping GCC countries to not only identify priorities and pathways for RE market, but also expanding their roadmap to consider other policies and measure to predict problems resulting from high share of RE in the energy portfolio and suitable solutions such as smart grid technologies.
- Collaboration among the GCC renewable energy research institutions international partners to ensure a technological support for renewable energy in the GCC region taking into consideration specificities of each individual market and economic strategies with more adapted measures.
- In Kuwait, landfill and manufacturers for recycling the material such as steel, wood etc. are not available in suitable and a very well designed. Therefore it is suggested that the government provide a private area specialised for landfill and encourage the private with the public sector to invest in recycling. That will reduce the life cycle assessment environmental impact and embodied energy by more than 60% and 50% respectively by reusing materials strategy.
- It is recommended to establish a National Energy Council (NEC) in Kuwait that has legal authority to effectively implement the actions. Energy sustainability such as wind energy touches the country's security and economic wellbeing especially with the decrease in oil. Therefore, NEC should be supervised by the highest executive authority in the country such as the Council of Ministers. It is highly recommend that NEC is chaired by the Prime Minister and the council members consist of energy stakeholders representatives including the ministers and/or chief executive officers of the Ministry of Electricity and Water, Ministry of Oil, Kuwait Petroleum Corporation, Public Authority for Housing Welfare, Municipality, Ministry of Finance, Ministry of Information, Ministry of Education, Kuwait Institute for Scientific Research, Kuwait University and Kuwait Foundation for the Advancement of Sciences.
- Energy produced by wind turbines is not free from negative impacts. It has been found that wildlife is killed with the collision of wind turbines in many cases. This source of energy also creates sound noise which is annoying to the vicinity of wind turbine installation projects. Visual performance is also

interfered by the wind turbine. If wind turbines are designed and planned carefully, many of these negative impacts can be minimized.

8.3.2 Future Work

- Implement more weather prediction output sensors in the wind assessment process in Kuwait to discover more windy places.
- As concluded in this research that wind turbine technology is one of the most favourable options, decision makers in Kuwait should consider using clean energy for different purposes.
- Inventory Carbon dioxide and Energy (ICE) and transportation emissions data deserves further study in Kuwait to have an accurate Life Cycle Assessment.
- Off shore wind turbine need to be investigated in Kuwait to increase the capacity of the wind energy.
- Dynamic loads should be analysed in future.
- 3D rotor and nacelle can be implemented on top of the towers to analyse in future.

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Appendices

Appendix- A: Wind turbines models and specifications of the top ten manufacturers

COMPANY	model	Axis Direction	ONSHORE / OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight(tonne)	Operation Temperature Range-C	SWEPT AREA (m²)	Servic e Life (year)	Cost £
VESTAS										Nacelle hub//blade// tower				
	V90	Pending	both	3.0	8.6-18.4		90	FROM 65-80-105	Pending	Pending	(-20)to (40)	6362	20	Pending
	V100	Pending	onshore	2.6	6.72-13.37		100	_	Pending	70tonne/unit for transport	(-20)to (40)	7854	20	Pending
	V105	Pending	onshore	3.3	Pending		105	site specific	Pending	70tonne/unit for transport	(-20) to (45)	8659	20	Pending
	V112	Pending	onshore	3.3	Pending		112	site specific	Pending	70tonne/unit for transport	(-20) to (45)	9852	20	Pending
	V117	Pending	onshore	3.3	Pending		117	91.5/1165 /114	Pending	70tonne/unit for transport	(-20) to (45)	10751	20	Pending
	V126	Pending	onshore	3.3	Pending		126	117/137	Pending	70tonne/unit for transport	(-20) to (45)	12469	20	Pending
	V164	Pending	offshore	8	4.8-12.1	11	164	site specific	8/20/8	35/blade-390/nacelle-steel tower	(-10) to (25)	21124	25	Pending

COMPANY	model	Axis Direction	ONSHORE / OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperature Range-C	SWEPT AREA (m^2)	Service Life (year)	Cost £
Gold wind										Nacelle hub//blade// tower				
	GW70	Pending	Pending	1.5	10.2-19	Pending	70.34	65	Pending	Pending	Pending	3886	Pending	Pending
	GW77	Pending	Pending	1.5	9-17.3	Pending	76.94	65/85	Pending	Pending	Pending	4649	Pending	Pending
	GW82	Pending	Pending	1.5	9-17.3	Pending	82.34	70/85/100	Pending	Pending	Pending	5325	Pending	Pending
	GW87	Pending	Pending	1.5	9-16.6	Pending	86.6	75/85	Pending	Pending	Pending	5890	Pending	Pending
	GW90	Pending	Pending	2.5	7-16.0	Pending	90	70/80	Pending	Pending	Pending	6362	Pending	Pending
	GW100	Pending	Pending	2.5	7-14.5	Pending	100	80/90	Pending	Pending	Pending	7823	Pending	Pending
	GW103	Pending	Pending	2.5	7-14.5	Pending	103	80/90	Pending	Pending	Pending	8332	Pending	Pending
	GW106	Pending	Pending	2.5	7-14.5	Pending	106	80/90	Pending	Pending	Pending	8825	Pending	Pending
	GW109	Pending	Pending	2.5	7-13.5	Pending	109	90	Pending	Pending	Pending	9331	Pending	Pending

COMPANY	Model	Axis Direction	ONSHORE / OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperature Range-C	SWEPT AREA (m^2)	Service Life (year)	Cost £
ENERCON										Nacelle, hub//blade// tower				
	E53	Pending	onshore	0.8	variable,11-29.5	Pending	52.9	60/73	Pending	Pending	Pending	2198	Pending	Pending
	E48	Pending	onshore	0.8	variable,16-31.5	Pending	48	50/55/60/76	Pending	Pending	Pending	1810	Pending	Pending
	E92	Pending	onshore	2.35	variable,5-16	Pending	92	85/98/104/108/138	Pending	Pending	Pending	6648	Pending	Pending
	E82E3	Pending	onshore	3	variable,6-18	Pending	82	78/85/98/108/138	Pending	Pending	Pending	5281	Pending	Pending
	E44	Pending	onshore	0.9	variable,16-34.5	Pending	44	45/55	Pending	Pending	Pending	1521	Pending	Pending
	E70	Pending	onshore	2.3	variable,6-21	Pending	71	57/64/74/85/98/113	Pending	Pending	Pending	3959	Pending	Pending
	E82E2	Pending	onshore	2.3	variable,6-18	Pending	82	78/85/98/108/138	Pending	Pending	Pending	5281	Pending	Pending
	E115	Pending	Pending	2.5	variable,3-12.8	Pending	115.7	92/149	Pending	Pending	Pending	10515.5	Pending	Pending
	E115	Pending	Pending	3	variable,4-12.8	Pending	115.7	92/149	Pending	Pending	Pending	10515.5	Pending	Pending
	E126	Pending	Pending	7.58	variable,5-12.1	Pending	127	135	Pending	Pending	Pending	12668	Pending	Pending
	E101	Pending	Pending	3.05	variable,4-14.5	Pending	101	99/135/149	Pending	Pending	Pending	8012	Pending	Pending

ENERCON

SIEMENS

COMPANY	Model	Axis Direction	ONSHORE/ OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperature Range-C	SWEPT AREA(m^2)	Service Life (year)	Cost £
SIEMENS										Nacelle, hub//blade // tower				
	SWT101/ 108	Pending	onshore	2.3	Pending	Pending	101/108	site specific	Pending	142	Pending	8000/9150	Pending	Pending
	SWT120-3.6/120-4.0/130-4.0	Pending	onshore	3.6-4.0	Pending	Pending	120/130	site specific	Pending	240	Pending	11300/11300 /13300	Pending	Pending
	SWT101/ 108/113	Pending	onshore	3	Pending	Pending	101/108/113	74.5-99.5/79.5/79.5-142	Pending	138to145	Pending	8000/9144/ 10000	Pending	Pending
	SWT154	Pending	offshore	6	Pending	Pending	154	site specific	Pending	360	Pending	18600	Pending	Pending

COMPANY	model	Axis Direction	ONSHORE/ OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight(tonne)	Operation Temperature Range-C	SWEPT AREA (m^2)	Service Life (year)	Cost £
SUZLON										Nacelle hub//blade/ tower				
	S95	Pending	Pending		Pending	Pending	95	80/90/100	Pending	Pending	Pending	7085	Pending	Pending
	S97	Pending	Pending	2.1	Pending	Pending	97	80/90/100	Pending	Pending	Pending	7386	Pending	Pending
	S88	Pending	Pending	2.1	Pending	Pending	88	80/100	Pending	Pending	Pending	6082	Pending	Pending
	S82	Pending	Pending	1.5	Pending	Pending	82	76.8	Pending	Pending	Pending	5281	Pending	Pending
	S66	Pending	Pending	1.5	Pending	Pending	66	74.5	Pending	Pending	(0) to 90	3421	Pending	Pending
	S52	Pending	Pending	0.6	Pending	Pending	52	75	Pending	Pending	(-5)to 90	2124	Pending	Pending

COMPANY	model	ONSHORE/ OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperature Range-C	Service Life year	Cost £
GE									Nacelle, hub,blad,tower			
	100-1.6	both	1.6	pending	7.5	100	96/ 80	blade=48.7 long	pending	pending	20	pending
	100-1.7	onshore	1.7	pending	7.5	100	96/ 80	pending	pending	pending	20	pending
	82.5-1.85	onshore	1.85	pending	8.5	82.5	80/65/100	pending	pending	pending	20	pending
	87-1.85	onshore	1.85	pending	8.5	87	80	blade=42 long	pending	pending	20	pending
	103-2.85	onshore	2.85	pending	pending	103	85	pending	pending	pending	20	pending
	103-3.2	onshore	3.2	pending	pending	103	70 to 98	pending	pending	pending	20	pending
	120-2.75	onshore	2.75	pending	pending	120	80/110 to 139	pending	pending	pending	20	pending
	120-2.5	offshore	2.5	pending	pending	120	110/139	blade=58.7 long	pending	pending	20	pending

COMPANY	model	Axis Direction	ONSHORE/ OFFSHORE	Rated Power (MW)	Operati -onal rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperatur e Range-C	SWEPT AREA(m^2)	Service Life (year)	Cost £
GAMESA										Nacelle, hub// blade// tower				
	G80/G87/G90/ G97/G114 2.0/G1142.5	Pending	onshore	2.0-2.5	9.0-19.0	Pending	80/87/90/97/114	60/67/78/90/93/100/120/140	blades length:39/42.5/44/47.5/56/56	Pending	Pending	5027/5945/6362/7390/10207/10207	20	Pending
	G128-4.5/G128-5.0-132-5.0	Pending	onshore	4.5-5.0	448/490	Pending	128/132	81/95/120/140	blades length:62.5/64.5	Pending	Pending	12868/13685	20	Pending
	G52/G58	Pending	onshore	0.85	19.44-30.8	Pending	52/58	44/49/55/65/74	blades length:25.3/28.3	Pending	Pending	2214/2642	20	Pending
	G128-5	Pending	offshore	5	490	Pending	128	80TO94+project specific	blades length:62.5	Pending	Pending	12868	20	Pending

COMPANY	model	Axis Direction	ONSHORE/ OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperature Range-C	SWEPT AREA (m^2)	Service Life (year)	Cost £
GUODIAN WIND POWER	UP6000-13IIA	Pending	onshore	6	11.7	Pending	Pending	Pending	Pending	Pending	Pending	Pending	20	Pending
	UP120/3000 IIIA	Pending	onshore	3	10.2	Pending	Pending	Pending	Pending	Pending	Pending	Pending	20	Pending
	UP100/3000	Pending	offshore	3	11.9	Pending	Pending	Pending	Pending	Pending	(-20) to (-40)	Pending	20	Pending
	UP2000-103IVB+	Pending	onshore	2	9.7	Pending	Pending	Pending	Pending	Pending	Pending	Pending	20	Pending
	UP2000-96	Pending	onshore	2	10.1	Pending	Pending	Pending	Pending	Pending	Pending	Pending	20	Pending
	UP1500-975	Pending	onshore	1.5	9.4	Pending	Pending	Pending	Pending	Pending	Pending	Pending	20	Pending
	UP1500-86 IIIB	Pending	offshore	1.5	10	Pending	Pending	Pending	Pending	Pending	(-20) to (-40)	Pending	20	Pending
	UP1500-82 IIIA/IIIA+	Pending	offshore	1.5	10.5	Pending	Pending	Pending	Pending	Pending	(-20) to (-40)	Pending	20	Pending
	UP1500-77/IIIA /IIIA+	Pending	Offshore	1.5	11.1	Pending	Pending	Pending	Pending	Pending	(-20) to (-40)	Pending	20	Pending

COMPANY	model	Axis Direction	ONSHORE/ OFFSHORE	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight (tonne)	Operation Temperature Range-C	SWEPT AREA (m^2)	Service Life (year)	Cost £
MING YANG										Nacelle hub//blade//tower				
	MY1.5Se	Pending	onshore	1.5	11.3	Pending	77.1	65/70/75/80	blades length/37.5	nacelle=65ton(us)/rotor=35ton(us)	(-40)to(+50)sur./(-30)to(+40)opr.	4368	20	Pending
	MY1.5S	Pending	onshore	1.5	10.8	Pending	82.6	65/70/75/81	blades length/40.3	nacelle=65ton(us)/rotor=35ton(us)	(-20)to(+50)sur./(-10)to(+40)opr.	5320	20	Pending
	MY1.5Su	Pending	onshore	1.5	11.3/10.8	Pending	77.1/82.6	65/70/75/82	blades length/37.5/40.2	Pending	(-45)to(+50)sur./(-40)to(+40)opr.	4368/5320	20	Pending
	MY1.5Sh	Pending	onshore	1.5	14	Pending	82.6	65/70/75/83	blades length/40.25	Pending	(-40)to(+50)sur./(-30)to(+40)opr.	5320	20	Pending

COMPANY	model	Onshore/Offshore	Rated Power (MW)	Operational rotor speed (rpm)	annual avg. wind speed (m/s)	Rotor Diameter (m)	Hub height (m)	Dimensions (m)	Weight(tonne)	Operation Temperature Range-C	SWEPT AREA (m^2)	Service Life (year)	Cost £
Nordex									Nacelle, hub,blad,tower				
	N100/3300	onshore	3.3	16.1-9	Pending	99.8	75/100	Pending	Pending	out side -30	7823	pending	pending
	N117/3000	onshore	3	14.1-7.9	Pending	116.8	91/120	Pending	Pending	pending	10715	pending	pending
	N131/3000	onshore	3	11.6-6.5	Pending	131	99/114	Pending	Pending	pending	13478	pending	pending
	N90/2500	onshore	2.5	18.1-10.3	Pending	90	65/70/80	Pending	Pending	pending	6362	pending	pending
	N100/2500	onshore	2.5	16.8-9.6	Pending	99.8	75/80/100	Pending	Pending	pending	7823	pending	pending
	N117/2400	onshore	2.4	13.2-7.5	Pending	116.8	91/120/141	Pending	Pending	up to out side 45	10715	pending	pending

Appendix – B: List of contacted companies

Company	Contact Name	Position	Contact details	Web address	Replied (Yes, No)
Vestas	-Velia Senatore - Michael Zarin	- Communications Partner, External Relations -Head of External Communications	E-mail: vestas-mediterranean@vestas.com -Tel.: +45 9730 0000 -Tel.: +39 099 460 6415 Email: veise@vestas.com	www.vestas.com	
Gold wind	-Mu Dan	- Media Contact	Email:info@goldwind-windenergy.de Tel：+86 01-6751-1888 - Tel: +0049-6821-9517368	www.goldwindglobal.com	

	-Elliot Titman	- Director at Gold wind Africa	Email: mudan@goldwind.com.cn		
Enercon			Tel: +49 4941 927-0 Fax: +49 4941 927-669 Email: info@enercon.de Phone: +49 421 / 24415100, Fax: +49 421 / 2441539 Email: sales.international@enercon.de	www.enercon.de	
Siemens	-Customer Support Center		Tel.: +49 180 524 70 00 Fax: +49 180 524 24 71 E-mail: support.energy@siemens.com	http://www.siemens.co.uk/en/news_press/index/news_archive/2014/major-uk-offshore-wind-manufacturing-site-to-be-built-by-siemens.htm http://www.siemens.co.uk/en/offshore-	

				wind.htm	
Suzlon	- Mr. Ravi Muthreja - Ms. Tanvi Agarwal - Mr. Ashish Kulkarni	- Head of Corporate Communications - Sr. Manager, Corporate Communications - Sr. Executive, Corporate	Email: suzloncorpcomm@suzlon.com - Phone: 91 020 670 21233 Email: tanvi.agarwal@suzlon.com - Phone:91 020 670 22662 Email: ashish.kulkarni@suzlon.com Email: digital@suzlon.com	www.suzlon.com	

		Communications (Digital)			
GE			http://www.ge-energy.com/contact.jsp	www.ge.com	
Gamesa	-Corporate Communication		Tel : + 34 91 503 17 00 Email : media@gamesacorp.com	www.gamesacorp.com	
Guodian United Power			Tel：86-10-57659000 Fax：86-10-57659200 Email: info_en@gdupc.cn	www.gdupc.com.cn	
Ming Yang Wind Power	-Marketing Department - Engineering Service Department - Overseas		-Tel ： 0760-28138392 Fax ： 0760-28138392 Mail：marketing@mywind.com.cn -Tel ： 0760-88588306 Fax：0760-88587776 Email:	www.mywind.com.cn	

	Business Department		engineeringservice@mywind.com.cn - Fax：0760-28138511 Email: overseasmarketing@mwyind.com.cn		
Nordex			Tel: +44 - 1 61 -44 59 900 Fax: +44 - 1 61 -44 59 988 Email: SalesUK@nordex-online.com	www.nordex-online.com	

Appendix-C: Example of correspondences with companies

6/26/2014 答复: Wind Turbine

答复: Wind Turbine
穆丹 [mudan@goldwind.com.cn]
Sent: Wednesday, June 18, 2014 11:55 PM
To: Badriya Almutairi

Dear Mr. Almutairi,

thank you for your email and interest on our products.

But I have to inform you, according our company rules and regulations please contact our PR department of Goldwind Headquarter in China.

Thank you for the understanding.

Mit freundlichen Grüßen / Best regards

Dan Mu
Personal & Verwaltung/ HR & Administration

Goldwind Windenergy GmbH
Pappelallee 41, D-22089 Hamburg, Germany

Office: Im Langental 6, D-66539 Neunkirchen, Germany
T: +49 68 21 95 17 - 368 ¬ F: +49 68 21 95 17 – 351

发件人: Badriya Almutairi [B.Almutairi@lboro.ac.uk]
发送时间: 2014年6月18日 14:22
收件人: 穆丹
抄送: info@goldwind-windenergy.de
主题: Wind Turbine

Dear Mr. Mu,

I am a PhD student at Loughborough University in the UK, doing my PhD on implementing wind turbines within the Gulf, supervised by Professor Dr Ashraf El-Hamalawi. I am sponsored by the Kuwaiti government to do my PhD.

Part of my work involves doing a comparison of different wind turbines, features, benefits, and costs if available.

I have looked at your literature and website online and realised that some of the information regarding your wind-turbines is not available, so would be grateful if you could provide me with more information. I am attaching a spreadsheet with the missing information.

Once I have this information, I can send you a summary table of all the different wind-turbines I have looked at and a comparison. In addition, if my work finds that the implementation of your wind-turbines within the Gulf is feasible, then there is a possibility that these will be purchased and used within the Gulf as my recommendations will be used as part of the decision-making process on whether to implement wind-turbines, and which ones are most suitable for the Gulf.

If you require any further information, please do not hesitate in

6/26/2014 Wind Turbine

Wind Turbine
Badriya Almutairi
Sent: Wednesday, June 18, 2014 1:08 PM
To: support.energy@siemens.com
Attachments: SIEMENS.xlsx (9 KB)

Dear Sir/Madam,

I am a PhD student at Loughborough University in the UK, doing my PhD on implementing wind turbines within the Gulf, supervised by Professor Dr Ashraf El-Hamalawi. I am sponsored by the Kuwaiti government to do my PhD.

Part of my work involves doing a comparison of different wind turbines, features, benefits, and costs if available.

I have looked at your literature and website online and realised that some of the information regarding your wind-turbines is not available, so would be grateful if you could provide me with more information. I am attaching a spreadsheet with the missing information.

Once I have this information, I can send you a summary table of all the different wind-turbines I have looked at and a comparison. In addition, if my work finds that the implementation of your wind-turbines within the Gulf is feasible, then there is a possibility that these will be purchased and used within the Gulf as my recommendations will be used as part of the decision-making process on whether to implement wind-turbines, and which ones are most suitable for the Gulf.

If you require any further information, please do not hesitate in contacting me or my PhD supervisor Professor Dr El-Hamalawi (carbon-copied in this email), or alternatively you can ring him at +44-1509-223206, with 44 being the United Kingdom telephone code.

I look forward to hearing from you.

Yours Faithfully,

Badriya Al-Mutairi

https://email.lboro.ac.uk/owa/?ae=Item&t=IPM.Note&id=RgAAAAD%2fP177yH19T4gRDIlsZwKTBwBL5rqaswy6SLGuq16Y3%2fn3AAAAQfQJAABL5rqas... 1/1

Ticket Nr./No.: 1-641317: Wind Turbine: System No: ISSUE=641317 PROJ=1

support.energy@siemens.com
Sent: Wednesday, June 18, 2014 2:08 PM
To: Badriya Almutairi

IMPORTANT: When replying, type your text above this line. --- WICHTIG: Bei Antwort, bitte Ihren Text oberhalb dieser Linie eingeben.

Siemens Infrastructure & Cities and Energy Customer Support Center
Ticket Notification

Additional Recipients / Zusätzlich Benachrichtigte:
Dear Badriya Al-Mutairi,

Thank you for your email and your interest in Siemens Energy.

The official statement concerning Siemens Energy Wind Power and possible projects can be found under http://www.energy.siemens.com/hq/en/power-generation/renewables/wind-power/.

However, we are sorry to inform you that we cannot provide any further information regarding Wind Power topics.

Thank you very much for your understanding.

If you have any further questions, don't hesitate to contact us again.

Kind regards

Siemens AG

Infrastructure & Cities

IC & Energy Customer Support Center

Humboldtstr. 59

90459 Nuremberg, Germany

Tel.: +49 (180) 524 7000

Fax: +49 (180) 524 2471

Email: support.energy@siemens.com

Internet: www.siemens.com/energy-support/en

Intranet: http://intranet.siemens.com/energy-support/en

Appendix-D the factors of all model names for each company

Company name	Model name	Rated power (MW)	Wind Class				Operation Temperature Range(°C)	System of Regulation Power		Cut-in (m/s)
			IEC IA	IEC IIA	IEC IIIA	IEC IV		Pitch	Stall	
Vestas (Denmark)	V90-1.8	1.8		X			-20˚C - +40˚C	X		4.0
	V90-2.0	2.0			X		-20˚C - +40˚C	X		4.0
	V100-1.8	1.8			X		-20˚C - +40˚C	X		3.0
	V100-2.0	2.0		IIB			-20˚C - +40˚C	X		3.0
	V110-2.0	2.0			X		-20˚C - +40˚C	X		3.0
	V90-3.0	3.0	X	X			-20˚C - +40˚C	X		4.0
	V100-2.6	3.0		IIB			-20˚C - +40˚C	X		3.0
	V105-3.3	3.3	X				-20°C - +45°C	X		3.0
	V112-3.3	3.3	IB	X			-20°C - +45°C	X		3.0
	V117-3.3	3.3		X			-20°C - +45°C	X		3.0
	V126-3.3	3.3			X		-20°C - +45°C	X		3.0
Gold wind (China)	GW70	1.5	X				NA	X		3.0
	GW77	1.5		X			NA	X		3.0
	GW82	1.5			X		• Ultra capacitors have a wider operating temperature range	X		3.0
	GW87	1.5		IIB			NA	X		3.0
	GW90	2.5								
	GW100	2.5		X			NA	X		3.0
	GW109	2.5		X	X		NA	X		3.0
	GW121	2.5			IIIB		NA	X		3.0

Enercon (Germany)	E48/800	0.8		X			Temperature control	X		
	E53/800	0.8		S (7.5m/s)				X		
	E44/900	0.9	X					X		
	E70/2300	2.3		X				X		
	E82E2/2000	2.0		X				X		
	E82E2/2300	2.3		X				X		
	E82E4/3000	3.0	X	X				X		
	E92/2350	2.35		X				X		
	E101/3005	3.05		X				X		
	E101E2/3500	3.5	X					X		
	E115/3000	3.0		X				X		
	E126/7580	7.58	X					X		
Siemens (Denmark &Germany)	SWT2.3-101	2.3		IIB			NA	X		NA
	SWT2.3-108	2.3		IIB			NA	X		NA
	SWT3.0-101	3.0	X				NA	X		NA
	SWT3.2-101	3.2	X				NA	X		NA
	SWT3-108	3.2	X				NA	X		NA
	SWT3.2-108	3.2	X				NA	X		NA
	SWT3.0-113	3.0		X			NA	X		NA
	SWT3.2-113	3.2		X			NA	X		NA
Suzlon (India)	S97-2.1	2.1			X		NA			3.5
	S88-2.1	2.1		X			NA	X		4.0
	S82-1.5	1.5			X		0° to 90°	X		4.0
	S66-1.25	1.25			X		0° to 90°	X		4.0
	S52-600	0.6		X			-5° to 90°	X		4.0
GE (USA)	GE1.7-100/103	1.7			X		-20° to +40° Serv.+50°	NA	NA	NA
	GE 1.85-82.5	1.85		X			NA	NA	NA	NA
	GE 1.85-87	1.85/1.6		X			NA	NA	NA	NA
	GE 2.5-120	2.5			X		NA	NA	NA	NA
	GE 2.75-120	2.75			X		NA	NA	NA	NA
	GE 2.85-100	2.85		NA			NA	NA	NA	NA
	GE 2.85-103	2.85		NA			NA	NA	NA	NA

	GE 3.2-103	3.2		X			NA	NA	NA	NA
Gamesa (Spain)	G80	2.0	X					X		1.5-3
	G87	2.0	X	X				X		1.5-3
	G90	2.0	X	X				X		1.5-3
	G97	2.0		X	X		Environmental Optional (High temp. and dust)	X		2.5-3
	G114-2.0	2.0		X	X			X		2.5-3
	G106	2.5	X					X		
	G114-2.5	2.5		X				X		2.5-3
	G128-4.5	4.5		X				X		1.5-3
	G128-5.0	5.0	X	X				X		1.5-3
	G132-5.0	5.0		X				X		1.5-3
Guodian United Power (China)										
Ming yang Recommended for cold weather and high elevation	MY1.5Se	1.5		X	X		-30°to+40°	X		3.0
	MY1.5S	1.5		X	X		-10°to+40°	X		3.0
	MY1.5Su	1.5		X	X		-40°to+40°	X		3.0
	MY1.5Sh	1.5		X	X		-30°to+40°	X		3.0
							For serv. temp. Up to +50°			
Nordex (Germany)	N117-2.4	2.4			X			X		3.0
	N100-2.5	2.5		X				X		3.0
	N90-2.5	2.5	X					X		3.0
	N131-3.0	3.0			X			X		3.0
	N117-3.0	3.0		X				X		3.0
	N100-3.3	3.3	X					X		3.5

They do wind turbines for high temperature and desert areas.

They give general information.

Not reply on the emails.

Appendix-E the selected model names specifications of the of the top ten companies

Model name	Rotor diameter (m)	Hub height(m)	dimensions(m)	Weight (tonne)	Tower Material	Blades Material	Swept area(m^2)	Operational rotor speed (rpm)	Cost £
V100-1.8 Best for low wind sites	100	80/95 /120	blades: 49 m Nacelle Length 10.4 m Width 3.5 m, height 5.4m Hub:Max. transport height 3.4 m Max. transport width 4 m Max. transport length 4.2 m Hub diameter=3.3m	Blades=7500kg Tower:80/IEC S160 metric tonnes 90/IEC S 205 metric tonnes Hub: Nacelle: used a cran. for 800 kg	tubular steel tower: S355 according to EN10024 A709 according to ASTM Hub material: cast iron EN GJS400-18U-LT/EN1560	Fibre glass reinforced epoxy and carbon fibres Nacelle material: cover: GRP Bedplate front: EN GJS400-18U-LT/EN1560	7854	9.3-16.6	
V110-2.0	110	Tower: 95/125 (50 Hz) 80 /95 (60 Hz)	Blades: 54 m Nacelle: length:10.4 Width:3.5 Hub: Max. transport height 3.4 m Max. transport width 4 m Max. transport length 4.2 m		tubular steel tower		9503		
GW82-1.5	82m				Tubular Steel Tower		5325m²		
GW109-2.5									
Gw121-2.5									

E48/800	48	50 m / 55 m / 60 m / 76 m				GRP (epoxy resin); Built-in lightning protection	1810	16 - 31.5 rpm	
E82E2/2.0	82	78 m / 85 m / 98 m / 108 m / 138 m				GRP (epoxy resin); Built-in lightning protection	5281	6 - 18 rpm	
S97-2.1	97	80/90/100/120	80/90Tower: top 2.97 m-end 4.04 m 100tower:top 2.97m, end 4.30m Blades length: 47.5 m		tubular steel tower Welded steel plate according to EN10025	Glass-fibre reinforced plastic (GRP)/Polyester	7386	12.0 to 15.5 rpm	
GE1.7/100	100	96	Blades:48.7m		tubular steel tower		7857.14		
GE1.7/103	103	80	Blades:50.2m		tubular steel tower		8335.64		
G97-2.0	97	78/90/100/ 120	Blades: 47.4m Tower: 75.685 m (Steel tower) 88.170 m (Steel tower) 98.664 (Concrete tower) 118.664 (Concrete tower)	Rotor: 47 t 78 m 165t 90 m 216 t 100m NA 120m 307 t	Modular steel (low alloy steel)	Pre-impregnated epoxy glass fibre+ carbon fibre	7390	9.6-17.8	Appr. 0.94£ (1.43 $)/MW (Shagaya) Total

									EPC cost roughly 1.31£(2$) /MW (KISR)
			Nacelle: 10.583 x 3.505 x 4.487	Nacelle: 72 t					
			Total:	Total:					
G114-2.0	114	80/93/ 125 and site spec.	Blades:56m	Rotor :64.198,52/80 64.198,52 /93(kg)	Modular steel (low alloy steel)	Fibre glass reinforced with epoxy or polyester resin.	10207	7.7-14.6	
			Tower:	145.361,04/80 206.278,33/93 (kg)					
			Nacelle:	92.826,55/80(kg) 92.826,55/93					
			Total:	Total:					
N117-2.4 specially developed for low-wind sites cooling system for the generator Nordex	117	91/120/ 141			tubular steel		10,715	7.5-13.2	

Appendix F: CO-EFFICIENTS AND FORMULAE

Parameter	Value	Description
Fundamental Basic Wind Velocity before altitude correction($v_{b,map}$) (m/s)	8.5	input by hand (see NA BS EN 1991-1-4 figure NA.1) (from map)
Altitude factor (C_{alt})	1	calculated
Fundamental Basic Wind Velocity ($v_{b,0}$) (m/s)(for Kuwait from KISR)	8.5	Characteristic 10 min mean wind velocity at 10m above GL
Directional Factor (C_{dir})	1	input by hand (See NA BS EN 1991-1-4 table NA.1)
Seasonal Factor (C_{season})	1	input by hand (See NA BS EN 1991-1-4 table NA.2)
Basic Wind Velocity (v_b) (m/s) [$v_{b\,=}\,C_d$ X C_{season} X $v_{b,0}$]→ $v_b = v_{b,0}$	8.5	calculated
Roughness Length (z_0) (m) Category II →0.05	0.05	Input by hand (see BS EN 1991-1-4 Table 4.1)
Roughness Length Terrain Cat II ($z_{0,\,II}$) (m)	0.05	calculated
Minimum Roughness Length (z_{min}) (m)	2	Input by hand (see BS EN 1991-1-4 Table 4.1)
Terrain Factor (k_r) [k_r =0.19X9$Z_0/Z_{0,h})^{0.07}$]	0.19	calculated
Orography Factor ($C_o(z)$)	1	Input by hand (see BS EN 1991-1-4 Section 4.3.3)

Turbulence Factor (k_I)	1	input by hand (See NA BS EN 1991-1-4 section NA.2.16)
Basic Velocity Pressure (q_b) [1/2 X p_{air} X v^2_b=1/2X1.225Xwind speed]	44.25	calculated
Size Factor (C_s) depend on the zone in the map table NA.3 -6.3.1 (BS2005)		input by hand (See NA BS EN 1991-1-4 section NA.2.20)
Dynamic Factor (C_d) depend on the zone in the map table NA.3 -6.3.1 (BS2005)		input by hand (See NA BS EN 1991-1-4 section NA.2.20)
Structural Factor (C_sC_d)		calculated
Force Coefficient without free end flow ($C_{f,0}$)		input by hand (See BS EN 1991-1-4 Figure 7.28)
End-effect Factor (ψλ)		For α_A <= α <= 180 (input by hand refer to figure 7.36)
Force Coefficient (C_f)		calculated

Appendix-G Calculation of Wind Force and Calculation of Coefficients and formulas.

z	Cr(z)	Vmz(m)	stander dev.	Turbulence intensity(Iv)	Peak velocity pressure(N/m^2)	Aref(m^2/m)	Wind Force Fw (kN/m)
0							
1	0.569189	4.838107622	4.75	0.981788826	115.1714774	6.24369375	0.746061512
2	0.700887	5.957540318	4.75	0.797308914	145.9878139	6.2073875	0.940185541
3	0.777925	6.612366468	4.75	0.71835099	164.7403596	6.17108125	1.054749625
4	0.832585	7.076973015	4.75	0.671190916	178.3705624	6.134775	1.135298139
5	0.874982	7.43734985	4.75	0.638668356	189.1287846	6.09846875	1.196648332
6	0.909623	7.731799165	4.75	0.614346014	198.0394003	6.0621625	1.24556754
7	0.938912	7.980752513	4.75	0.59518197	205.6577698	6.02585625	1.285736564
8	0.964283	8.196405712	4.75	0.579522313	212.3197228	5.98955	1.319388331
9	0.986662	8.386625314	4.75	0.566377991	218.2442349	5.95324375	1.34798342
10	1.00668	8.556782547	4.75	0.555115194	223.582217	5.9169375	1.372531579
11	1.024789	8.710708487	4.75	0.545305816	228.4421872	5.88063125	1.393761175
12	1.041321	8.851231861	4.75	0.536648466	232.904853	5.844325	1.412215592
13	1.05653	8.980500834	4.75	0.52892373	237.031905	5.80801875	1.428311464
14	1.07061	9.100185209	4.75	0.521967399	240.8715807	5.7717125	1.44237557
15	1.083719	9.211608697	4.75	0.515653688	244.4623275	5.73540625	1.454669164
16	1.095981	9.315838408	4.75	0.509884327	247.8352952	5.6991	1.465404561
17	1.1075	9.413747172	4.75	0.504581216	251.0160808	5.66279375	1.474756755
18	1.11836	9.506058011	4.75	0.499681361	254.0259799	5.6264875	1.482871775
19	1.128633	9.593376573	4.75	0.495133279	256.8829032	5.59018125	1.489872814
20	1.138378	9.676215244	4.75	0.490894413	259.6020614	5.553875	1.495864801
21	1.147648	9.755011359	4.75	0.486929213	262.1964839	5.51756875	1.500937893
22	1.156487	9.830141184	4.75	0.483207709	264.6774188	5.4812625	1.505170151
23	1.164933	9.901930781	4.75	0.479704424	267.0546448	5.44495625	1.508629639
24	1.173019	9.970664558	4.75	0.476397533	269.3367177	5.40865	1.511376089

25	1.180776	10.03659208	4.75	0.473268213	271.531167	5.37234375	1.513462222
26	1.188227	10.09993353	4.75	0.470300125	273.6446545	5.3360375	1.514934818
27	1.195398	10.16088416	4.75	0.467479003	275.6831033	5.29973125	1.515835596
28	1.202308	10.21961791	4.75	0.464792328	277.6518034	5.263425	1.516201923
29	1.208975	10.27629039	4.75	0.462229056	279.5554997	5.22711875	1.516067411
30	1.215417	10.33104139	4.75	0.459779399	281.3984641	5.1908125	1.515462415
31	1.221647	10.38399696	4.75	0.457434649	283.1845573	5.15450625	1.514414442
32	1.227679	10.4352711	4.75	0.455187024	284.9172795	5.1182	1.512948506
33	1.233526	10.48496733	4.75	0.453029547	286.5998149	5.08189375	1.511087426
34	1.239198	10.53317987	4.75	0.450955937	288.235068	5.0455875	1.508852078
35	1.244705	10.57999474	4.75	0.448960526	289.8256962	5.00928125	1.506261617
36	1.250058	10.62549071	4.75	0.447038177	291.3741367	4.972975	1.503333659
37	1.255264	10.66974005	4.75	0.445184229	292.8826309	4.93666875	1.500084451
38	1.260331	10.71280927	4.75	0.443394434	294.3532442	4.9003625	1.496529009
39	1.265266	10.75475968	4.75	0.441664913	295.7878845	4.86405625	1.492681242
40	1.270076	10.79564794	4.75	0.439992118	297.1883178	4.82775	1.48855406
41	1.274768	10.83552651	4.75	0.438372791	298.556182	4.79144375	1.48415947
42	1.279346	10.87444406	4.75	0.436803939	299.892999	4.7551375	1.479508662
43	1.283817	10.91244581	4.75	0.435282803	301.2001854	4.71883125	1.474612079
44	1.288185	10.94957388	4.75	0.433806836	302.4790623	4.682525	1.469479488
45	1.292455	10.98586754	4.75	0.432373682	303.7308634	4.64621875	1.464120034
46	1.296631	11.02136348	4.75	0.430981159	304.9567428	4.6099125	1.458542297
47	1.300717	11.056096	4.75	0.429627239	306.1577817	4.57360625	1.452754337
48	1.304717	11.09009725	4.75	0.42831004	307.3349943	4.5373	1.446763735
49	1.308635	11.1233974	4.75	0.427027807	308.4893334	4.50099375	1.440577633
50	1.312474	11.15602478	4.75	0.425778904	309.6216954	4.4646875	1.434202767
51	1.316236	11.18800602	4.75	0.424561802	310.7329242	4.42838125	1.4276455
52	1.319925	11.21936623	4.75	0.423375073	311.823816	4.392075	1.420911846
53	1.323545	11.25012906	4.75	0.422217378	312.895122	4.35576875	1.414007499

54	1.327096	11.28031686	4.75	0.421087462	313.9475524	4.3194625	1.406937855
55	1.330582	11.30995072	4.75	0.419984147	314.9817791	4.28315625	1.399708032
56	1.334006	11.3390506	4.75	0.418906324	315.9984382	4.24685	1.392322891
57	1.337369	11.36763542	4.75	0.41785295	316.998133	4.21054375	1.384787051
58	1.340673	11.39572308	4.75	0.416823045	317.9814357	4.1742375	1.37710491
59	1.343921	11.42333059	4.75	0.415815682	318.9488901	4.13793125	1.369280651
60	1.347115	11.45047409	4.75	0.414829985	319.9010127	4.101625	1.361318266
61	1.350255	11.47716891	4.75	0.41386513	320.8382954	4.06531875	1.353221561
62	1.353345	11.50342965	4.75	0.412920333	321.7612061	4.0290125	1.344994168
63	1.356385	11.5292702	4.75	0.411994854	322.6701911	3.99270625	1.336639562
64	1.359377	11.5547038	4.75	0.411087993	323.5656758	3.9564	1.328161061
65	1.362323	11.57974306	4.75	0.410199084	324.4480664	3.92009375	1.319561844
66	1.365224	11.60440003	4.75	0.409327495	325.3177507	3.8837875	1.310844952
67	1.368081	11.6286862	4.75	0.408472627	326.1750994	3.84748125	1.302013301
68	1.370896	11.65261257	4.75	0.407633908	327.0204671	3.811175	1.293069687
69	1.373669	11.67618963	4.75	0.406810796	327.8541933	3.77486875	1.284016794
70	1.376403	11.69942744	4.75	0.406002775	328.6766029	3.7385625	1.274857198
71	1.379098	11.72233562	4.75	0.40520935	329.4880075	3.70225625	1.265593374
72	1.381756	11.7449234	4.75	0.404430053	330.2887056	3.66595	1.256227701
73	1.384376	11.76719962	4.75	0.403664436	331.0789839	3.62964375	1.246762468
74	1.386961	11.78917275	4.75	0.40291207	331.8591174	3.5933375	1.237199879
75	1.389512	11.81085093	4.75	0.402172547	332.6293705	3.55703125	1.227542056
76	1.392028	11.83224197	4.75	0.401445475	333.3899971	3.520725	1.217791041
77	1.394512	11.85335338	4.75	0.400730481	334.1412413	3.48441875	1.207948807
78	1.396964	11.87419238	4.75	0.400027206	334.8833382	3.4481125	1.198017253
79	1.399384	11.8947659	4.75	0.399335308	335.6165139	3.41180625	1.187998214
80	1.401774	11.91508064	4.75	0.398654457	336.3409861	3.3755	1.177893461
81	1.404134	11.93514301	4.75	0.397984339	337.0569647	3.33919375	1.167704704
82	1.406466	11.95495921	4.75	0.397324651	337.764652	3.3028875	1.157433596

83	1.408769	11.9745352	4.75	0.396675104	338.464243	3.26658125	1.147081736
84	1.411044	11.99387675	4.75	0.396035419	339.155926	3.230275	1.136650668
85	1.413293	12.0129894	4.75	0.395405327	339.8398825	3.19396875	1.126141888
86	1.415515	12.03187851	4.75	0.394784571	340.5162879	3.1576625	1.115556845
87	1.417712	12.05054923	4.75	0.394172905	341.1853118	3.12135625	1.104896939
88	1.419883	12.06900658	4.75	0.39357009	341.8471178	3.08505	1.09416353
89	1.42203	12.08725536	4.75	0.392975896	342.5018642	3.04874375	1.083357934
90	1.424153	12.10530024	4.75	0.392390102	343.1497043	3.0124375	1.072481426

Appendix H Acceptance of the conference paper

Universal Researchers in Civil and Architecture Engineering
www.urcae.org

July 22, 2015

Badriya Almutairi,
Loughborough University,
School of Civil and Building Engineering, England.

To Whom It May Concern,

International Conference on Green Buildings, Civil and Architecture Engineering (ICGBCAE'15) is for the scientists, scholars, engineers and students from the Universities all around the world and the industry to present ongoing research activities, and hence to foster research relations between the Universities and the industry. ICGBCAE'15 is sponsored by Universal Researchers in Civil and Architecture Engineering (URCAE) under Universal Researchers.

Herewith, the Universal Researchers in Civil and Architecture Engineering's Scientific and Technical Committee is pleased to inform you that the peer-reviewed & refereed conference paper id: U1215302, titled as "Review of Wind Energy Implementation in GCC Countries" and authored by Badriya Almutairi, and Aashraf El-hamalawi, has been accepted for Oral presentation at the conference and publication in Proceedings of the Dubai conference Dec. 2015.

We would like to kindly invite Badriya Almutairi, to present the research paper at the conference site in Dubai. We would greatly appreciate if you could facilitate granting the conference delegate the necessary visa.

Sincerely Yours,

Conference Chair
URCAE 2015
Dubai (UAE)
www.urcae.org
Email: editor@urcae.org

Conference Venue:
Holiday Inn Dubai - Downtown Dubai
Al Rigga Street, Dubai, United Arab Emirates
Phone: 0124 455 1 260 (Reservations) 971-4-2288889 (Front Desk)

International Conference on Green Buildings, Civil and Architecture Engineering
ICGBCAE'15: Dec. 25-26, 2015 Dubai (UAE)

Appendix I Acceptance of the conference paper

The 4th International Congress of -
& Water Management, Desertification
Agricultural Techniques

UEAG
Union Euro Arab of geomatics
Istanbul/ Turkey
7/10 Novembr 2017

...rth edition of the International Congress of the Water Management, Energy, ...
Agricultural Techniques
Scientific Days of Geographical Applications, Geometric Sciences and Digital Technologies
Istanbul Turkey, 7-10 November 2017

Dear: **Almutairi Badriya** ; Ashraf El-hamalawi
Loughborough University, School of Civil and Building Engineering, Epinal Way, Loughborough LE11 3TU

Participation approval

The Union Euro-Arab Geomatics has the honor to inform you of the decision of the Scientific Committee of **the Fourth edition of the International Congress of the Water Management, Energy, Food and Agricultural Techniques** , which will be held in Istanbul, Turkey from 7 to 10 November 2017 , in acceptance summary of your research is titled:

Investigating the Feasibility and Soil-Structure Integrity of Onshore of Wind Turbine Systems in Kuwait

That you will present in **the Fourth edition of the International Congress of the Water Management, Energy, Food and Agricultural Techniques** You are required to provide us with the full work paper and your CV including you photo before the deadline indicated in this Email. atigeo_num@yahoo.fr
We thank you again for your participation and you are welcome to **the Fourth edition of the International Congress of the Water Management, Energy, Food and Agricultural Techniques**

Best regards of Euro Arab Union of geomatics
Dr. Mohamed AYARI
President of U.E.A.G

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