DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

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Future of Renewable Energy Penetration in Kuwait As Oil Producer Country

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Declaration of Authentication

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed by: **MAHAMMAD M A M J ALSAFAR**

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Abstract

Kuwait have a moral obligation to follow the global trend of utilizing renewables to limit and reduce the climate change. the government have set their expectations on 15% of the total national power production to be sourced from renewables by the year 2030. Kuwait, who is oil producer country, is inexperienced in renewables and to be considered immature in the field. This paper studies weather Kuwait is able to develop a considerable segment of renewables in its electricity network or would the government compromise, the analyses were conducted based on supplier's perspective.

After the paper had investigated the potentiality of solar and wind resources in Kuwait using the literature and HOMER Pro as its tools, it was found that they have enough potential to be harnessed and utilised. Therefore, three different cases were created that serves different objectives. In Case 0, HOMER simulation of base case produced similar statistics as the real energy model in Kuwait, with power production of 74.1 TWh/year and carbon emission of 105 MMt. Hence, the load profile created for HOMER was concluded to be feasible. Best system configuration was then found in Case 1 namely; solar PV-wind turbine grid connected system. The best system configuration is selected based on the area required (101 km_2) and NPC ($121B). Meanwhile, annual reduction in CO_2 emissions depend on the amount of electricity kWh/year sourced from renewables which is similar in all configurations since both wind turbine and solar PV have 20% capacity. Although solar PV grid connected system had lower NPC, and Lower land requirement, it had limited power generation in terms of its reliance on sun time. In that sense, adding wind turbine to solar PV results in a reduced NPC and area while at the same time it has distributed energy production and reduced surplus energy potential.

Finally, Case 2 projected the growth of electricity demand (4%) and population (8.4%) for the year 2030 in the simulation. Therefore, the national annual power production increased to 77.1 TWh, with 15% renewable power production of 11.5 TWh/year using the selected system configuration. The system has $125B NPC and require 108 km_2, which is more than the current permitted area for renewable project in Kuwait. Since Kuwait is financially capable that much of a cost is not a major problem (note: NPC behavior might be flawed and reasons are stated in 5.2.2). However, "New Kuwait" vision for sustainability is not feasible in that specific configuration if Kuwait is not welling to permit dedicate more are for renewable projects.

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1 Introduction

There has been a surge in the level of awareness regarding the importance of energy and the issues about the inevitable problems related to its generation. Around a century ago, there was sequential mass discovery of oil occurring (i.e. in Texas in 1901 and 1938 in Kuwait) (Wells, 2020). More power plants were built to power heating and to produce electricity. electricity generations were installed at higher capacities into different sectors. Due to electricity demand for various uses, providers have been compelled to ensure that it enhances convenience for its users. In the last decade, it has been quite difficult to meet the rising electricity demand, because of challenges related to environmental (i.e. rising CO_2 content and climate change) and economic issues (i.e. economic growth) (Koh & Lim, 2010). Apart from the rapid economic growth and harsh climate, energy inefficiency has further aspects. The country has been compelled to increase production and minimize exportation. These options are causing serious issues to Kuwait in trying to meet its future energy demands, because of its oil reliance as an income source plus the country's vision for sustainability of energy. The exhaustion of conventional energy resources and the accumulating impact of energy generation using the fossil fuels has been creating more apparent signs of environmental strains by the day, resulting in climate change (Mgbemene, 2011; Barrett et al, 2015).

The increased reliance on non-renewable sources of energy is not viable because of their unsustainability in terms of quantity available and the pollution that they cause. Pollution attributed to high levels of greenhouse gases (GHG) is linked to conventional power generation and shifting to green energy in Kuwait can be instrumental in reducing it (EIA, 2019). Great masses of GHG emission can be major factor for the climate change. Controversially, according to Paris Climate Agreement there is an unequivocal change in climate in form of global warming (Teske, 2019). If this increase in global temperature is reached, topography of earth will change, water surfaces will dry out and risk of flooding will increase and cause sequential changes in forms of life on earth (Hoegh-Guldberg, 2018). Therefore, global warming has to be constrained to less than 2˚C and this cannot be attained without an essential transfer to more sustainable technologies (Teske, 2019). Solar energy systems (PV panels, thermal solar energy, Parabolic solar energy and solar cooling systems), wind energy systems (on and offshore wind turbines) are essential faces of futuristic energy matrix.

The energy sector in Kuwait is witnessing far-reaching and rapid changes. Reduction in costs, policy and innovation frameworks are fuelling unprecedented growth of renewable energy across Kuwait. The urge to address climate change and advance sustainability in Kuwait are also strengthening the energy transition momentum. In this regard, numerous nations are increasing their ambition level to hasten the use of renewables. In spite of this potential, transfer to renewable energy have always been a challenge since it provides its potential for reducing the use of highly carbonated fossil fuel, hence CO2 emissions. According to Jin Yang et al (2016), China has a share of about 67% of the global primary energy consumption and 73% its electricity demand is met by coal, calling for an aggressive transfer of energy sources to renewables. Renewable energy can be induced to 45%-50% whilst over 70% of electricity can be renewable based. Another leading country in renewable energy sector is UK. In 2008 UK participated in EU regulations, which requires EU members, at that time, to achieve 15% renewable energy by 2020 (Elsevier, 2008; DECC, 2011). Even for UK the task was challenging given the small window time (12 years) and the need to increase its renewable existence in the electrical grid from 4% to at least 30%, which was the easiest option to increase the renewable energy output (%) (DECC, 2011).

Similarly, country members of Gulf Cooperation Council (GCC) have high electricity demand growth rate (4-5%). It being high than worlds average, GCC issued their renewable energy regulations for the years 2030-2035 (IRENA, 2016, 21). Electricity demand is expected to grow additional 281GW (*Ibid*). Therefore, they decided moving toward dominating natural gas power generation to compensate the decrease in oil, resulting in 8% reduction in carbon footprint per capita in the region (*Ibid*, 16). Renewable energy will have a major role by 2035, solar and wind energy will be able to generate over 60 GW and 45GW, respectively. In Kuwait only, the solar energy will add 10.3 GW, Photovoltaic (PV) panels portion will be 45% and Concentrated Solar Power (CSP) is the remaining 55% of the total renewable contribution (*Ibid*, 42) .

Locally, in 2017, Kuwait announced its ‘New Kuwait’ vision for the year 2035. It included multiple pillar for diversification of the economy and creating more sustainable life. That included investing in sustainable technologies and higher implementation of renewables. the total renewable energy contribution on 2017 was less than 1% of the electric grid (KISR, 2019), by 2020 Kuwait’s share of renewable should have increased to be 5% of its electricity supply (IRENA, 2016, 42). Since 2016, different institutions (i.e. Kuwait Institute for Scientific

Research (KISR) and Kuwait Oil Company (KOC)) from different sectors (development and oil) have been investing in solar energy and less in wind energy in their projects. However, the last decade witnessed over 70% drop in crude oil prices in Kuwait in comparison to its highest average, $111.1 per barrel (KIBS, 2017; OBG, 2020). According to the information presented by Kuwait Institute of Banking Studies (KIBS, 2017, 12), during the most recent drop in oil prices, which occurred April 2020, Kuwait lost at least $20billion of its income from oil (Ibid, 15).

High governmental deficits and the raw experience in renewable technology raised technical challenges about the possibility to achieve 15% RE contribution by 2035 as a 'New Kuwait vision' target for sustainability. This paper will look at the possible scenarios where this could be achieved from an engineering perspective, by studying the feasibility of 'New Kuwait' vision regarding increasing RE penetration in electricity grid.

1.1 Brief Profile of Kuwait

Kuwait is a small economy that has abundant reserves within fossil fuels. The economy mainly relies on oil revenues and exports. Oil accounts for about half of the GDP, 80% of the income of government, and 95% of the exports (Ramadhan et al, 2013). Kuwait remains a major exporter of oil and crucial member in the Organization of the Petroleum Exporting Countries (OPEC). Ramadhan and Hussain (2012) also contend that Kuwait is also a producer of moderate amount of dry natural gas and uses a large quantity of the natural hydrocarbon resources for meeting the increasing local demand for electricity. The rapid rise in total consumption of electricity has mainly been because of the increase of population and per capita consumption. The increased demand for electricity over the years has been influenced by various factors, particularly high oil revenues driving economic activity growth, high rate of population growth, improved living standards, more electrical appliances' penetration, low prices of electricity, and the desert hot weather (Ramadhan et al., 2013). The demand profile has been strongly influenced by high temperature and led to widespread utilization of the air-conditioning systems. Among the aforementioned factors, low prices of water and electricity sustained by water subsidy program and government electricity. Due to the high demand of electricity and the increasing shift towards sustainable development, Kuwait should shift to renewable energy sources in order to meet the demand and enhance sustainability (Ramadhan

& Naseeb, 2011). Over-depending on unsustainable energy sources could be detrimental in its quest for achieving sustainable development.

1.2 Aims and Objectives

This thesis will assess the feasibility of energy production diversification with renewable energy contribution of 15% in the country's overall electricity matrix by 2030. To accomplish this aim, the study will seek to achieve various objectives

- To find the best arrangement of renewables (solar PV and/or wind turbine) for Kuwait with highest potential for reducing the load on grid to cover for electricity demand.
- To find possible penetration percentage of renewable energy in year 2030, with assumption;
    - Electricity demand in Kuwait grow at the same rate (annually).
    - Economy in Kuwait grow at the same rate (annually).

1.3 Overview of The Methodology

1. Based on literature;
    - Define the current situation of Kuwait and future energy need
        - Location and size, population
        - Financial state
        - Environment and climate (weather), CO2 emissions
        - Create an electricity demand profile for Kuwait
        - Energy portfolio: map of the current grid mix
        - Forecast of the demand
        - Average type of household selected
        - Ongoing projects: i.e. Al-shagaya (wind, PV)
2. Resource potential
    - Assess the suitability of solar energy
        - The amount of Irradiance and prove its enough for solar applications, list solar technologies in terms that can be used for modeling.
    - Assess the suitability of wind energy
        - Locations should be used, sizes Wind speed in Kuwait at different locations
3. Software selection: based on the objectives of the project multiple software might be used which will help in assessing RE systems in detail;
    - HOMER Energy Pro
4. The location for the analysis will be selected. details of the location will be provided
5. Meteorological data is added
6. Input details and prices of system components (i.e. wind turbine, PV, inverter, storage) and grid are determined. They will be used in HOMER
7. Two main scenarios will be considered financially and technically. One to determine the feasibility of 15% RE by 2020 (based on modelling of ongoing projects in Kuwait) and other to aims to maintain for year 2030
8. assess the energy price after introducing renewables

Note: Time and financial constraints are assumed (limited time and specific budget for the investments)

1.4 Dissertation Structure

This dissertation will be structured as follows: Chapter 1 Introduces the main problem which is the absence of power diversification in Kuwait electricity network with respect to other nations, it also high Kuwait vision for 2030 and provide brief profile of Kuwait, Chapter 2 will cover the Literature Review regarding Kuwait current position in terms of oil dependent position in both sectors; economy and energy it also touch on different points in current energy profile, Chapter 3 covers investigation of solar and wind resources in Kuwait and briefly present the challenges for harnessing these resources, Chapter 4 covers the methodology, specifically creation of demand profile for the Kuwait and modelling of four scenarios using HOMER Pro software for different configurations and load profiles, the scenarios will be categorized in two different cases; the first will be based on the current demand profile with solar-grid, wind-grid and solar wind grid configurations, while the other case (scenario 4) will be based on a predicted load profile for year 2030 and 2050 with the most suitable system configuration deduced in first case. Chapter 5 will cover the findings of the scenarios and Discuss whether the 15% renewable penetration is feasible or not. Chapter 6 covers the conclusions and future works.

2 Literature Review

The need to review countries position based on past history and future projections of electricity consumption is an essential requirement for countries in order to evaluate their source of power and also to conclude whether these resources are reliable and/or sufficient in the long run. Applying the same theory on Kuwait, specific scenarios have been established for analysis based on current energy state and future expectations in order to have insight on future electricity needs and to value renewable energy existence in future energy mix.

2.1 Kuwait Situation

2.1.1 Location, Size and Population

Kuwait is found in Western Asia bordering Saudi Arabia form and Iraq, with a population of slightly above 4.6 million as by 2018, basing on the elaboration by Ministry of Electricity and Water (MEW, 2019). During the 10 years period (2008-2018) Kuwait has witnessed 25.5% growth in its population, due to immigrations and increase in mortality rates (Ibid, p.43). In general, population in Kuwait can be complex because many records do not count Kuwait's stateless population, they can over 300 thousand people. By population, Kuwait ranks 129 globally, and the population density is 240 per square kilometre. Also, Kuwait is found in a region which is among the driest and unhospitable deserts (Alhajeri et al., 2019). It also experiences a desert climate characterized by high temperatures, long and hot dry summers. A large proportion of the country's population is found in the capital city and mostly occupying coastal regions of Kuwait figure (2-1), thus, making it to be among the most urbanized nations globally. It has an abundance of hydrocarbon resources and produces a modest quantity of natural gas.

Kuwait is considered to be a small country with total area of 17,818 km$_2$. The government policies and property rights to land suggests that, as oil producer country lands in Kuwait are pre-owned by the governmental institution Kuwait Oil Company (KOC), in which they run geophysical analyses before categorizing the land. If the land preserves petroleum, it will be used for oil production otherwise it will be categorized as residential or commercial land for example. Consequently, limited areas of land can be designated for harnessing renewable energy, that is after being approved by council of ministers and the national assembly.

Figure 2-1: Kuwait Map, (Alsarraf, 2015, p.2).

2.1.2 Economy

Despite Kuwait having a geographically small size, it is wealthy and has a relatively open economy. Agricultural production remains quite negligible because of its arid climate. Kuwait is not an industrial country due to the dearth in natural resources and manpower. Therefore, the economy is mainly dependent on oil as well as oil products, which account for over 50% of its GDP (Al-Nassar et al., 2019). Oil prices have been fluctuating significantly for the last decade, there has been a drastic drop in oil prices since mid-2014 and the country experienced a deficit in the budget in 2015. This deficit increased to 16.5% of the Gross Domestic Product in 2016. Also, there was a decline in the overall fiscal surplus to 0.5 percent of the GDP in the 2016/2017 financial year (Alhajeri et al., 2019).

Future adoption of renewable energy systems requires large financial investments, dedicated for implementation and development of the technologies. According to the Ministry of Finance (MOF, 2019) Kuwait's revenue for the fiscal year 2019-20 is mostly from its oil exports which account for almost 90% of the revenue figure (2-2) while remaining revenue is from different sources. Kuwait's revenues of the fiscal year were estimated K.D. 15.81 billion, that is equivalent to about £41.33 billion (~$51.7B). However, the expenditures exceeded the revenues by £21.6 billion (~$27.8B) for the same period (Ibid). This was expected to be the case since oil prices were volatile as yet. The global market of oil is easily affected, whether it is a political issue or a development of an alternative. Countries like South Korea, China and even USA, who are main importers of Kuwait oil have shifted their attention toward renewable energy systems for their increasing reliability. Henderson (2020) argues that although the global dependence on oil and other fossil fuels is still unquestionable, the prices of crude oil were affected nevertheless because it was threatened to lose its position in energy source monopoly. OPEC (2019, 7) pointed out that Kuwait has GDP growth rate of 1.8% for the year 2019, which is considered to be decent, given it is higher than Saudi Arabia (0.3%) but similar to UAE. Meanwhile, KISR (2019) predict higher GDP annual growth rate for future years, 2.8% on average. The fiscal deficit was cover by the reserves from yesteryears' profits, it will however, negatively factor in the amount of investments in potential RE projects.

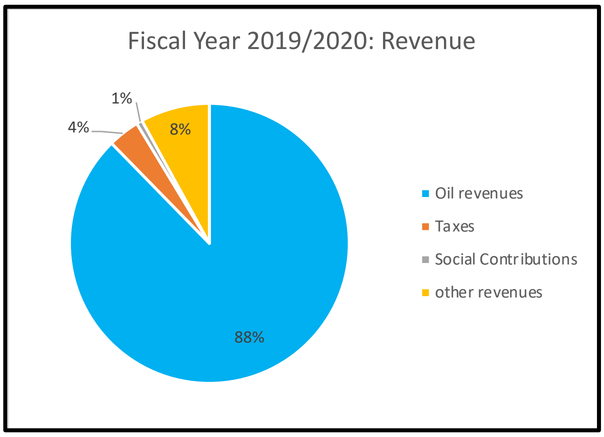


Figure 2-2: Sources of income for Kuwait based on Kuwait Ministry of Finance data (MOF,2020).

In addition, the prosper economy and excessive availability of oil and gas drive Kuwait to apply heavy subsidises to its cost of electricity. Since 2017, electricity tariffs were increased and according to the new pricing plan, consumers are charged KWD 0.012 (~$0.039) per kWh on average. Meanwhile, the kilowatt-hour electricity costs Kuwait between $0.115 to $0.135 to produce (Ansari, 2013, p.1; Bachellerie ,2012, p.52; Ezzahi, 2017, para. 9). Despite the fact that Kuwait is has an abundance of oil, the cost of power production ($/kWh) is at standard, since it is dependent on the overall production process and oil prospection technology. However, the electricity subsidy is quite high, and consumers are only paying for a fraction of the actual cost. Since consumers pay $0.039 for unit power consumption, the subsidy is about 72% which is in range according to Shehabi (2017)

2.1.3 Energy production and demand

Kuwait is among the top 10 producers of oil and has the sixth largest oil reserve globally. With its small population compared to other large oil producers, its economy performs quite well, but mainly relies on revenues generated from oil exports. The sector makes up about 90 percent of the export revenues, while the revenues that Kuwait generates from oil exports over 50% of its GDP (Alhajeri et al., 2019). Similar to other oil producers, Kuwait is grappling with a transforming energy world. In the midst of the coronavirus pandemic, shifting demand, technology and supply have led to an energy world whereby the volatility of oil prices and market uncertainty are the unique features.

Kuwait's conventional sources of power are oil and Natural gas that are prospected, produced, transfared and distributed by governmental institutions. Ministry of Electricity and Water (MEW) and Ministry of Oil (MOO) are joint institutions, each have different roles and operate on two separates yet vertically integrated sectors. Both of power and electricity industry and oil industry, are fully state-owned in Kuwait. MEW and Kuwait Petroleum Corporation (KPC), which is another side of MOO that administration in the operation field, govern all stages of power production, from production of oil and gas to electricity generations and exports. This presents an advantage of lower price per kWh for the end-user since KPC apply zero charges on providing the fuel, oil and gas, required for electricity generation.

Kuwait is one of the main exporters of oil, as a member in OPEC, and also has one of the highest per capita energy consumption rates, its hydrocarbons are used to meet the rising electricity demand. MEW (2019) stated that there was a 30 percent elevation in energy consumption rates in the country, between years 2008 and 2018 only. The rapid increase in consumption requires high During 2010s, the country went through recurring blackout and brownouts as result of the rapid increase in consumption of electricity that caused reserve margins to drop creating supply-demand mismatch (KISR, 2019). The demand for electricity is expected to raise analogous with the growth in population in the country, estimated to be around 4.2 million people in 2016 (Population Reference Bureau, 2016, p.7; Wood & Alsayegh, 2014) and around 4.6 million in 2018 (MEW, 2019). Kuwait has high peak load growth rates, averaged at approximately 6% annually (MEW, 2013). Therefore, improving and expanding the electricity generation sector in Kuwait is of high significance to support energy supply and abjure potential blackouts at times of peak demand.

Installed electricity capacity grew from 2.25 MW only in 1950s, which was the capacity of first power station in Kuwait, into 13 383 MW (~13.38 GW) by 2010 (MEW, 2009; EIA, 2019). Moreover, recent records indicate new electricity production units were installed throughout the years 2010 to 2018, total of 5.4 GW was added to the total installed capacity, to cover for the excessive demand (EIA, 2020; KISR, 2019). Figure (2-3) illustrates incremental growth of

Kuwait supply capacity for electricity since 2008. Recently, as in 2018, the total capacity is 18.8 GW (KISR, 2019) from eight power stations. shown in table 2-1.

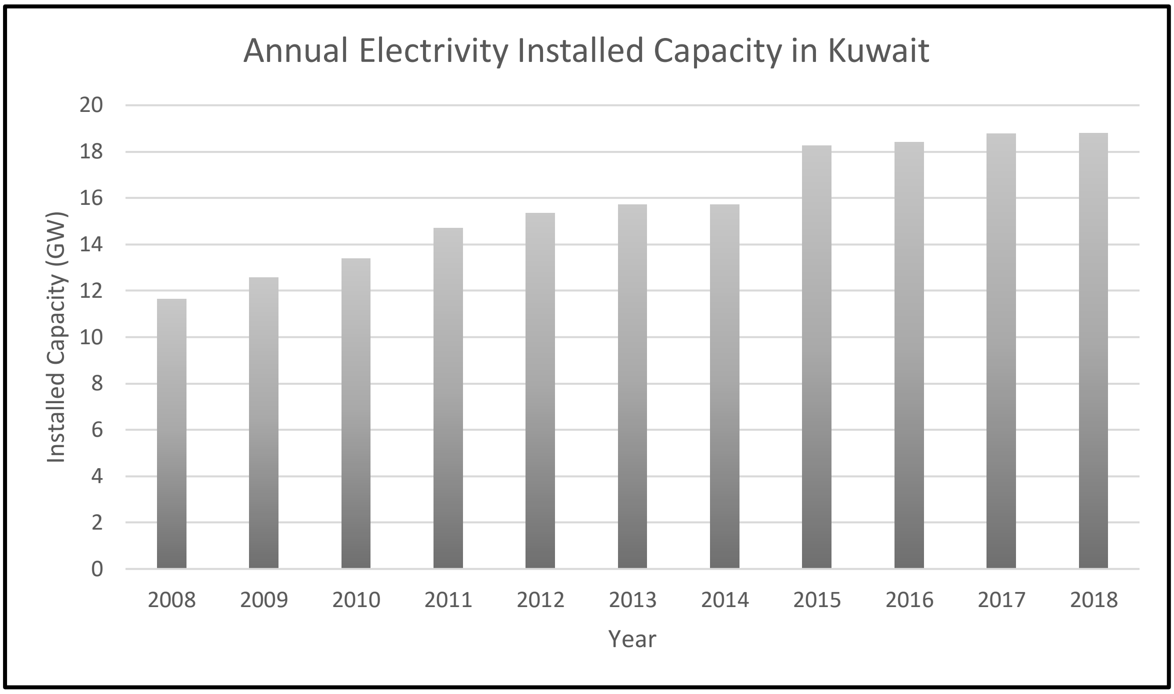


Figure 2-3: Annual installed electricity capacity for years 2008 to 2018 in Kuwait, sourced from (EIA, 2020; MEW, 2019)

Table 2-1:Current, as in 2018, Installed electricity generation capacity based on power plants (MEW, 2019).

	Power Station/Plant	**Installed Capacity (MW_e)**
1	Doha East	1,122
2	Doha West	2,541
3	Subiya	5,867
4	Shuwaikh	252
5	South Shuaiba	720
6	North Shuaiba	876
7	Az-Zour South	5,806
8	Az-Zour North	1,540
	Total	18,794

These power plants are the main providers of electricity in the country that work around the clock to satisfy the demand. According to KISR (2019, 35), the final electricity consumption of the year 2015 was approximately 44.6 TWh. Residential sector was the highest consumer of electricity that year, its share was estimated to be more than half the country's total electricity consumption, precisely 27.2 TWh/year. Services sector followed with a third of total demand, 15.2 TWh/year. Since Kuwait have hot dry weather, sea is the main source of water for the country. Though, to cover country worth of drinkable water demand, water desalination systems are used, which in turn consumes 2.2 TWh of power annually. MEW (2019, p.105) presented an updated information for year 2018, total electricity generation and final electricity consumption were recorded 74.1 TWh/year was 73.4 TWh/year. The total residential share from that was 29.9 TWh, it is well below the half and about 9% increase compared to 2015 statistics. Yet, residential sector remains the highest among sectors in electricity demand Figure (2-4).

Total energy consumption is the total demand consumed in the end by the residents/people. total primary energy demand is the input demand of energy including the losses of energy in energy sector (i.e. during the combustion of oil and gas to produce electricity)

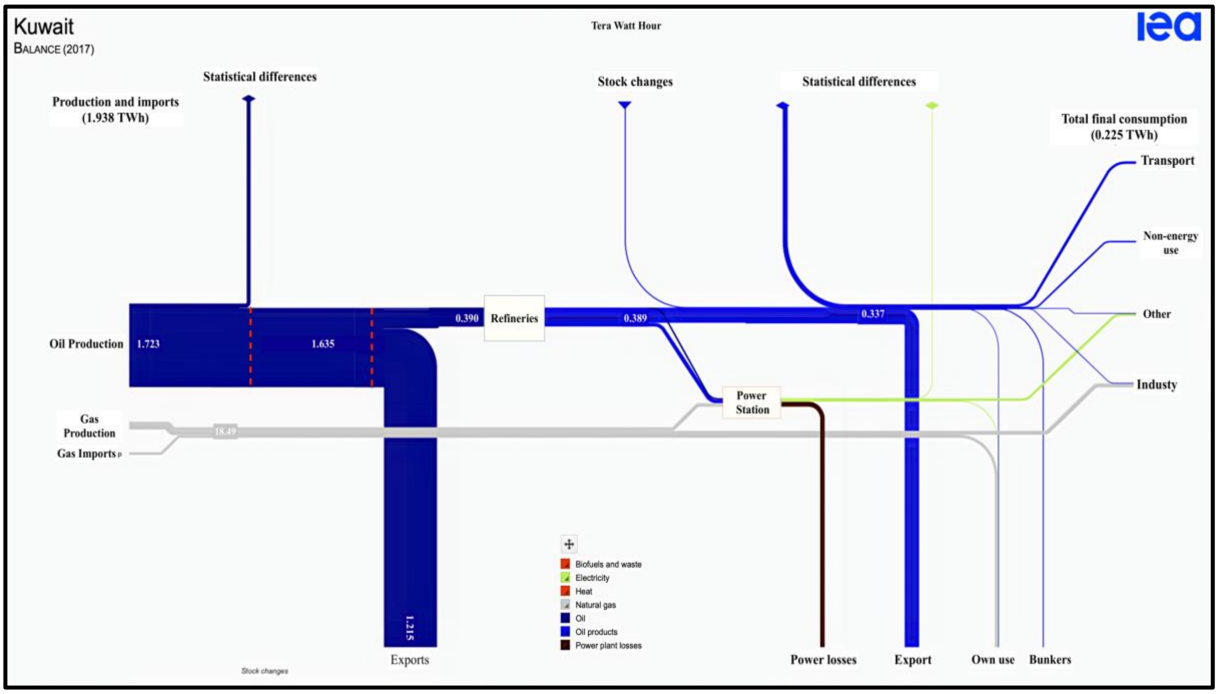


Figure 2-4: oil and natural gas production and their contribution in forming the grid map of Kuwait (IEA, 2017)

Kuwait is considered to be one of the hottest countries in the world, its temperatures exceed 50°C during the day in summertime. The elevated heat also continues during evenings (30 - 42 °C), this in addition to dusty weather, factor in completely neglecting outside ventilation for most if not all people. Leaving no other option but to resort to cooling systems around the clock and inevitably result in electricity consumption, hence, base load (figure 2-5). Ramadan and

Hussain (2012) claim that there are several aspects influence electricity demand in Kuwait such as average income per capita, population and total GDP. However, none of which explain the increase in electricity demand for a given year. Through the course of the year the main difference, which corelated with the weather, is human behavior and specifically use of Air Conditioning systems (A/C).

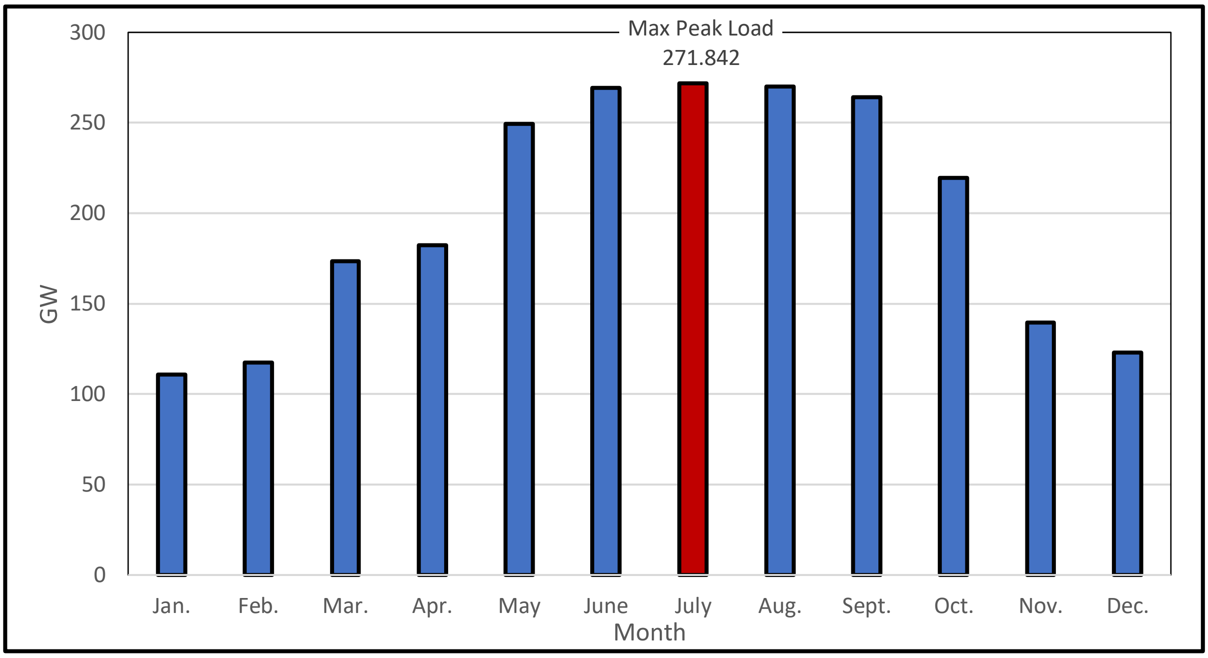


Figure 2-5: peak electricity energy consumption during 2018, red bar: the highest peak load in the year (MEW, 2019).

Quotative analytical study was conducted by Jaffar et al (2018) based on 250 survey respondents in Kuwait. Main aspect the questionnaire covered was household behavior, including the use of space conditioning systems, cooling and heating. Jaffar found that all households relayed on AC to cool their homes, 44% of the households cool their homes for eight months of the year, mainly from March to October (figure 2-6). This specific finding of the research if compared with MEW records in (figure 2-5), electricity demand cluster can be picked up from it, supporting the aforementioned hypothesis and emphasize A/C utilization impact on the electricity demand. Wood and Alsayegh (2012) found, the base load was 4500MW circa, which accounted for about two fifth of the total installed capacity then. More importantly was AC inefficiency impact on the average daily deference in the base load, it was about 1000MW difference between maximum load at three in the afternoon and minimum load at four in the morning, the difference is roughly 8% of total installed capacity. Moreover, Kuwait Institution for Scientific Research estimates that 70% of the annual peak load demand and over 45% of annual electricity consumption is dedicated for AC systems accounts.

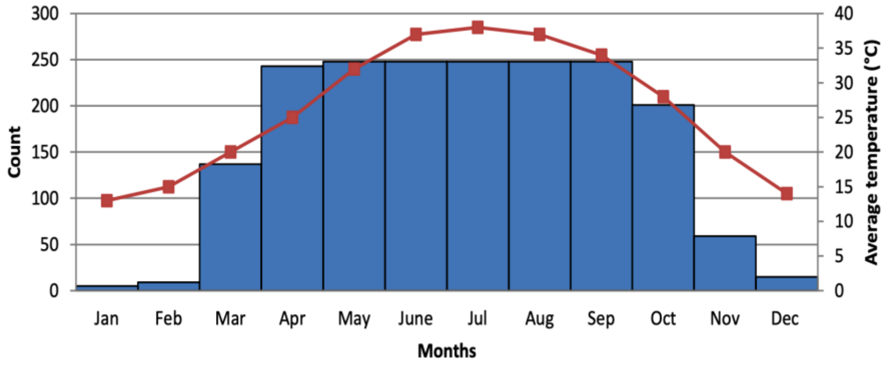


Figure 2-6: Monthly AC by survey sample and average monthly external temperature in Kuwait (Jaffar et al, 2018).

2.1.4 Environment, Climate and Emissions

Electric power systems usually consume large quantities of fossil fuels for them to not only reliably generate electricity, but also meet the rising electricity demands. This is linked to the substantial environmental costs because of the rising environmental discharges, including greenhouse gases and atmospheric pollutants which result from the combustion of fossil fuels. Notably, carbon dioxide emissions attributed to electricity generation constitute the larger proportion of global greenhouse gas emissions (US EPA, 2019). In Kuwait, electricity and water demand increased by more than two-fold in 2015 compared to the demand levels in 2000. As a way of meeting this substantial demand growth, the power sector usually depends on cogeneration plants fueled by fossil fuels (MEW, 2015). Water desalination and power generation systems often work simultaneously in order to desalinate seawater and generate electricity through the cogeneration power plants. Various studies conducted in Kuwait which have tackled air quality demonstrate that some atmospheric pollutants occur at dangerous levels (Ettouney et al, 2009; Jallad & Espada-Jallad, 2010; Nasrallah et al., 2003). For instance, Al-Baroud et al (2012) established that the SO2 and NOx concentrations surpassed the limits of air quality that the Environmental Protection Agency, EPA, had set. The Kuwait EPA has often emphasized that there is need to improve air quality and reduce air pollution.

Recently, the UN Development Program and UNDP Kuwait came up with the Kuwait Integrated Environmental Management (KIEM) system to review the existing environmental regulations and develop new standards for air pollution (UNDP Kuwait, 2019). Part of its task is evaluation of air quality data, and to effectively handle the task, there is need to create an updated and reliable emissions inventory. Conversely, the current air quality standards in the country do not reflect the emission inventories. The monthly levels of pollution tend to be higher in the summer for all pollutants because of the higher energy demand in hotter months (Alhajeri et al, 2019). Despite this, SO2 emissions tend to be slightly lower because of the higher energy demand impacts.

Lowering GHG emissions is among the drivers for the implementation of renewable energy in the world and Kuwait. The high availability of these gases poses detrimental impacts on sustainability of the Kuwait environment, thus making it critical to minimize their production. It was reiterated during COP21 where member states committed that they would work towards attaining zero emissions by 2051 (Byrne et al., 2016). In order to attain this, reducing or totally shifting from the usage of fossil-fuel power is a promising strategy with renewable energy sources such as nuclear energy, hydro power, PV, and wind energy being better replacements. Kuwait could alternatively embrace carbon capture technologies. Ki-Moon (2016, p.5) suggests that to ensure Kuwait commits fully for CO2 emissions, there is need to phase out subsidies imposed on fossil fuels. The total amount of carbon dioxide released by burning fossil fuels in the process of producing and consuming energy was measured as 106.5 million Mt (CIA, 2020).

High temperatures impact animal and human health lead to a rise in sea levels, extreme droughts, and more flooding. Such negatives motivate the Kuwait Government to invest in renewable energy (Buckley & Nicholas, 2016). The cost factor is the other key driver behind Kuwait embracing RE. The eventual costs associated with the implementation of REs are significantly lowered compared to the ones of the conventional power plant. For example, the solar photovoltaic costs are falling due to the development of advanced technologies, particularly related to crystalline silicon panels (Byrne et al., 2016). Also, the costs are lower due to the incentives and subsidies from the government on RE (Alberici et al., 2014). The cost reductions are quite observable in solar PVs and wind turbines due to the development of highly performing and more efficient solar systems and turbines.

2.2 Real Energy Model

The main points of the literature review ‘Kuwait situation’ will be used to create a model for Kuwait’s electricity network. The information will be used as a base case to check the validity of simulation under the same conditions. Based on the literature, energy in Kuwait is only provided by oil and natural gas power stations. Values of total installed capacity, total consumption and load factor are provided in table (2-2).

Table 2-2: National electricity data based on literature, (MEW, 2019).

Installed Capacity (GW)	Electricity Production (TWh/year)	Peak load (GW)	Load Factor* (%)	Total Electricity Consumption (TWh/year)
18.8	74.1	13.91	60.4	65.8

*Load Factor = (Elec. Prod. *8760 x Peak Load) x 100; *8760 is hours in a year

Electricity consumption in table (2-2) refers to the energy used by consumers. Because about 8.3 TWh/year are consumed at the power stations. Later on, in the simulation, at station power consumption will be included in the total consumption.

The financial aspects in the literature, revolves around the cost of K electricity production on Kuwait, which will be selected as $0.135/kWh. The selling price of unit electricity that will be purchased by consumers will be selected as $0.039/kWh. This is based on the aforementioned information about the cost and price of unit electricity in Kuwait in section 2.1.2. Also, from previous section (2.1.4) and EIA (2020) statement, Kuwait has 1420 gCO_2/kwh emissions. Similarly, Nazari (2010) concludes his analysis by stating sulphur dioxide and nitrogen oxide emissions in thermal power plants which were found to be 2.57 gSO_2/kWh and 2.31 gNO_x/kWh, respectively. different values for Each of the emission might be found from source to another, it is mostly because Kuwait have different types of combustion systems. Steam, gas turbine and combined cycle power plants can variety of emissions at different amounts.

2.3 Renewable Energy Projects

Kuwait has several governmental institutions contributing at different levels in the power sector, all with different mandates. MEW is a vertically integrated utility that oversees all aspects of production, transmission and distribution of electricity. Kuwait Foundation for Advancement of Science (KFAS) sponsors renewable energy projects including recent distributed-photovoltaic projects, while the design and implementation of the first phase at the Shagaya complex project was managed by KISR. The absence of coordination and harmony between these various institutions is believed to be the main reason for the slow development and deployment of renewable energy technologies locally. The dearth of private sector participation in Kuwait’s power sector has also contributed to the slow adoption of renewables.

Kuwait has adopted what can be considered as aggressive steps toward the development and implementation of renewables in order to achieve higher renewable penetration in the grid. The objective of penetration is aimed to be 15% of the total consumption of electricity in the year 2030, this will require continuous deployment of renewable technologies and forecasting the demand growth. Nuclear power generation reactor projects were under surveillance, but soon after the Fukushima reactor failure in japan the plans were revoked. Meanwhile, several projects were initiated at different scales, from solar system on public car parks to power plants with multiple renewable energy technologies. KISR and other responsible institutions provide little details to none about the target sector of the large-scale projects. However, power productions are measured by the number of houses in which their electricity demand can be covered.

Some of the small-scale projects were implemented on a car parks at couple of co-operative supermarkets. In these projects, grid connected PV systems were installed to produce 1,730 MWh of electricity energy annually. in addition of the two supermarkets, the projects will meet the need of more than 21 homes for a whole year. Other small projects aimed to build integrated PV systems for Kuwait homes, in which 150 homes have their electricity grid integrated by PV systems. The total capacity installed in this project is estimated to be around 1.5 MW_P, capable of producing around 2,440 MWh of electricity annually. Renewable energy production at this scale is translated into CO_2 emission reduction of about 2,200 tonnes/year. The information is sourced from Kuwait Foundation for Advancement of Science.

Among the large-scale renewable projects is the Alshagaya. The project is overseen by different governmental institution and is planned to be the largest renewable power plant, with 2000 MW_P capacity sourced from multiple renewable technologies namely; solar PV, solar thermal and wind power technologies. The project entered the electricity grid plan in 2011 and is expected to be completed by 2030 after finishing the three phases. The first phase included developing 70 MW capacity coming from solar PV (10 MW), solar thermal (10 MW) and wind power technologies (50 MW). This phase was projected for completion by 2017, however, it was included in the grid late 2018 (KISR, 2016). Further details about phase two and phase three are not available to the public, in general, there are challenges to find the appropriate data from official sources or other researches.

Al-Khairan IWPP is another project that is projected to be in service starting 2021, and it will be included to the electricity plan. The idea of the projects involves exploiting conventional thermal power, it is subdivided into three stages each is estimated to have 1500 MW installation capacity. First stage is planned for completion in 2021 while the second stage is expected to be completed by 2030. There is not enough information about the final stage, but it can be assumed to be fully completed by 2040. Moreover, Al-Nuwaiseeb is another thermal power project that is expected to be ready for power generation in the near future. This one was also broken in three phases with the first phase being planned for operation by 2022, its power production capacity was estimated to be 3000 MW for the first stage only (MEW, 2016). Other projects including the ones mention previously are provided in table (2-3) with the estimated capacity for each.

Table 2-3: renewable pilot projects in Kuwait.

Project	Capacity (MW)	Start	End	Comment
Alshagaya	2000	2011	2030	Renewable energy technologies First phase to produce 70 MW was completed in 2018
Al-Khairan IWPP	4500	2021	2030	1500 to be installed by 2021
Al-Nawaiseeb thermal power project	6000	2019	2022	3000 MW to be installed by 2022
Al-Abdaliya Integrated Solar Combined Cycle	280	2017	2019	Partly use Renewable Energy technology

3 Renewable Resource Potential

Generally, Renewable energy is defined as energy obtained from ecological resources, naturally repetitive and infinitely replenished flow of energy occurring in the environment. Solar, wind, tidal, geothermal and biomass are examples of the renewable energy. Adopting and utilizing these resources has proven to be a major step toward satisfying the growing energy demand by more sustainable means. Renewable sources such as solar, wind, tidal and others have made noticeable penetration in the international energy markets. The increasing attentiveness regarding renewable resources and its applications over the past decades have resulted in rapid development in renewable technologies. Of these, cost reduction and technical advancements in terms of reliability, efficiency and durability. Further improvements are required for the technologies to realize higher deployment of these natural resources.

Kuwait have already started deploying small-scale pilot projects featuring solar and wind energy. There are no official records of future projects but in the ongoing ones PV plants are dominating and wind turbines have smaller portion. In this section of thesis, solar, wind and tidal energy potentials in Kuwait will be assessed for feasibility of implementation.

3.1 Solar Potential

It is very important to be aware of solar radiation availability at a particular geographical location for better solar energy systems development and for the estimation of their efficiencies and output. In Kuwait, solar energy is one of the predominant sources of renewable energy. Profoundly, harnessing solar energy requires high solar irradiations and long hours of sunshine per day. According to previous renewable energy data records, Kuwait has potential for exploiting excessive amounts of solar energy during summer times (Bou-Rabee, 2017). Al-Enizi *et al* (2011) paper analyzed the potential of solar energy in Kuwait using a simple formulated approach based on clear sky atmosphere formulas, shown as follows. the global horizontal insolation S_H (kW/m2) is proportional to clearance index K_t and to the average extraterrestrial solar insolation $S_{ET}(ave)$ (kW/m2), which is the average amount of solar insolation before entering the atmosphere.

$$S_H = K_t * S_{ET}(ave)$$

Annual average clearance index table (3-1), were provided by National Aeronautics and Space Administration (NASA) website for Kuwait over 22 years (1983-2005). The value of clearance index reflects the radiation condition, High value (>0.5) indicate clear sky in which solar radiation is mostly direct beam while low ones correspond with grey sky in which solar beams are diffused (Al-Enizi *et al*, 2011).

Table 3-1:Monthly average clearance index at Kuwait area (Al-Enizi et al, 2011) in comparison with HOMER generated.

Latitude 29.37º Longitude 47.97º	22 Year Average K_t	NASA generated K_t
January	0.52	0.531
February	0.57	0.582
March	0.56	0.568
April	0.56	0.568
May	0.62	0.630
June	0.69	0.692
July	0.68	0.682
August	0.67	0.679
September	0.65	0.667
October	0.60	0.618
November	0.50	0.518
December	0.47	0.470
Annual Average	0.59	0.6

Al-Enezi *et al* (2011) used different meteorological data for Kuwait area such as latitude angle (L = 29.33º), longitude angle (γ = 47.5º) to find clearness index K_t, which is almost cloudless atmosphere for eleven months. Other data were used such as sunlight time t (variable from 6am-6pm) and the corresponding hour angle $H = 15(t - 12)$ were used in the function, hence, developed model. The model used the aforementioned function of horizontal insolation.

$$S_H = [-0.3807 \times 10^{-6} n^2 + 0.001124n + 0.6139]_{K_t} \times \frac{33048}{\pi}\left[1 + 0.034cos\left(\frac{360n}{365}\right)\right] \times [cosL \cdot cosH \cdot cos\delta + sinL \cdot sin\delta]$$

The results can be obtained for any hour of the day all year long. Consequently, hourly, daily or monthly total solar energy can be found for Kuwait area. According to Al-Dousari (2019) and Al-Otaibi Kuwait has an average solar intake of about 9-11 h/d of sunlight and one of the highest solar irradiation levels in the world 5.5-6 kW/m2 with an average diurnal solar insolation of 5.8 kWh/m2/day and diffused horizontal radiation (DHI) of 1.6 kWh/m2. It is noteworthy to point out that only 1 kW/m2 is required, in order to activate a PV cell. Therefore, even the DHI is important for PV applications.

From the developed module, it is found that peak horizontal solar radiation in Kuwait varies between winter and summer. Because during the midst of summer months (June-July), the elevated temperature degrees are associated with clear sky, hence high clearance index K_t values. Moreover, the calculated S_H during winter times (i.e. January) were around 3.89 kWh/m2 table 2017, that is just less than a half of its value for summer times (i.e. June) that reaches 8.16 kWh/m$_2$. In Figure (3-1) the monthly average proposes high potential for solar energy to invest in, especially if compared with its potentials in European countries whom monthly average is only 2.8 kWh/m$_2$.

Table 3-2: Annual average solar horizontal radiation for Kuwait area

Latitude 29.37º Longitude 47.97º	22 Year Average (kWh/m^2)
January	3.89
February	4.96
March	6.09
April	6.91
May	7.8
June	8.16
July	7.76
August	7.29
September	6.28
October	5.05
November	3.82
December	3.26
Annual Average	5.94

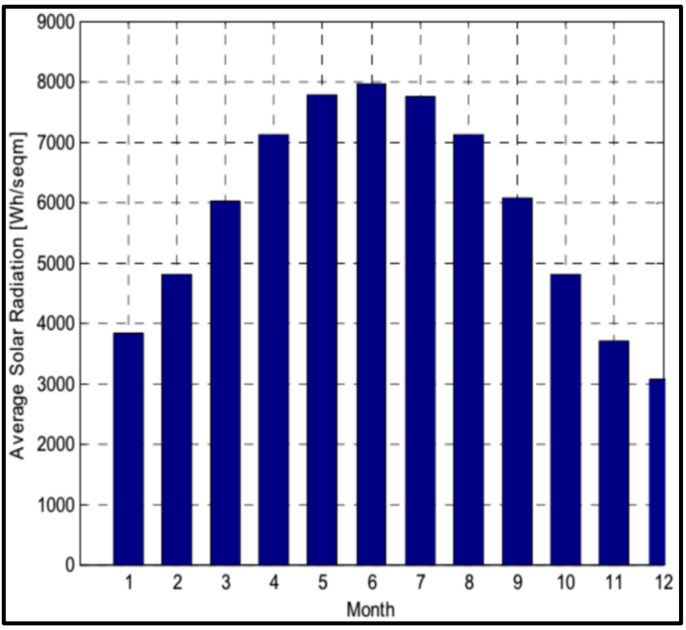


Figure 3-1:Monthly average solar horizontal radiation for Kuwait area

Sizing of PV

The size of PV systems can be determined from the obtained solar radiation data. Manufacturers of PV panels provide performance data for different modules. There are many types of PV panels available, the best of which is mono semi-crystalline solar module. SUNPOWER manufactures high performance monocrystalline PV module (Maxeon3), it has ~22.6% efficiency, area of 1.768 m$_2$ and provide nominal power of 400 W$_p$ for each of that type. It is safe to assume its implementation in Kuwait at plant scale based on the average horizontal solar radiation values. if the plant is installed in 15 km$_2$ area maximum power generation would be;

$$Max\ Power\ Output\ = \frac{plantarea}{single\ PV\ module\ area} \times\ single\ module\ nominal\ power$$

$$Max\ Power\ Output\ = \frac{15{,}000{,}000\ (m^2)}{1.768\ (m^2)} \times\ 400\ (W_p) = 3.2\ GW/day$$

Power generation of this size can cover about 30% of Kuwait's electricity demand in June (Figure 2-5). However, this is done under the assumption of ideal conditions of solar radiation never drops below 4 kWh/m2, government willing to provide 15 km2 area for PV projects and Kuwait is able to buy 8 million panels of Maceon3. Also, the calculations disregarded the angle factor to the production. More detailed analysis of PV will be done by simulation using HOMER software.

Feasibility of PV in Kuwait area is challenged by its weather condition. aeolian processes are common occurrence in terrestrial and marine environment in Kuwait and neighboring countries. According to Wiesinger et al (2018) the northern region of the Persian Gulf witnesses more dusty days in comparison to the southern parts. Kuwait, which is included in the norther portion, had mean total annual dusty days of 255 days. The intensity of dust in weather varies from desertification level to sandstorms level, both propose challenging problems. During sandstorms the solar irradiance is affected and gathering of dust or sand masses are inevitable, figure (3-2) shows the dust accumulation on PV arrays. The compiled dust over PV panels would probably affect its performance. Experiment was conducted to analyze the technical performance of dusty PV panels and it found up to 8% reduction in efficiency of conversion in comparison with its output when clean (Islam & Jason, 2018). Moreover, KISR are also looking into the accumulation of dust on PV modules' performance from slightly different angle. Direct sun arrays on the PV modules and the heated PV surfaces could potentially heat up the sand particles and can eventually create hotspots, permanently damaging PV cells and reduce their efficiency. This is possible because the afflicted layers are made of silicone, which is a vulnerable to UV light, hence, cause it to wear.

Figure 3-2: before and after cleaning PV modules at different locations in Kuwait.

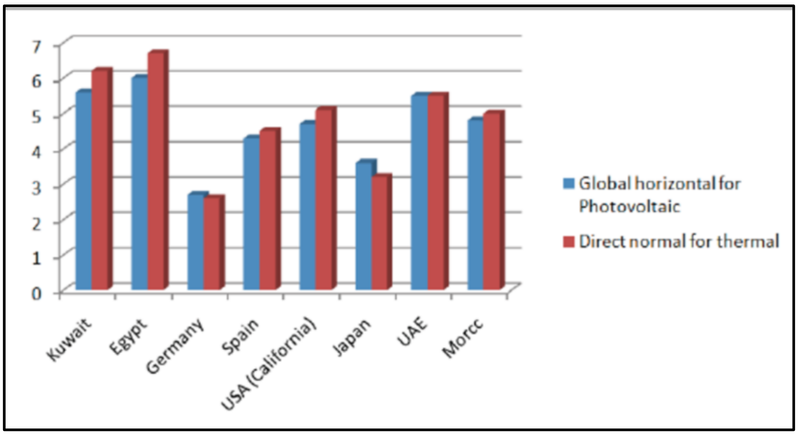


Figure 3-3: Global Horizontal and Direct Normal Irradiation of Kuwait in comparison with other countries kW/m2/day. (El-Sayed & Steven, p.29)

<u>HOMER Resource</u>

Solar GHI data in HOMER were generated using the previously listed data of clearance index and solar radiation tables 3-1 & 3-2. Thus, Figure 3-4 is generated by HOMER.

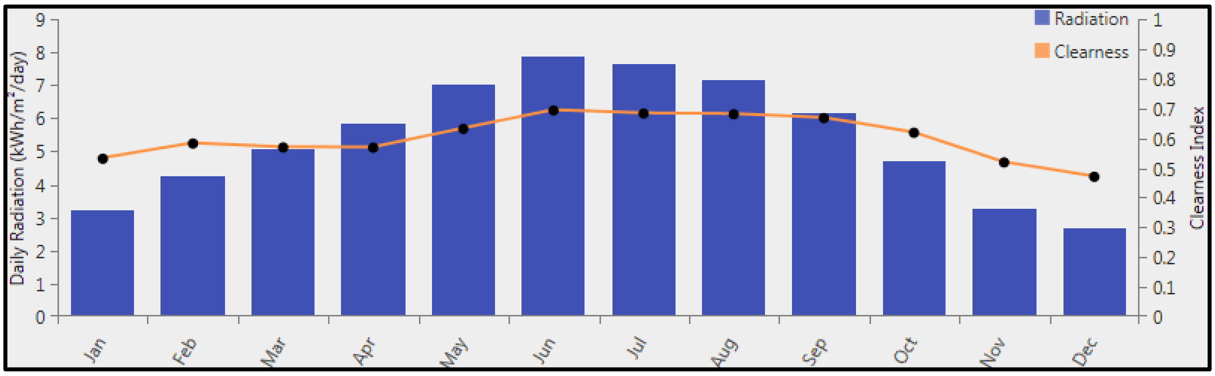
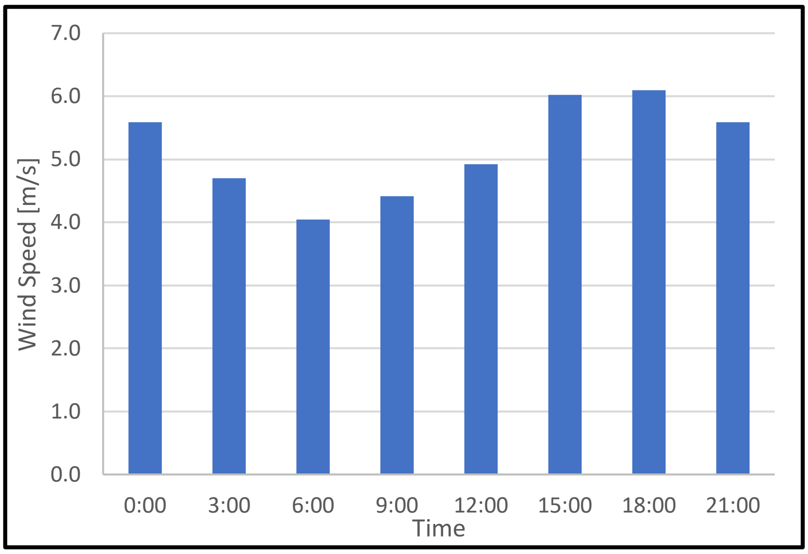


Figure 3-4: Solar GHI data for KUWAIT.

3.2 Wind Potential

Burueau Ocean Energy Management (BOEM, 2009) defines the wind as air in state of motion, produced as a result fluctuating solar radiation absorption by the earth. Wind energy is the leading renewable source and its technology has been developing rapidly. In many countries have wind energy excessively utilized, UK as an example. Similarly, IRENA (2016) stated based on conducted analysis Kuwait has promising potentials for wind energy resource. Wind energy is widespread, with average wind speeds exceeding 5 m/s being common, figure (3-5) and table (3-3) illustrate average wind speed during the day for a week data set. In general, wind resource is quite difficult to predict, it varies with year, seasons, time of the day. Thus, forecasting wind speed for days ahead is a matter of reliability.

Table 3-3: Periodic average wind speed



Time	Average Wind Speed (m/s)
00:00	5.60
03:00	4.70
06:00	4.00
09:00	4.40
12:00	4.90
15:00	6.00
18:00	6.10
21:00	5.60
Daily Average	5.17

Figure 3-5:periodic average wind speed in Kuwait based on a week data set, sourced from Windfinder.

These wind speeds are on a periodic basis of three hours throughout the day. The values are the same in both table and figure and they are the averaged values for week worth of wind speed data, these data are based on real time wind speed during summer 2020 (28th June – 4th July), the average wind speed at all time was found to be 5.17 m/s. It is important to know the wind speed values because it determines the wind power density (WPD) at the area of rotor, Kuwait has an annual average of 1454 w/m2 at hub height of 30 m above the sea level (Al-Salem et al, 2018). the energy that can be obtained from wind streams is proportional to the cube of its velocity, in other word, doubling wind velocity increases the available energy in the wind by factor of eight.

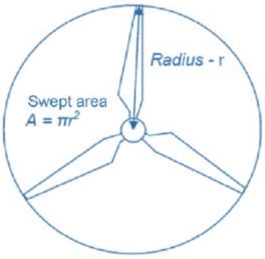
However, there is a theoretical limit to which the wind energy can be utilized by the wind turbine to produce output energy, that is known as Betz's limit. According to betz's law only 59.3% of the energy in the wind is used to generate power. This could be the main factor of lowering the efficiency of wind technologies. In practice, the maximum efficiency of commercial wind turbines is between 40 – 50% at ideal wind speed. For instance, Kuwait have installed 10 MW capacity of wind turbines in Al-Shegaya pilot project, total of 5 wind turbines 2 MW each from Gamesa wind turbines. To include the wind turbine in simulations later on, the closest model registered in HOMER was found to be Enercon E-82 E2, the obtain data about the wind turbine is listed in table (3-4).

Table 3-4: Enercon E82 wind turbine specification, HOMER

Wind Turbine	Rated Power	Rotor Diameter	Hub Hight	Cut-in wind speed	Cut-out wind speed
Enercon	2000 kW	82 m	78m/85m/138m	2 m/s	24 – 34 m/s

Wind turbine power output (kW) for Enercon wind turbine is provided by HOMER in figure (3-6). The findings of power output are governed by the following equation of the wind power (kW).

$$Energy\ in\ the\ wind: P_{wind} = 0.5\ \times \rho \times A \times v^3$$



ρ is the density of air in kg/m$_2$, A is the swept area of wind turbine in (m$_2$) and v is the velocity of air in m/s. By calculating the wind power, power output from the wind turbine can calculated.

$$Wind\ turbine\ power\ output: P_{output}(kW) = C_p\ \times P_{wind}(kW)$$

For ideal conditions, wind turbine will have Betz coefficient of C_p = 0.593. it is noteworthy to mention that utility wind turbines have achieved 70% – 80% of that.

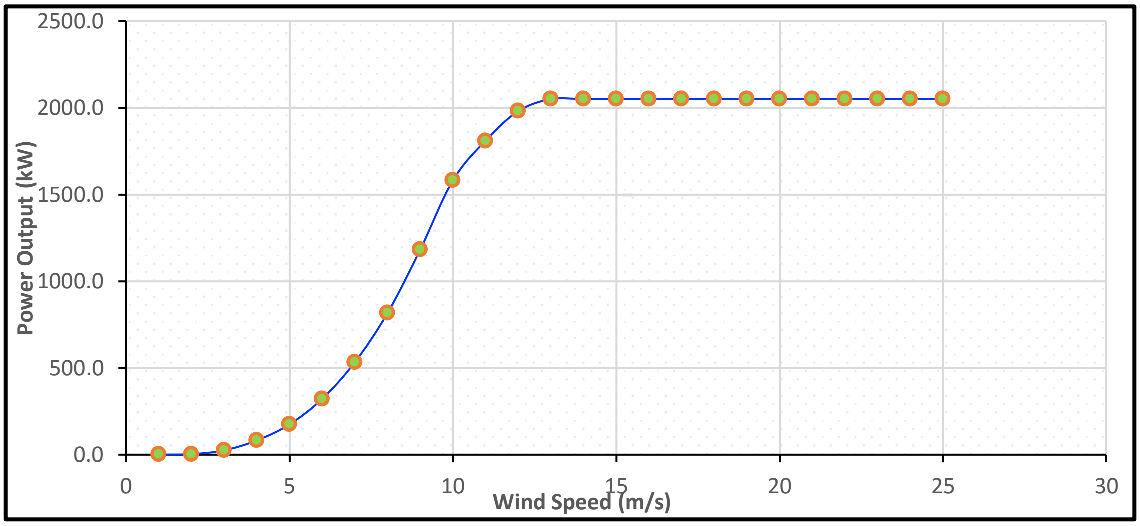


Figure 3-6: Enercon 82 m diameter wind turbine power output for a given wind speed, HOMER

This model will be used during the analytical simulation of wind energy at later section. Wind turbine produces 3 kW power output when wind speed is 2 m/s, which matches the value in table 3-4. Rated power was found to be 2050 kW which is a bit higher than the value mentioned. Finally, the cut-out wind speed is 24 m/s. Cut-in is simply wind speeds at which the wind turbine starts generating electricity and cut-out is wind speed at which wind turbine is engineered to stop operation to prevent operation failure and possible damages on the on the component.

The equations of power production mentioned earlier are combined to have a single general term to apply the values of wind speed in table 3-4, result of this process is in table 3-5. Assuming constant air density of 1.225 kg/m2, rotor diameter similar to Enercon E82 (82 m) and limiting factor C_p equivalent to Betz coefficient (C_p=0.593). Power output is calculated as follows (wind speed is 5m/s for this illustrative example).

$$P_{output}(kW) = C_p \ \times 0.5 \ \times \rho \times \pi \times \left(\frac{D}{2}\right)^2 \times v^3$$

$$P_{output}(kW) = 0.593 \ \times 0.5 \ \times 1.225 \times \pi \times \left(\frac{82}{2}\right)^2 \times 5^3 = 240 \ kW$$

The output calculated is 240 kW and by comparing it with the power output for the same speed in HOMER (figure 3-6) there is over 60 kW difference. Two variants are possibly the main reasons of this difference, air density and limiting factor. There is no mention for air density upon which HOMER based its results and more likely the difference because the limiting factor is not taken as Betz coefficient. In that case, to have $P_{output} = 174 \ kW$as in HOMER, C_p have to be 0.430 while other variables remain as is from the equation. List of calculated wind turbine power output is listed in table 3-5, each is calculated for the obtained average wind speed.

Table 3-5: Wind turbine power output based on daily average wind speed in Kuwait.

Time	Average Wind Speed (m/s)	P_{output} (kW)
00:00	5.60	337.0
03:00	4.70	199.0
06:00	4.00	123.0
09:00	4.40	163.0
12:00	4.90	226.0
15:00	6.00	414.0
18:00	6.10	435.0
21:00	5.60	337.0
Daily Average	5.17	279.0
+Variables are set to be: $C_p = 0.953, D = 82\ m, \rho = 1.225\ kg/m^2$		

One of the main components for harnessing wind energy is wind speed, It varies depending on the site. Wind turbines have to be installed in spacious flat land free of wind disruptive geographical features, buildings and living forms such as trees. These can block or intervene in the wind streams, hence effect the power produced by wind turbines. In Kuwait, residential areas and districts with skyscapes are situated near the sea region (The Gulf) as shown in Figure 3-7a, this explains the low wind speeds at the east side of the country while it is higher on the northwest. Wind direction could be another possible factor for the wind speed gradient, the kinetic energy in the air dissipate from it is form as wind and transform into other forms of energy. High WPD correspond with high wind speeds, at the same location of wind speed 5.4 m/s in Figure 3-7a, WPD is at its peak of 175 W/m$_2$ Figure 3-7b and 280.3 Figure 3-7c W/m$_2$ at hub heights of 10 and 30 meters, respectively. It also can be said that, further wind turbine hub from sea level will be exposed to higher WPD.

According to Al-khaldy et al (2018), the maximum wind speed at each of station varies from 17.32 to 23.90 m/s. Compared to Kuwait Airport statistics (land wind data) from (Al-nasser et al, 2005) the monthly average wind speed in offshore locations is 32.35–35.2% higher than those over land in Kuwait, which presents high potential for offshore wind turbine projects However, the focus of this thesis will be narrowed on the onshore/land wind turbines, because the marine traffic within the limited sea borders of Kuwait have to be studied first, before proceeding to hypothesize and analyze the off-shore wind turbine.

The bit that worries the operator is not only the tendency of wind to blow and when not, but also the rapidity with which it picks up and drops off, it is the slope of wind output that is a concern, in terms of steep ramp rates that could occur when the drop in wind speed output coincides with an increase in electric demand, or vice versa. The frequency of occurrence of these situations, both on theoretical and practical level is undeniably dependent on the weather first and foremost. Despite the attempt to predict wind behavior, its fluctuations remain hard to forecast

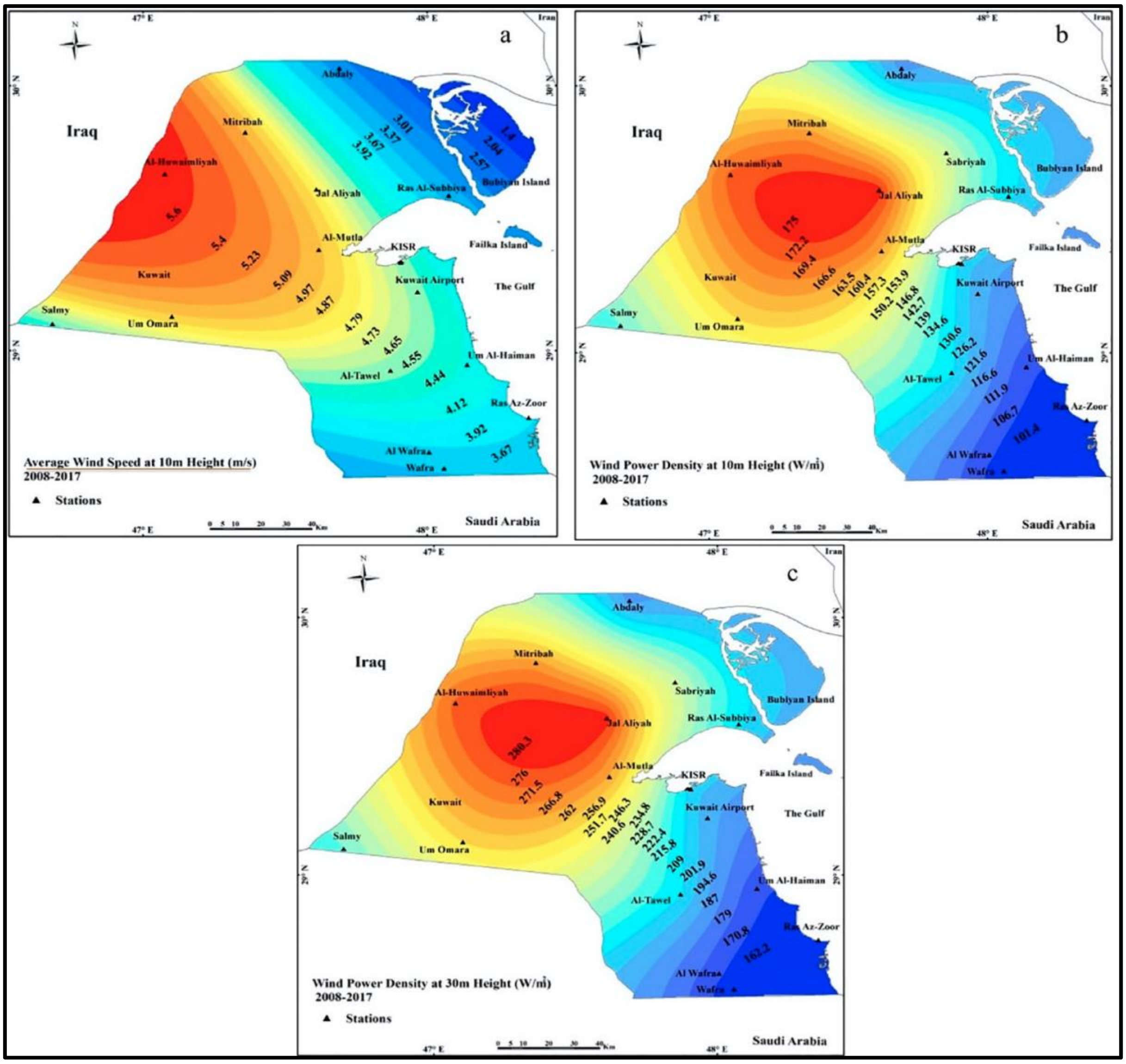


Figure 3-7: Average wind speed (m/s) (a); (b) Wind Power Density (W/m$_2$) distribution from 14 meteorological stations across Kuwait at hub height 10 m (b) WPD at hub height 30 m (c), (Al-Dousari et al, 2020).

HOMER Resource

This will be done by choosing different locations in HOMER and select the location that provides results of the highest amount of power for further scale up. Six locations were chosen to be the target of this analysis in HOMER as shown in figure (3-8), the location where picked up away from residential areas and two of these (circled in red) were chosen based on figure (3-7a). The locations in HOMER are selected to geographical coordination, none of which were selected at the bottom of the map because these sites are already reserved for residential projects.

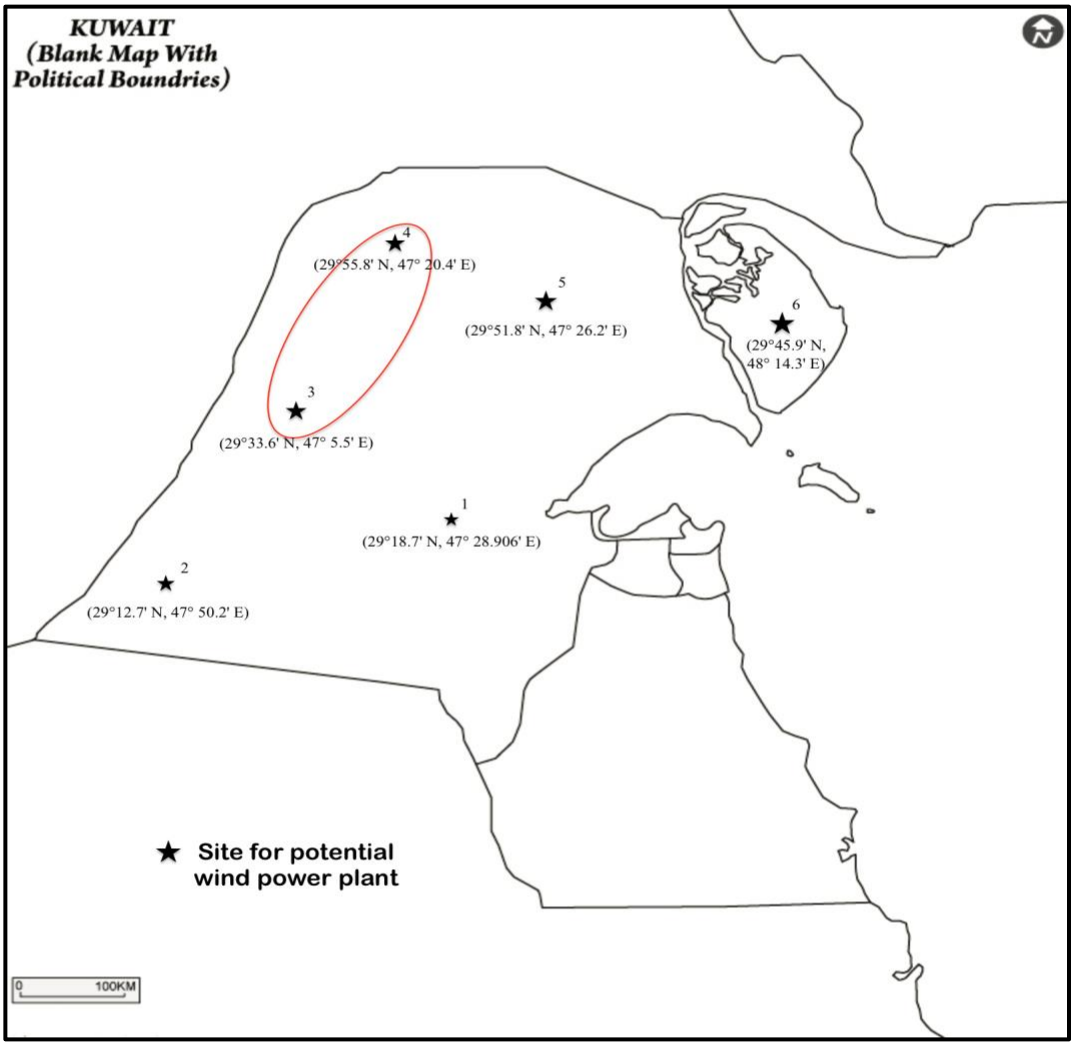


Figure 3-8: Selected sites for wind power production across Kuwait.

Based on analysis of the resource using HOMER, the monthly average wind speed is listed in table (3-6).

Table 3-6: Monthly average wind speed (m/s) at the selected sites.

Months	WS (m/s): Site 1 3, 4, 5	WS (m/s): Site 2	WS (m/s): Site 6
January	4.22	4.31	4.53
February	4.47	4.54	4.81
March	4.64	4.68	4.89
April	4.31	4.46	4.6
May	5.17	5.16	5.49
June	5.75	5.97	5.93
July	5.36	5.87	5.46
August	5.14	5.55	5.24
September	4.64	4.77	4.83
October	4.19	4.41	4.38
November	4.33	4.44	4.52
December	4.31	4.33	4.62

Among the sites, 'site 6' had the highest annual average wind speed 4.94 m/s but that site deselected because the site is basically an island and the water surface that separates it from the rest of the country create a challenge and the cost of preparation would deem it financially infeasible. Moreover, the difference in wind speeds between site 6, 2 and even the rest is negligible, the difference in the annual average speeds is about 0.07-0.24 m/s, at that amount the wind turbines will not even rotate. Higher wind speed data was implemented in HOMER, it was taken from Kuwait international airport by (Al-Nasser et al, 2005, p.2153). Annual average wind speed of 5.03 m/s at 30 m MSL (figure 3-9).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average (m/s)	4.3	4.8	5.3	5.3	5.4	6.7	6.2	5.5	4.4	4.0	4.2	4.2

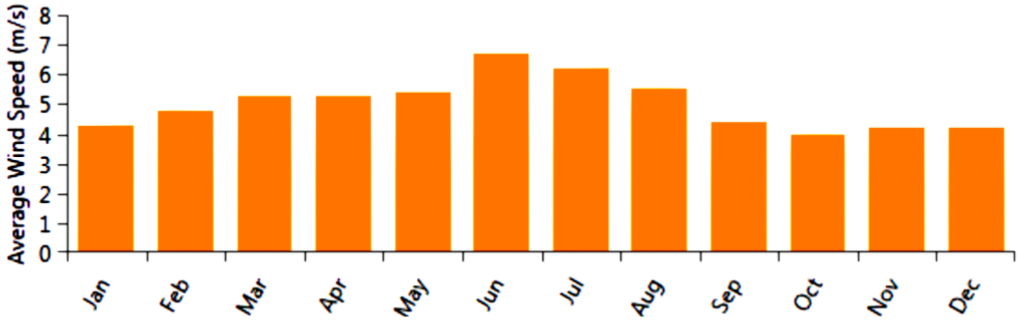


Figure 3-9: Wind speed profile implemented in HOMER.

3.3 Temperature

Kuwait is considered to have one of the harshest environments, dry most of the year and temperature reaches elevated levels. HOMER temperature profile is sourced from NASA database. The following figure (3-10) illustrates the temperature profile that will be used for simulation.

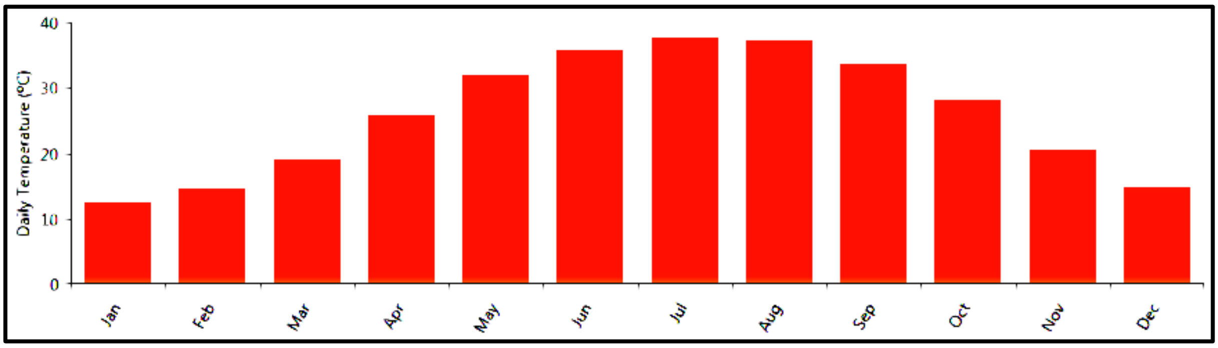


Figure 3-10: Average monthly temperature in Kuwait, HOMER.

Validity of the data was proved by online sources, by comparison they present very close temperature measurements table (3-7). Some of many varying factors that could alter the temperature measurements are the location at which it was measured, time at which it was measured in, humidity saturation and wind in Kuwait.

Table 3-7: Temperature in Kuwait, (Climatestotravel, 2020; MEW, 2019).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min (°C)	8	10	14	20	25	29	30	30	26	21	14	9
Max (°C)	19	22	28	33	40	45	46	46	43	37	27	21
Mean (°C)	14	16	21	27	32.5	37	38	38	35	29	21	15

4 Methodology

Although HOMER is created for microgrid cases, in this project, which is 25 years long, it will be used to simulate the national grid. Also, due to the fact the project will take the supplier (government) perspective in the financial aspects, some financial variables will have different meanings. Because of HOMER limits capability to accommodate the national scenario different assumptions will be presumed and it is worthy to note that net present cost (NPC) is calculated to account for the cost and income, which are basically ($0.135/kWh) for generation and income from consumers ($0.039/kWh consumed).

4.1 Preliminaries: Demand Profile

In order to analyse renewable energy penetration in grid mix, detailed information about the total electricity demand and load profile for Kuwait are necessary, this information is then used for HOMER simulation and further analyses. However, there is a lack of such detailed data when it comes to energy sector for the country. None of the papers and articles that were referred, which reviewed electricity consumption in the country, provided information of hourly electricity demand profile, including Ministry of Electricity and Water (MEW) electricity data records.

Moreover, authors of “A Methodology for Electric Power Load Forecasting” were contacted for the data analyzed in their paper. It had an hourly electricity demand for three years period, which is the requirement of this section. Although the data were not available by the authors, the data were provided by the officials at MEW. Thus, a request was made to an official in the MEW for a year worth of hourly electricity demand in Kuwait. However, according to the officials, electricity demand and detailed energy information at national scale Kuwait are considered to be classified to some extent, complete information are not to be published or shared. Therefore, load profile was created by distributing each month average load data to have 24 hours (00:00-23:00) averaged load for each given.

Despite the fact that HOMER provide the option of synthetic electric load data, it is more realistic to import scaled data of a real demand of electricity. In order to create load profile for HOMER, data from MEW electricity book was used, MEW (2019) provides an average peak load (MW) data for every month of year 2018 (table 4-1) along with average peak loads for the day 10th July 2018 with a time step of 30 minutes, a page from MEW that included the day data can be found in the appendix figure (A-1 & A-2).

Table 4-1: The average peak load (MW) in Kuwait for every month of year 2018, (MEW, 2019).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5700	6046	7367	8250	10545	12575	13215	12113	12646	9978	6387	6131

The day data were implemented in Excel and were plotted in hour time step figure (4-1). The variation in the load pattern (blue bars) throughout the day was close to the sinusoidal waveform, for simplicity this pattern was analysed by finding the absolute difference between the hourly value of the load (blue) 'L' and the average load (red) 'A' table (4-2).

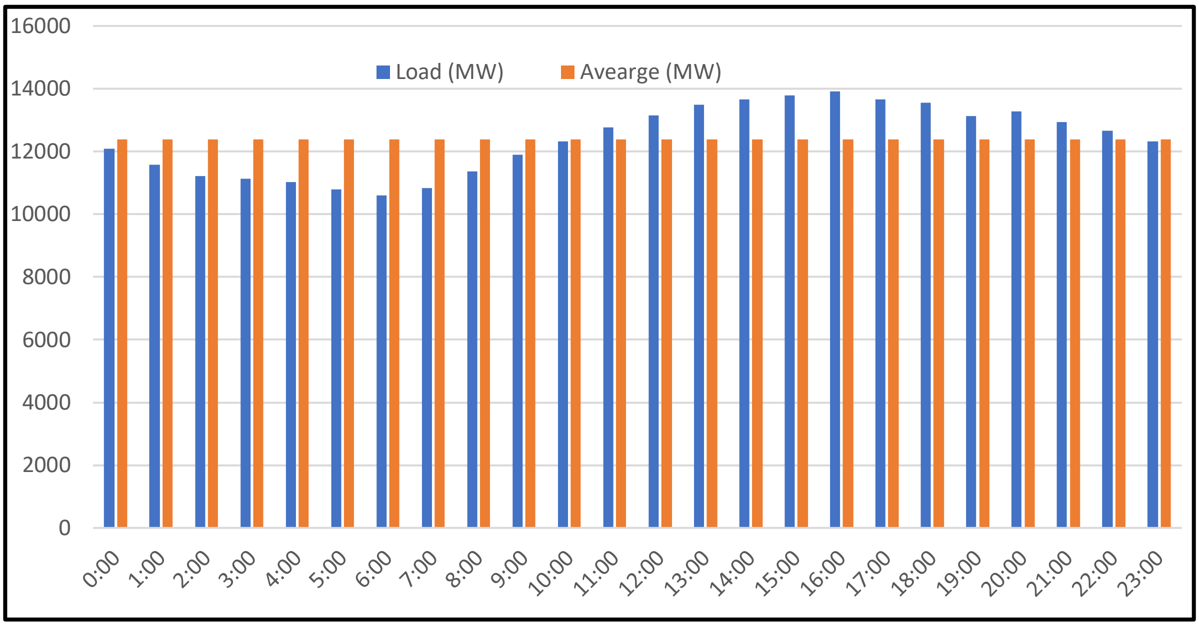
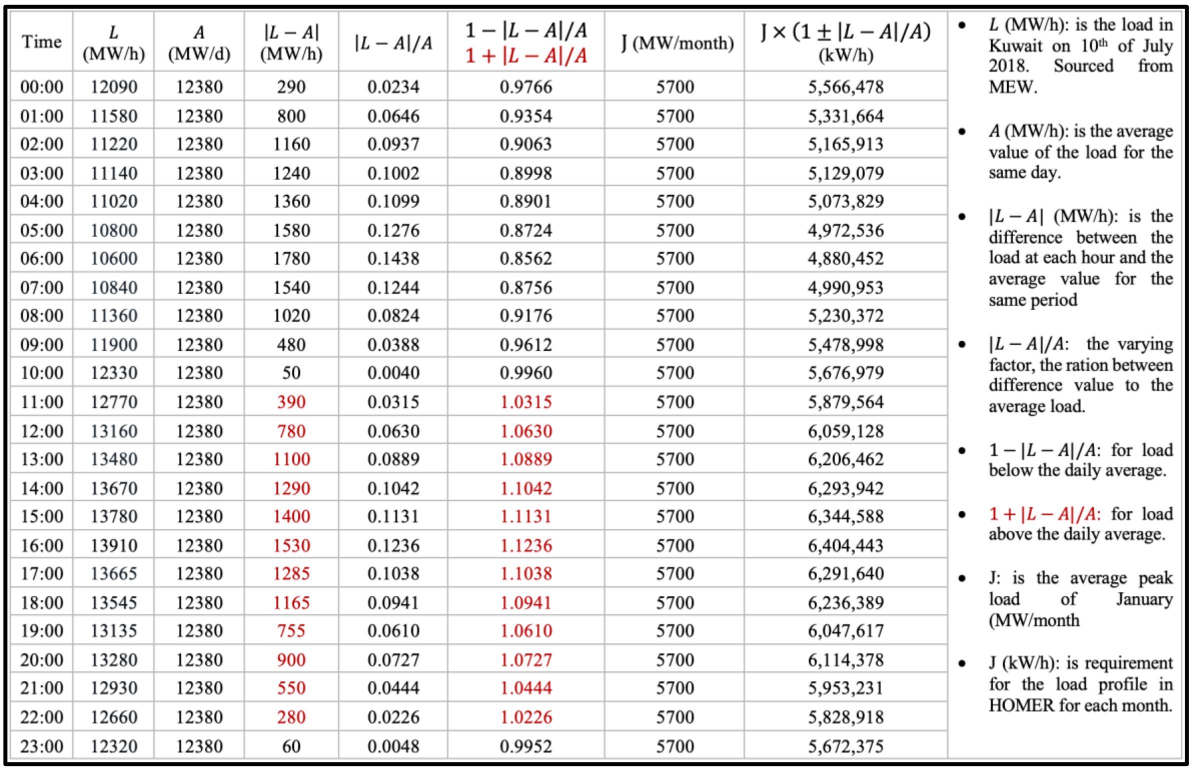


Figure 4-1: load profile for a day (10.07.2018) in Kuwait (Blue), average value for the day (Red), (MEW, 2019).

The difference ($|L - A|$), was then used to create a create varying factor ($|\mathrm{L} - \mathrm{A}|/\mathrm{A}$) to imitate similar pattern of load from figure (4-1) to the average peak loads of each month in table (4-1). The following calculations were done by two sections, loads below average had the varying factor subtracted from one ($1 - |\mathrm{L} - \mathrm{A}|/\mathrm{A}$) and loads above the average value had the varying factor added to one ($1 + |\mathrm{L} - \mathrm{A}|/\mathrm{A}$). The method was used to calculate the value for each hour. The calculated values ($1 \pm |\mathrm{L} - \mathrm{A}|/\mathrm{A}$) were then multiplied by the average peak load to have the 24 hours values. Results from calculations are presented in table (4-2)

Table 4-2: Load profile for January denoted by J (kW/h).



Time	L (MW/h)	A (MW/d)	$\|L-A\|$ (MW/h)	$\|L-A\|/A$	$1-\|L-A\|/A$ $1+\|L-A\|/A$	J (MW/month)	$J \times (1 \pm \|L-A\|/A)$ (kW/h)
00:00	12090	12380	290	0.0234	0.9766	5700	5,566,478
01:00	11580	12380	800	0.0646	0.9354	5700	5,331,664
02:00	11220	12380	1160	0.0937	0.9063	5700	5,165,913
03:00	11140	12380	1240	0.1002	0.8998	5700	5,129,079
04:00	11020	12380	1360	0.1099	0.8901	5700	5,073,829
05:00	10800	12380	1580	0.1276	0.8724	5700	4,972,536
06:00	10600	12380	1780	0.1438	0.8562	5700	4,880,452
07:00	10840	12380	1540	0.1244	0.8756	5700	4,990,953
08:00	11360	12380	1020	0.0824	0.9176	5700	5,230,372
09:00	11900	12380	480	0.0388	0.9612	5700	5,478,998
10:00	12330	12380	50	0.0040	0.9960	5700	5,676,979
11:00	12770	12380	390	0.0315	1.0315	5700	5,879,564
12:00	13160	12380	780	0.0630	1.0630	5700	6,059,128
13:00	13480	12380	1100	0.0889	1.0889	5700	6,206,462
14:00	13670	12380	1290	0.1042	1.1042	5700	6,293,942
15:00	13780	12380	1400	0.1131	1.1131	5700	6,344,588
16:00	13910	12380	1530	0.1236	1.1236	5700	6,404,443
17:00	13665	12380	1285	0.1038	1.1038	5700	6,291,640
18:00	13545	12380	1165	0.0941	1.0941	5700	6,236,389
19:00	13135	12380	755	0.0610	1.0610	5700	6,047,617
20:00	13280	12380	900	0.0727	1.0727	5700	6,114,378
21:00	12930	12380	550	0.0444	1.0444	5700	5,953,231
22:00	12660	12380	280	0.0226	1.0226	5700	5,828,918
23:00	12320	12380	60	0.0048	0.9952	5700	5,672,375

- L (MW/h): is the load in Kuwait on 10th of July 2018. Sourced from MEW.
- A (MW/h): is the average value of the load for the same day.
- $|L-A|$ (MW/h): is the difference between the load at each hour and the average value for the same period
- $|L-A|/A$: the varying factor, the ration between difference value to the average load.
- $1-|L-A|/A$: for load below the daily average.
- $1+|L-A|/A$: for load above the daily average.
- J: is the average peak load of January (MW/month
- J (kW/h): is requirement for the load profile in HOMER for each month.

This table passively finds HOMER requirement for load profile, it finds the hourly demand profile from the averaged value. Hence, the average of a month worth of load values at a specific hour of the day (i.e. the average of the load at 12 am for the 31 days of January is 5.566 GW). Columns of L, A, $|L-A|$ and $|L-A|/A$ are important to find $1 \pm |L-A|/A$ ratio that was then multiplied with the average peak load of January (5700 MW) to find the hourly average. This method assumes the average load of the month is the same at any given day or hour, the distribution of the average is mainly based on the pattern of load in the day. Daily variation of the load was assumed to be the same for the whole year, plotting the months of the year based on this assumption would result in unrealistic identical trend graph for everyday figure (4-2), having the load to always be at minimum load at 6:00 and maximum load at 16:00.

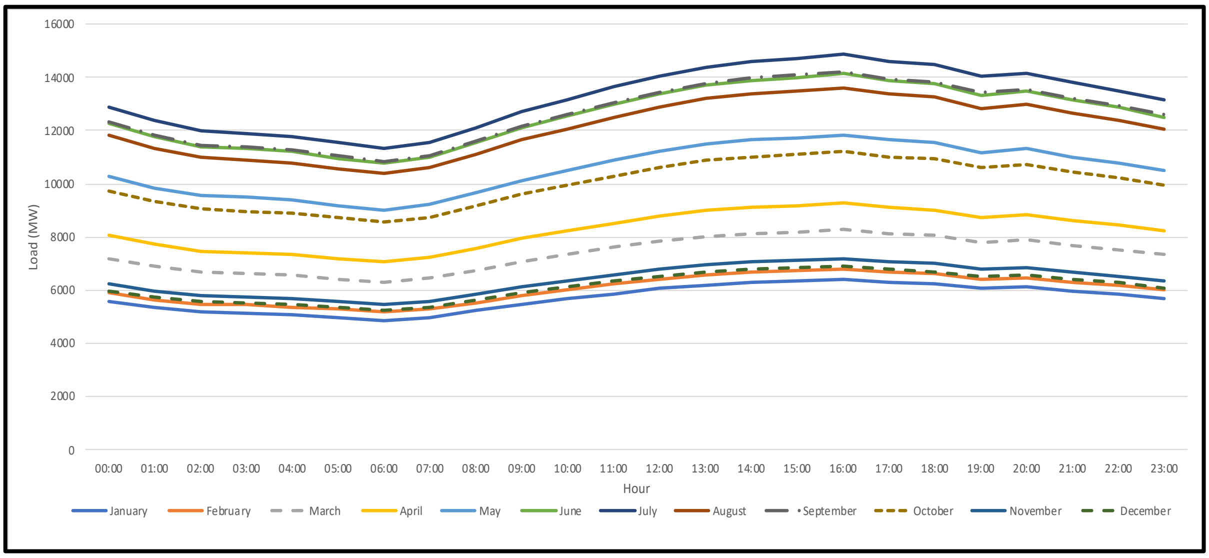


Figure 4-2: Hourly variation in the load (MW) for a day in each month.

Another flaw in this method can be seen in the trend line for the months, summer months (June-September) and especially July have relatively sharp variations in load values while winter months at the bottom tend to be blunter. Due to using the same offset percentage $(1 \pm |L - A|/A)$ for all days in these months, varying from 0.8562 to 1.1236 throughout the day. However, HOMER can optimise the similarity by setting the random variability at the appropriate settings.

4.2 Preliminaries: HOMER Load

Load profile is essential component to analyse renewable energy penetration and generation, also to determine its coverage of the total electricity demand. Using the demand profile created earlier from MEW and by averaging month values for a given hour, load profile for both weekdays and weekends in each month was created separately and added to HOMER as shown in figure 4-3. Random variability for both day to day (%) and time step (%) is set for the synthetic self-generated load data to add noise factor to the values. In this case, the imported data is user generated. However, the method of generating the load profile (explained in the previous section) has number of flaws that can be overcame by adding appropriate amount of perturbation factor to it. HOMER assembles a yearlong array of the imported load data and process each time step by multiplying the value in that time step by the perturbation factor α, the process is governed by the following equation of perturbation factor.

$$\alpha = 1 + \delta_{ts} + \delta_d$$

where δ_d is the daily perturbation value and the time step perturbation value is δ_{ts}. Random variability was set at different rates to investigate the effect of this input and find the most appropriate, figure (4-4).

Time	January	February	March	April	May	June	July	August	September	October	November	December
00:00	5.57	5.90	7.19	8.06	10.30	12.28	12.91	11.83	12.35	9.74	6.24	5.99
01:00	5.33	5.66	6.89	7.72	9.86	11.76	12.36	11.33	11.83	9.33	5.97	5.73
02:00	5.17	5.48	6.68	7.48	9.56	11.40	11.98	10.98	11.46	9.04	5.79	5.56
03:00	5.13	5.44	6.63	7.42	9.49	11.32	11.89	10.90	11.38	8.98	5.75	5.52
04:00	5.07	5.38	6.56	7.34	9.39	11.19	11.76	10.78	11.26	8.88	5.69	5.46
05:00	4.97	5.27	6.43	7.20	9.20	10.97	11.53	10.57	11.03	8.70	5.57	5.35
06:00	4.88	5.18	6.31	7.06	9.03	10.77	11.31	10.37	10.83	8.54	5.47	5.25
07:00	4.99	5.29	6.45	7.22	9.23	11.01	11.57	10.61	11.07	8.74	5.59	5.37
08:00	5.23	5.55	6.76	7.57	9.68	11.54	12.13	11.11	11.60	9.16	5.86	5.63
09:00	5.48	5.81	7.08	7.93	10.14	12.09	12.70	11.64	12.16	9.59	6.14	5.89
10:00	5.68	6.02	7.34	8.22	10.50	12.52	13.16	12.06	12.59	9.94	6.36	6.11
11:00	5.88	6.24	7.60	8.51	10.88	12.97	13.63	12.49	13.04	10.29	6.59	6.32
12:00	6.06	6.43	7.83	8.77	11.21	13.37	14.05	12.88	13.44	10.61	6.79	6.52
13:00	6.21	6.58	8.02	8.98	11.48	13.69	14.39	13.19	13.77	10.86	6.95	6.68
14:00	6.29	6.68	8.13	9.11	11.64	13.89	14.59	13.38	13.96	11.02	7.05	6.77
15:00	6.34	6.73	8.20	9.18	11.74	14.00	14.71	13.48	14.08	11.11	7.11	6.82
16:00	6.40	6.79	8.28	9.27	11.85	14.13	14.85	13.61	14.21	11.21	7.18	6.89
17:00	6.29	6.67	8.13	9.11	11.64	13.88	14.59	13.37	13.96	11.01	7.05	6.77
18:00	6.24	6.61	8.06	9.03	11.54	13.76	14.46	13.25	13.84	10.92	6.99	6.71
19:00	6.05	6.41	7.82	8.75	11.19	13.34	14.02	12.85	13.42	10.59	6.78	6.50
20:00	6.11	6.49	7.90	8.85	11.31	13.49	14.18	12.99	13.57	10.70	6.85	6.58
21:00	5.95	6.31	7.69	8.62	11.01	13.13	13.80	12.65	13.21	10.42	6.67	6.40
22:00	5.83	6.18	7.53	8.44	10.78	12.86	13.51	12.39	12.93	10.20	6.53	6.27
23:00	5.67	6.02	7.33	8.21	10.49	12.51	13.15	12.05	12.58	9.93	6.36	6.10

Figure 4-3:Scaled hourly average electrical load profile (GW) to be implemented in HOMER.

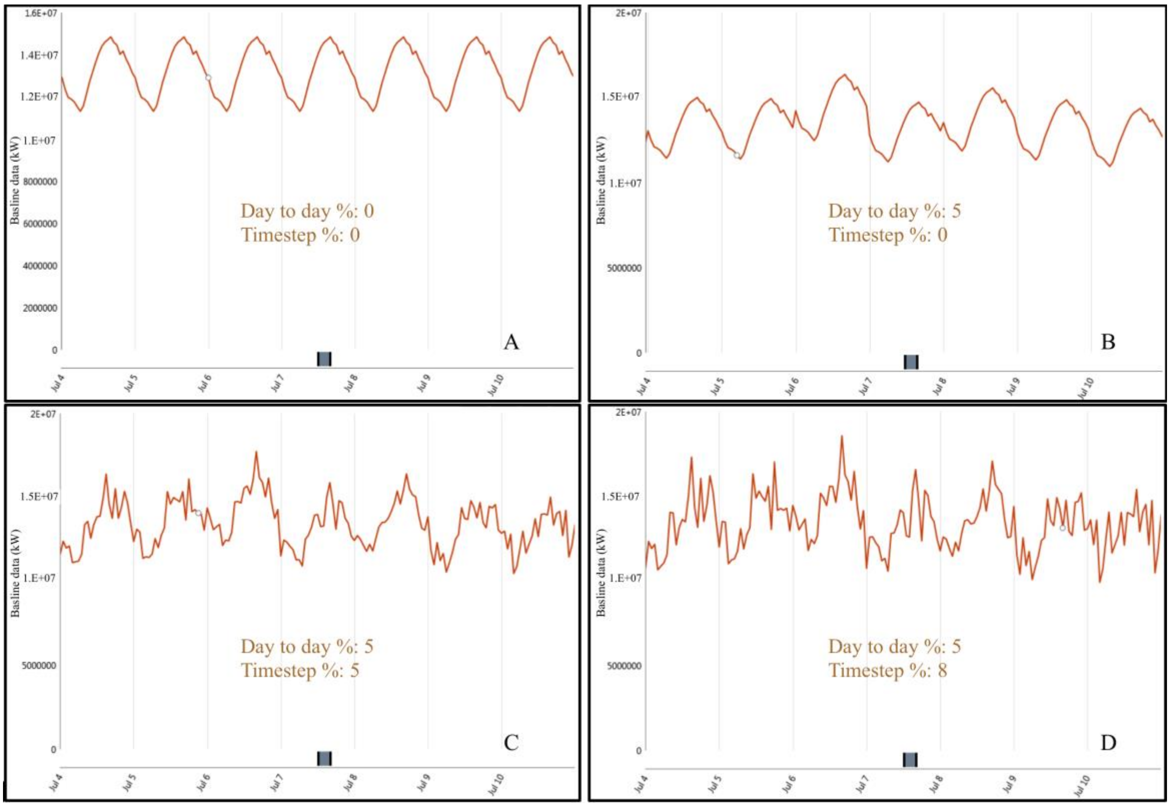


Figure 4-4: The effect of random variability at different day-to-day and time step perturbation percentages.

The figure represents four different settings of random variability on the average peak load. These settings were implemented on the same period of time, a week in the peak month from July 4 to July 10 at an hourly time step. The software generated identical trend for the days of the week, both daily and time-step perturbation values were set to zero figure (4-4A). Introducing 5% to daily perturbation resulted in variation of the loads from day-to-day figure (4-4B). Likewise, adding 5% to time-step perturbation introduced fluctuations in the load on hourly basis (time-step), figure (4-4C) present the effect of both perturbation values on the load. Finally, time-step randomness was raised to 8%, leading to sharper fluctuations of load along the day figure (4-4D). Perturbation values do not have an effect on renewable penetration in HOMER. Yet, in practice, high fluctuations of the load are harder to control under high wind and solar penetration. Therefore, figure (4-4C) is considered to be the best case that over comes the flaws of creating the load profile (mentioned in previous section). Hence, Monthly profile was created by HOMER based on the randomised load (kW) figure 4-5.

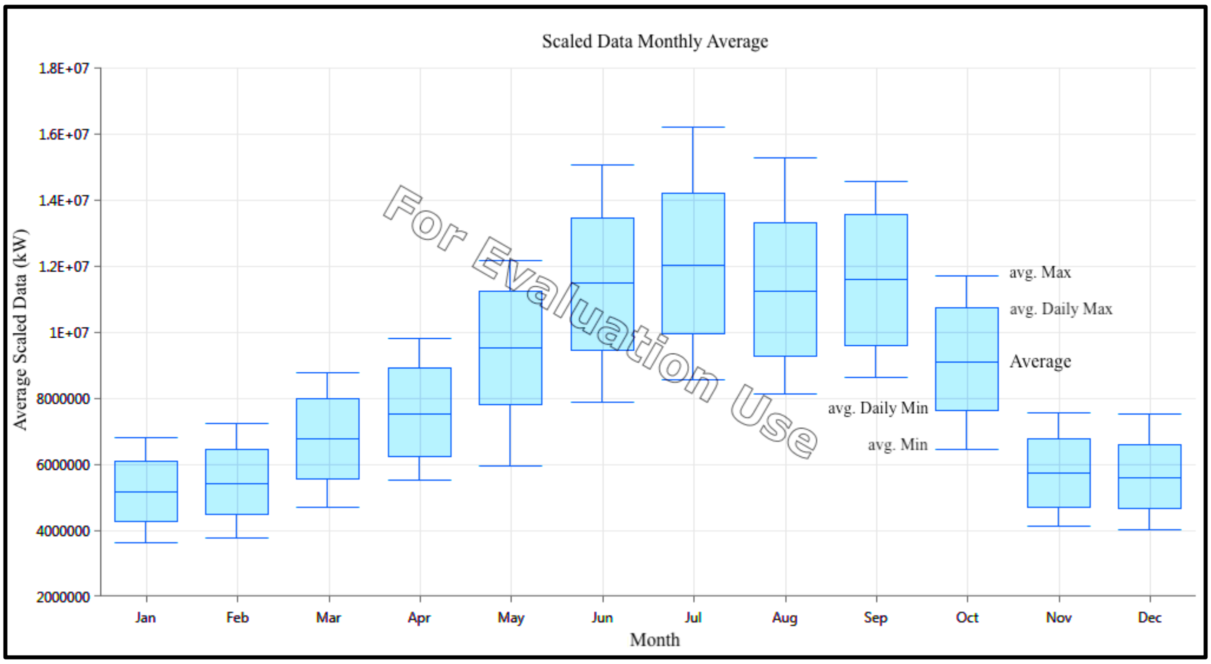


Figure 4-5: Candle chart of monthly average data, HOMER.

The candles in the chart represent five different concepts. The average load of each month is illustrated in terms maximum and minimum primary loads with respect to the month, these are at each end of the extension lines. Daily high and daily low, at each end of the bar, are maximum and minimum primary loads for the averaged day values for that month. The load profile is very important component for the simulation, HOMER will compare the renewable energy production power and the penetration (%) of each and both sola PV and wind systems.

4.3 Renewable Energy Penetration Modelling

HOMER is a software that helps in designing and evaluating energy systems technically and financially. It assists the user to define the type of application and enable input for load profile, can work on minimal data inputs as it self-generates the required data and assists in defining the type of application, load profile (as shown previously 4.2) and energy system.

The very first case will be of a base case (Case 0) in which load profile will be evaluated and the simulated Kuwait's grid will be compared to the actual data (2.2) for the same conditions and inputs. Another two main cases are considered in this thesis aiming to study the 'New Kuwait' vision of sustainability of energy. The second case (Case 1) will be revolved around three scenarios to decide the best wind and/or solar energy system configuration(s) that accomplishes 15% renewable energy penetration in the grid for the current energy demand. The third case (Case 2) will focus on maintaining the renewable fraction for the best configuration, with a forecasted energy demand for year 2030, assuming 4% total growth from the current electricity demand (Alotaibi, 2011).

4.4 Case 0: Grid & Validity Simulation

Case 0 is a base case that will revolve around a simplistic model of the grid in Kuwait. It will be focused on the electrical, financial and emission aspects rather than fuel as source of power or type of power plant. In this case and later on, the electric energy source from non-renewables will be assumed as 'Grid' produced, disregarding the thermal energy constraints. Thus, 'Grid' component will be used in HOMER instead of the 'Generator'. This case not only oversee whether the grid in simulation will result in matching the real grid in Kuwait (section 2.2), but it will also evaluate the validity of the load profile that was created for the analysis. The configuration of this case is shown in figure (4-6).

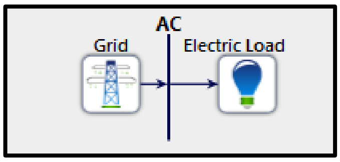


Figure 4-6: Base case system configuration, HOMER.

Since base case only contains the grid for electricity supply, HOMER in some cases does not approve of excluding renewable system in the configuration. Including a component of any renewable system (i.e. wind turbine) would solve the problem, but in that case, it should be at its minimal capacity and its financial aspect can be neglected. Also, The Discount and inflation rates for the project will be 2.5% and 0.5%, respectively (Central Bank of Kuwait, 2020; Plecher, 2020).

Set up

Grid component will be added and set in a 'Scheduled Rates' strategy, with purchase capacity of 18.8 GW. The purchase capacity represents the total installed capacity of fossil fuel power plants for Kuwait table (2-1), as it achieves the supply-demand match through oil and gas power plants. The cost of power production will be based on the governmental expenditures to produce kWh electricity energy (the fossil fuel sourced will be refered to as energy purchased when the renewables are add to grid mix). On the other hand, the income will be only from the electricity consumptions, which will be sold to consumers. Both cost and revenue will be accounted for in the NPC calculations of financial part of the analysis.

More importantly, the study will be on the electricity of Kuwait as a whole system. The price of electricity in Kuwait differs from one sector to another ranging from $0.016/kWh for residential sector to $0.081/kWh for governmental and commercial sectors (KUNA, 2017). The average price for all sectors was calculated to be $0.039/kWh. This, however, is considered as consumers' pay price when it is subsidised by 72% approximately (~$0.14/kWh unsubsidized), which does not determine Cost of Energy (COE). The reason that consumer price is not valid, is because the electricity system is not of a house or an office but the whole Kuwait. Thus, it is more appropriate to assign the actual cost of electricity production as the COE input. Therefore, the COE will be set as $0.135/kWh (Krane & Monaldi, 2017, p.9) and it will be used to represent Kuwait's expenditure to generate kWh electricity from conventional power stations table (4-6). This could be lower than the actual export price, but it was assumed due to the mutual benefit of Gulf power grid.

Table 4-3: Electricity cost of generation & selling price, (Krane & Monaldi, 2017).

Electricity Cost and Price in Kuwait	
Actual Cost Production ($/kWh)	Subsidised consumer price of Electricity ($/kWh)
0.135 ± 0.02	0.039 ± 0.01

Based in the literature the actual cost on the government to produce electricity is \$0.135/kWh. It might seem very high if compared to the consumer price which is \$0.039/kWh. This is mostly because the consumer price is heavily subsidised in Kuwait. The traditional power plants in Kuwait are assumed to be already installed, hence initial costs can be neglected and set to zero. This will narrow the scope to energy transition instead of renewable-nonrenewable cost comparison because the answer of that is already known.

Another input for the grid component is the emissions, section 2.2 explains the view on emissions inputs in more depth. In summary, GHG emissions are set as follow; 1420 (CO_2 g/kWh), 2.57 (SO_2 g/kWh) and 2.31 (NO_x g/kWh).

Note: since base case only contains the grid for electricity supply, HOMER in some cases does not approve of excluding renewable system in the configuration. Therefore, including a component of any renewable system (i.e. solar PV) minimal capacity would solve the problem and its financial inputs can be set to zero.

4.5 Case 1: Current Renewable energy penetration, 2020

The case will aim to find the best configuration of renewable system(s) that can supply 15% of the current total Kuwait electricity demand. The increase in renewable penetration (%) will be focused on solar PV and Wind turbines in a grid connected system. This case will be divided into three scenarios in which solar PV system, wind turbine system and solar-wind systems are to be examined for 1%, 5%, 10% and 15% penetration and results will be analyzed. At the end of these scenarios, insight on the capacity and size of solar PV and wind power stations that are required to satisfy each percentage of the total electricity demand in Kuwait will be discussed. The environmental and financial aspects of these modelled scenarios will be compared and analysed. Then, a recommendation for the type of system and installation will be provided. For instance, whether the is distant large power plant is the best option or should the outlook consider focusing on microgrids.

Based on the aforementioned renewable pilot projects (i.e. Al-Shagaya) the focus was directed toward solar and wind energy. These projects were initiated to assess the feasibility of solar PV and wind turbines in Kuwait, their energy production is evaluated for the potential of matching the renewable supply to parts of country’s demand during the day or even a part of it. This will ultimately help the government achieve its sustainable objectives, namely;

diversify the grid energy mix, reduce electricity imports from GCC during summer times and ultimately move the country toward greener and more sustainable energy. The objectives are aimed to be reached by achieving the target of 15% electricity production from renewable sources.

The analyses will compare energy production, renewable penetration, carbon emissions and the overall performance for each of the systems technically and financially. Figure (4-7) below illustrates each of the systems configurations when each is connected to the grid. It is noteworthy that the scenarios are reflecting national scale load demand, the renewables (PV & wind turbine) used are not dispatchable by nature, which require including 'Grid' component in these setups to be grid connected.

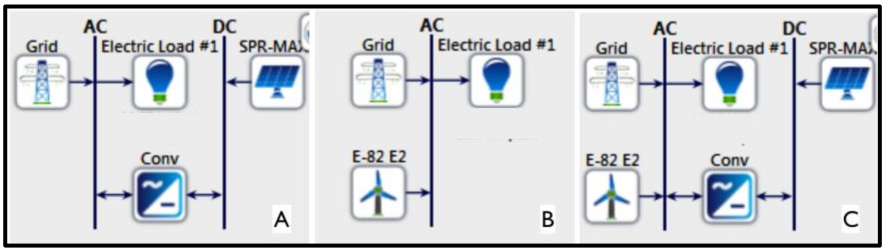


Figure 4-7: Schematic configuration of grid connected (A) solar PV system, (B) wind turbine system and (C) hybrid system.

4.5.1 Components Characteristics

HOMER provides a library of different models for renewable technologies which can be used to setup the project. However, more up to date technologies are surfacing which promote the option of creating foreign sources models, as in PV and wind turbine. Grid component will be based on the existing power stations in Kuwait as listed in the literature. Converter is varying component based on the power strategy, enabling the power export from renewables correspond with options of larger and more capable energy converters. The opposite is also true, increasing the converter size leads to higher power exports. The characteristics of the systems components are provided.

Solar PV setup

The solar PV used for simulation is a model that was invented by German company SUNPOWER. SPR-MAX3-400 is considered to be one of the advanced solar panels that has 400 W nominal power. Practically, the actual output depends on many factors such as location, tilt and shading. Nevertheless, it is very important to select advanced technology when it comes to renewables, PV properties that was setup in HOMER are listed in table (4-4):

Table 4-4: SPR-MAX3-400 properties.

<table>
<tr><th colspan="7">Technical Properties</th></tr>
<tr><th>Rated Capacity</th><th>Efficiency</th><th>Temperature Coefficient</th><th>Operating Temperature</th><th>Area</th><th>Derating Factor</th><th>Lifetime</th></tr>
<tr><td>0.4 kW/unit</td><td>22.6 %</td><td>-0.29 %/ºC</td><td>50ºC</td><td>1.75 m_2</td><td>88 %</td><td>25 years</td></tr>
</table>

<table>
<tr><th colspan="3">Costs</th></tr>
<tr><th>Capital</th><th>Replacement</th><th>Operation and Maintenance</th></tr>
<tr><td>$400/kW</td><td>$100/kW</td><td>$9/kW-year</td></tr>
</table>

The component was modelled accordingly assuming the price is lower for mass order. Rated capacity will be changed to the total capacity of PV arrays in order to have the results.

Wind turbine setup

Wind turbines can have AC or DC type electric bus. Both types can be provided by HOMER. Although DC generator wind turbines provide higher capacities for shorter hub heights (lower relative cost), it requires inverters (additional cost) or needs to be close to the consumer for low power losses. In other words, they are more suitable for wind integrated building applications. On the other hand, AC generator are more suitable for utility-scale and grid connected applications. After all, alternating current are better for transmitting power, especially if the wind turbine generates three-phase alternating current. Based on literature, air conditioning systems contributes for over 45% of the electricity demand in summers figure 2-5, which runs on AC power. Therefore, AC wind turbines will be the focus of the wind system analysis for Kuwait.

Enercon E-82 wind turbines, has 84 m hub height in addition to the properties mentioned in table 4-5, In HOMER, operating capacity of renewables is the capacity of energy produced rather than the rated one. For example, Enercon wind turbine with 2000 kW rated capacity that is only producing 400kW, hypothetically, offer 400 kW only for its operating capacity. The ratio of operating capacity to the rated one is called capacity factor.

Table 4-5: Enercon wind turbine properties.

Wind Turbine: Enercon E82 E2				
Rated Capacity	Overall Loss Factor	Electric Bus	Lifetime	Rotor Diameter
2,000 kW/unit	0 %	AC	15 years	82 m
Capital Cost	Cost of Replacement	O&M Cost		
$3.5 M	$250,000	$42,000/MW/year = 82,000/year		

Capital cost is the initial cost in the installation process (Windustry, 2019), O&M cost is annual cost found by (IEA, 2017) and cost of replacement was set by estimation.

Converter setup

Converter usually have inverting and rectifying capabilities depending on the size of application and the use for it. In this case the converter is used for large PV power plant requiring central converter/inverter that converts DC to AC to feed the grid. In Kuwait each building has a central converter (AC – DC), thus there is no need for the rectifying capabilities. Therefore, PV dedicated inverter with lifetime of 15 years was used with variable capacity to ensure least cost option is promoted. Converter properties of inverter are presented in table (4-6)

Table 4-6: Converter properties as in HOMER.

Converter			
Inverter		Rectifier	
Lifetime	Efficiency	Relative capacity	Efficiency
15 years	98.5%	N/A	95 %

Grid setup

Grid component will have the same attributes as the base case (Case 0).

4.5.2 Scenario 1: Solar PV System

The general challenge for installing the PV systems on large scales is related to geographical area. Most pilot projects in return tend to be implemented on top of car parks or buildings roofs instead of dedicating large area for solar power station to be close from the consumer. This scenario will focus on PV in utility scale for its analyses which will aim to find the appropriate solar PV capacity and configuration that can achieve highest renewable penetration (15%) at minimum cost. Then evaluate the technical and financial feasibility of that configuration along with monitoring the carbon emission values.

Through repetitive simulation of PV system, it was found that high renewable penetration corresponds with low operating temperature, higher derating factor (%) and higher ground reflectance, table (4-7).

Table 4-7: Renewable energy penetration influence.

Higher RE Penetration (%)	Operating Temperature (°C)	Derating Factor (%)	Ground Reflectance (%)
↑	↓	↑	↑

Although these can have obvious effect on the penetration percentage, they cannot be changed since they are either technological, natural or related Kuwait's weather. For example, ground reflectance was set based on desert sand albedo (40%). Leaving the only variable that could increase the solar penetration is the installed capacity.

This scenario will look at different simulations with solar PV system. First simulation: will be representing the Alshegaya PV project at its current capacity (10 MW), to understand the position of Kuwait from its target. In second simulation: the installed PV capacity will be increased to achieve 15% penetration, and the converter capacity will be increased to ensure minimum electricity excess table (4-8).

Table 4-8: Capacity inputs for the PV scenario.

Installed Capacity	Simulation 1	Simulation 2						
PV (MW)	10	425	1,050	2,100	3,200	4,250	5,300	6,350
Converter (MW)	10	420	1045	2.07	3200	4200	5100	6200

Since the PV used in this scenario is a DC type, high capacity DC-AC inverter is used to feed in the grid. Different converter capacities were used to ensure complete conversion to the power. Excess energy in some cases might be managed by installing storages. However, this option will not be considered as the surplus generation at the national level might require at least several tens of gigawatt storage.

Note, it is assumed that conventional (oil and natural gas) power station are the only constituents of the “Grid” and operating the grid means operating the conventional power stations.

4.5.1 Scenario 2: Wind Turbine System

This scenario will have wind turbine component instead of solar PV in the analysis, similar grid and load settings are used as the previous one and the system will be grid connected. Based on web searches and HOMER library, the average lifetime of wind turbines is 15 years introducing replacement cost.

From section 3.2 the geometrical location for installing wind turbines is considered influential in terms of the power production, wind stream and speed is different from one site to another. At first, the wind power plant will have capacity of 10 MW, that is 5 x 2 MW wind turbines, mimicking the Al-shagaya wind project capacity and then scale it up to meet 15% renewable fraction. Main difference is that wind turbines that were used in Al-shegaya has DC electricity generator while in this scenario AC generator in wind turbines are used. Because they are more robust and can have fast dynamic response if coupled with Synchronous Motors.

For starters, It is very important to choose the right location for the wind power plant, wind is location constrained. The location should be chosen at which wind has the highest potential to reach high speeds, but generally the higher the better (section 3.2). However, if the wind speed data is implemented in HOMER, the location of the power plant is irrelevant and power production remains unchanged. In this scenario the simulation will be done for wind power stations with 5, 213, 1065, 2130 and 3195 wind turbines which are equivalent to 10 MW, 426 MW, 2130 MW, 4260 MW, 6390MW.

4.5.1 Scenario 3: solar & wind systems

This scenario aims to find the best configuration of renewable energy systems in order to achieve 15% penetration in Kuwait total electricity production. The renewable energy system will consist of both solar PVs and wind turbines and in the same manner as the previous scenario the results will be presented for five simulations. The first will represent the Alshagaya renewable project at its current stage (10MW solar PVs and 10MW wind turbines). The other simulations will represent 1%, 5%, 10% and 15% renewable to fossil fuel power production fractions table (4-9). The feasibility of this scenario for the 15% is more important than the previous scenarios, because it is more of a resemblance to a real project than the other ones and more commonly found at national scale.

Table 4-9: solar-wind renewable system capacity (MW) & quantity of modules.

Renewable Penetration (%)	1		5		10		15	
Constituents of Renewable System	CPTY (MW)	Qty	CPTY (MW)	Qty	CPTY (MW)	Qty	CPTY (MW)	Qty
Wind turbine	212	106	1050	525	2125	1063	3175	1588
Solar PV	212	530k*	1050	2625k	2125	5312k	3175	7892k

*k: stands for "thousand" modules

Quantity (Qty) of a system refers to the electricity generating units (solar PVs and wind turbines). Moreover, the feasibility of this scenario specifically will be assessed with respect to the renewable fraction. The assessment will be revolved around the size of the renewable power station, the estimated time to achieve the project and its financial feasibility. The size of the power station is important due to the fact that if the project demands large piece of land and does not benefit the citizen there will be high possibility that it might be disregarded by the National Assembly. Time is crucial determinant of feasibility because of the time limit which is 2030. However, to determine that the renewable project is financially feasible it has to have positive and preferably high Return of investment (ROI).

4.6 Case 2: Projected Renewable Penetration, 2030

This case aims to maintain the 15% renewable energy penetration in Kuwait's electricity network for the future years. The target renewable fraction should be achieved and found feasible in 'Case 1', in which simulations were conducted on the assumed Kuwait load profile for year 2020. Nevertheless, the predictions of growing population, increase in appliances and personal smart wears, and electrification trends indorse growth in electricity demand. MEW (2019, p.43) estimated growth rate of 4% in energy demand between the years 2009-20 (10 years). Likewise, similar growth rates will be assumed for year 2030 load profile; in order to project the requirements to maintain the 15% renewable penetration for that year. this case will have only one scenario, revolving around the most suitable/feasible renewable system grid connected configuration.

4.6.1 Scenario 4: Solar-wind systems in the future

This scenario aims to find the means to maintain the 15% renewable penetration in the grid using solar PV and wind turbines. Thereafter, a decision will be chosen, regarding whether wind and solar power generations are sufficient to cover the required amount of Kuwait's electricity demand, or should Kuwait focus on investing more of its resources in developing another renewable/sustainable source of power. Since the scenario will take place in Kuwait in 2030, there will be continues growth in population and electricity demand. figure (4-8) presents these growths, assuming the annual growth occurs at a constant rate.

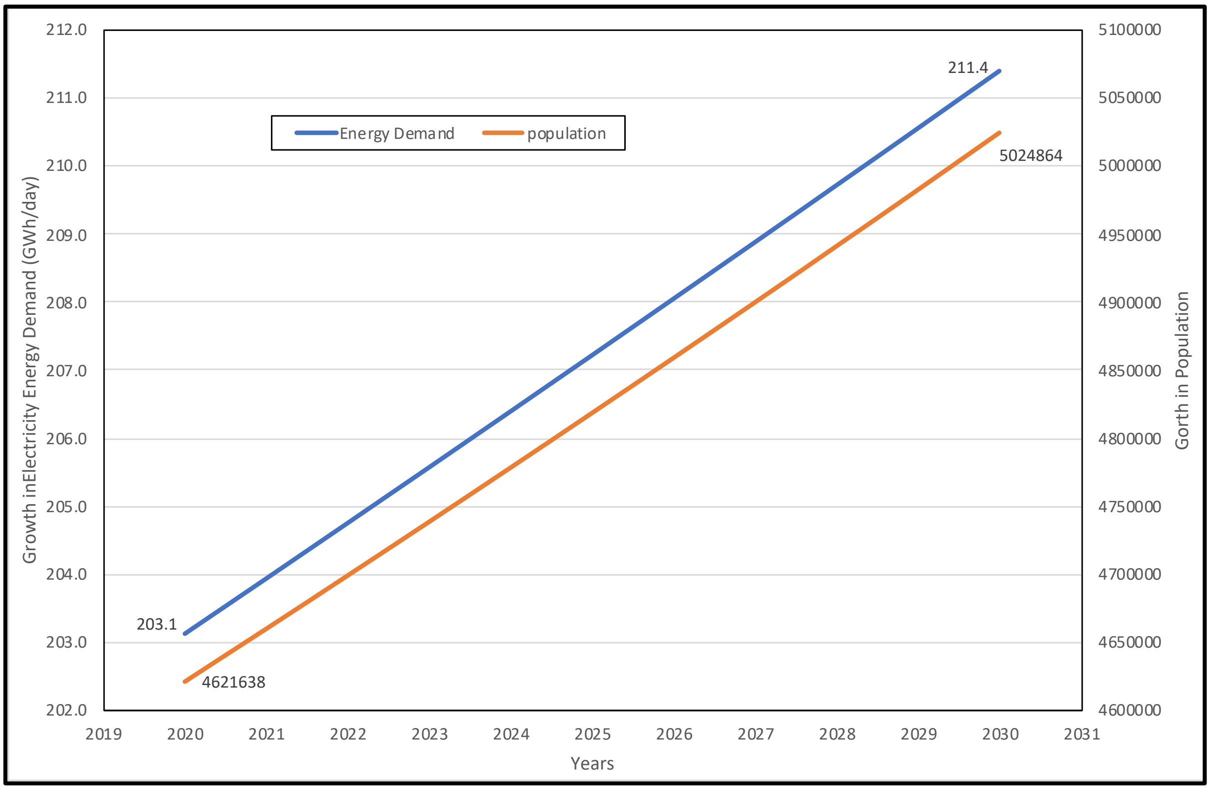


Figure 4-8: Projected growth in population and electricity energy demand.

The growth in Kuwait population and its demand of electricity will be projected as labeled in figure (4-8) and listed in table (4-10) for the year 2030.

Table 4-10::Estimated growth rate in Kuwait population and electricity demand

Year	Average Annual Electricity Demand* (GWh/day)	Population** (Million)	Average Demand Per Capita (kWh/year)
2020	203.1	4.62	15,820
2030	211.2	**5.01**	**15,365**

*estimated growth rate 4% from 'Case 1' load profile
** estimated growth rate 8.4% from 2020 Kuwait population record (MEW, 2019, p.43)

The estimated annual electricity demand will be implemented in HOMER to generate the predicted load profile for 2030. Meanwhile, the input capacities for the renewable systems will be used from the table (4-11), in order to investigate the feasibility of Kuwait's vision for 2030.

Table 4-11: Capacity input for 1, 5, 10 & 15 percent penetration for year 2030.

Renewable Penetration (%)	1		5		10		15	
Constituents of Renewable System	CPTY (MW)	Qty	CPTY (MW)	Qty	CPTY (MW)	Qty	CPTY (MW)	Qty
Wind System	220	110	1100	550	2200	1100	3300	1650
Solar System	223	558k*	1116	2790k	2233	5582k	3350	8375k

*k: stands for "thousand" modules

Note: Number of PV panels and wind turbines will be discussed in the result section of this scenario.

5 Results and Discussion

In this section the results for the HOMER generated models will be presented along with discussion of suitability and feasibility. There will only be mention for the scenarios since they were already categorised in the methodology. Determinants of feasibility are the technicality (i.e. viable penetration, low waste of energy and most importantly the area of land it requires) and finance (i.e. realistic costs and recoverable investment). These will be mentioned in the discussion if appropriate. Finally, it is worth noting that feasibility of a system is only based on limited factors and in no mean these results represent the complete analysis of reality.

Note: the NPC in the tables are discounted one, with specified discount and inflation rates.

5.1 Case 0: Base Case (Grid Only)

Since the base case only contains conventional power plants in its grid matrix, it is typical to have 0% renewable penetration. Also, the surplus electricity generation is nonexistent, because HOMER links it with renewable energy generation. A crucial assumption was mentioned for this case, which is already built fossil fuel power stations, which allows initial cost to be set to zero. The results from base case simulation are listed in table (5-1).

Table 5-1: Base case simulation results.

Elec. Production (TWh/year)	Energy Purchased (TWh/year)	Total Discounted NPC ($B)	LCOE ($)	O&M Cost ($B)	CO_2 Emission (M. Mt/year)
74.1	74.1	138	0.135	10	105.3

Based on simulation results the 18.8 GW installed capacity will result in production of 74.1 TWh/year, identical value was found for the consumption. Because the grid component in HOMER operates just to satisfy the demand. Since the consumption in simulation is similar to the actual one of Kuwait (2.2), it proves that correct electric inputs were used and viable load profile was created. At this point the 'Electricity Production', 'Electricity Consumption' and 'Energy Purchased' have the same value but in the next scenario results of each one will be different from the other. Electricity production is the total electricity generated regardless of the source (non/renewable), including the excess energy production form renewables at low demands. Electricity consumption is the electricity used by people in Kuwait and it will always be the same for the 2018 load profile (from simulation perspective). Finally, Energy purchased will always represent the power drawn from the grid (conventional sources). Thus, in this case it is similar to the energy consumption but later on it will be lower for higher renewably sourced electricity production. Table (5-2) explains the behavior of these terms for grid only and for grid connected renewable energy production.

Table 5-2: EP, EC and EPu behavior in this case and the next ones.

	Electricity Production (EP)	Electricity Consumption (EC)	Energy Purchased (EPu)
Grid only*	Identical		
Grid Connected Renewables**	EP = EC + [excess energy prod.]	Stays the same for a given load profile, will increase with load growth (Case 2)	Covers part of the demand RE was not able to satisfy. it is purchased form grid & always EPu < EC
Comment	It is the total production regardless of the source EP is never lower than EC		
*Represent Case 0; **Represents Case 1&2			

In addition, the financial elements in the results table (5-1) is for the Net Present Cost (NPC), Levelised Cost of Energy (LCOE) and Operation and Maintenance cost (O&M). NPC is simply sum of costs spent minus sum of the revenues gained over project’s lifetime. Since O&M is the only cost along the project lifetime (assumption: power stations are already built), the nominal total NPC value is $178B over the project’s lifetime. That is accounting for the sellback (income from selling the electricity at rate $0.039/kWh), which is constant annual income of about $2.9B (only dependent on the load profile). However, considering the real discount rate 1.99%, the discounted total NPC is $138B over the projects lifetime, that is $40B was saved up from the cost. Figure (5-1) shows nominal and discounted NPC for grid only system.

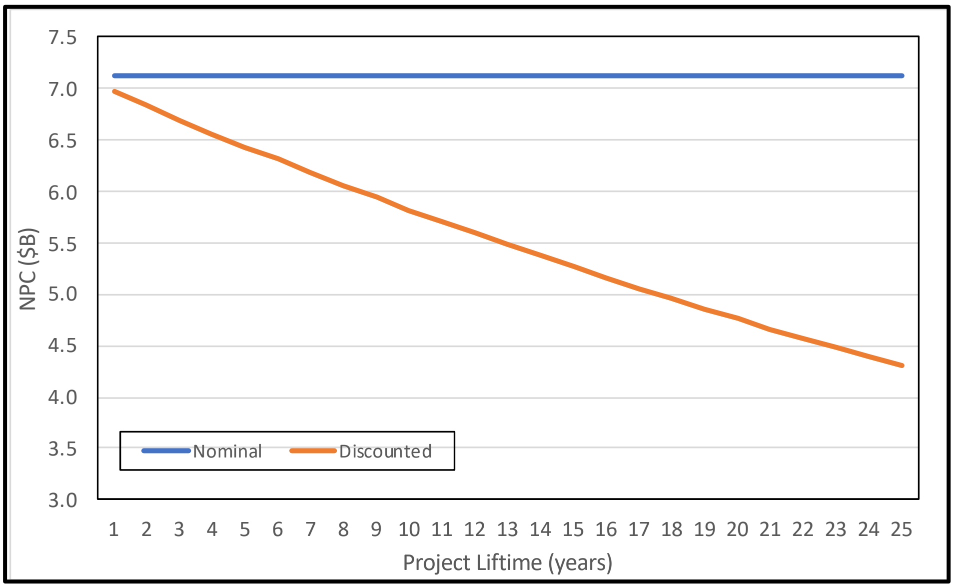


Figure 5-1: Nominal and Discounted NPC.

The revenue is calculated based on the consumer price ($0.039/kWh) for the total electricity generation of 74,132,602,880 kWh, which is constant for the same load profile (Including Case 1). Thus, the discounted NPC is be calculated as follow;

$$NPC_N = project\ lifetime([Initial + O\&M]_{cost} - [Utility\ tariff]_{income})$$

$$NPC_N = 25([0 + 0.135 \times 74{,}123{,}602{,}880] - [0.039 \times 74{,}123{,}602{,}880])$$
$$= \$178\text{B}_{nominal}$$

That is the nominal NPC for the project's lifetime (25 years). However, to find the discounted NPC the first year is different than the rest of the years.

$$NPC_{D:year\ 1} = NPC_{N\ year\ 1} \times (1 - Real\ discount\ rate)$$

$$NPC_{D:year\ 2:25} = NPC_{D\ year\ 1:24} \times (1 - Real\ discount\ rate)$$

After using annual 2.5% discount rate and 0.5% inflation rate, HOMER provide the annual 'Real discount rate', which is 1.99%. Thus,

$$NPC_{D:year\ 1} = 7.1 \times (1 - 0.0199) = \$7.0\text{B}$$

$$NPC_{D:year\ 2} = 7.2 \times (1 - 0.0199) = \$6.8\text{B}$$

Then, by summation the NPC_D for the 25 years it will be \$138B as in table (5-1). The value (\$0.135) in calculations represent the LCOE to produce kWh electricity in Kuwait. The income was based on the subsidised utility prices (\$0.039/kWh). The overall net present value (NPV) is (-\$138B) (NPC=-NPV).

The environmental elements in the simulation results shows that the total carbon dioxide emissions were measured at 105.3 million metric tons while the actual estimated value was 106.5 MMt, which are very close from each other. Furthermore, the SO_2 and NO_x emissions were found to be 191 kMt and 171 kMt, respectively.

5.2 Case 1: Scenario 1

This scenario will introduce solar PV system to the grid and it will be investigated for 15% solar penetration (15% of the production will be from solar resources).

5.2.1 10MW PV system

The first simulation the PV capacity was set to be 10 MW, representing Al-Shegaya PV project, results for that are shown in the table (5-3) below.

Table 5-3: Simulation results for 10 MW PV capacity.

Electricity Generation (TWh/year)	PV Production (GWh/year)	PV Penetration (%)	NPC (\$B)	COE (\$)
74.1	17.5	0.024	138	0.135

The validity of the load profile and other simulation inputs were determined by the results of the base case simulation. Since the same load profile was used the total power production is also 74.13 TWh in this scenario, which is very close to the official recorded one 74.11 TWh/year. Moreover, solar PV system had 10 MW installed capacity and was able to produce 17.5 GWh/year covering only 0.024% of the total electric. Of course, not all energy produced from PV is fed in the grid, since the converter has only 98.5% efficiency for its inverting capability, which is translated to over 400 kWh loss in PV energy production per year, hence inverters only outputs 17.1 GWh/year for consumption. This is achieved by Both PV systems and inverters operate for 4,387 hours (~ 6 months of the year) on average annually, figure (5-2) illustrate the PV power output.

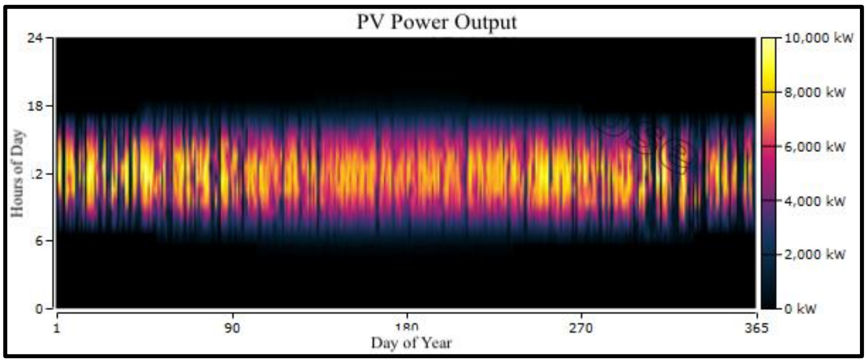


Figure 5-2: PV power output intensity.

PV energy production is limited at the sunlight period creating a colored belt. Thus, in summer the belt is 2-3 hours wider than winter period and more consistent production throughout the summer months. Winter PV productions are showing in brighter color for some days. for example, days between 301 (28th Oct.) and 333 (29th Nov.) has higher power outputs that reaches 9,500 kW circa. this is illustrated in figure (5-3)

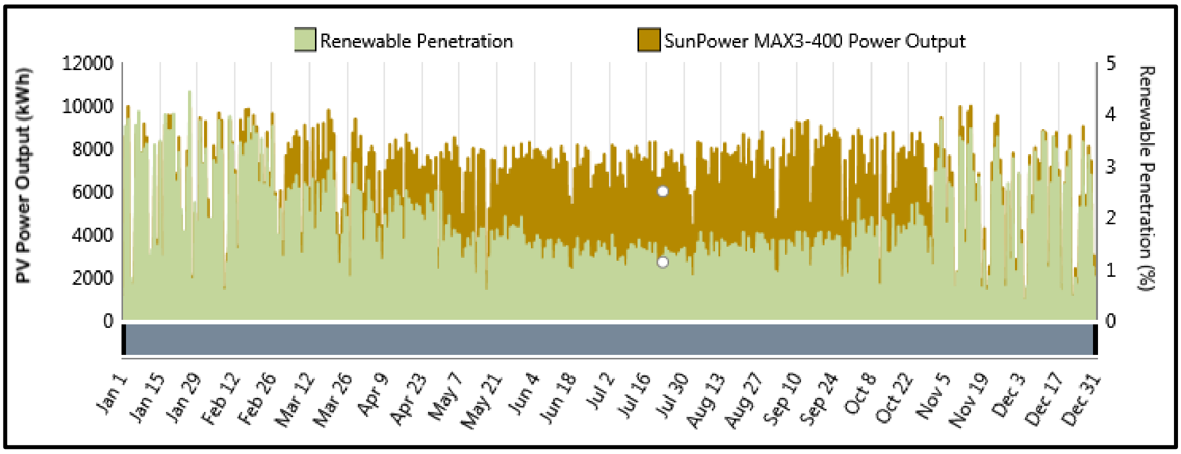


Figure 5-3: Power output (kWh) and renewable penetration (%) throughout the year for 10 MW PV capacity.

The difference could be due to higher clarity index during the winter and/or less dusty days after rainy ones, cleaner PV panels absorb higher amounts of solar radiations. Another reason might be the summer temperatures in Kuwait, elevated temperatures could affect the performance and decrease the efficiency of electric systems. figure (5-4) shows the cell temperature which are clearly higher than the operation temperature table (4-4).

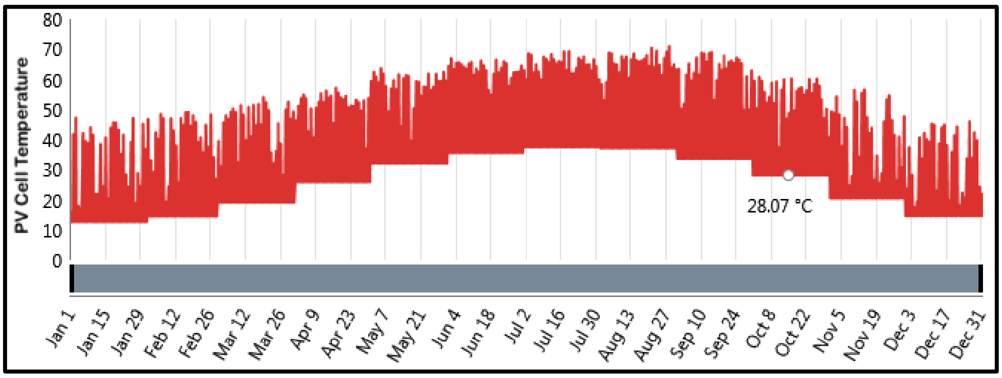


Figure 5-4: PV Cell temperature throughout the year.

The cell temperatures are shaved off because of the imposed monthly temperature profile, at which it drops as low as specified by HOMER inputs table (3-10). Finally, there was zero unmet load which is expected since the load is covered by the grid with 18.8GW capacity. Also, the zero-excess power (%) might be due to low power production of renewables (PV), that the load was not satisfied at any given time. Therefore, there is a need to increase PV capacity for higher independence (higher renewable fraction) from the conventional power generation methods (grid). Noteworthy, In HOMER renewable fraction and renewable penetration are defined by different equations. However, since thermal load, which differentiate the two, was not defined in HOMER both notations has the same value.

Since results of NPC are for the whole supply system, it includes cost of total production form conventional and renewable source. Cost of power production is mainly from conventional power plants. The cost used in calculations for financial analysis is from producer/government point of view and the income is the grid purchases that is paid by the consumer, both were respectively mentioned before as $0.135/kWh and $0.039/kWh. Moreover, the discounted NPC was found to be $138B for the total project lifetime. Almost all of the cost is spent on operation and maintenance the conventional power since PVs contribution in this is negligible. Thus, Cost of Energy (COE) remains the same ($0.135) if compared with the base case.

5.2.2 Increasing PV capacity

PV system capacity was increased to increase the renewable penetration in the grid to 15%, demonstrate the amount of load that can be met by PV and witness the reduction in grid imports and CO_2 emissions. For zero storage capacity any surplus energy generation will be neglected if it is lower than 0.003% of the total generation. Surplus generation is only sourced from dispatchable renewables. PV power production and exports depend on the capacity of the converter. Appropriate converter sizes were chosen to accommodate the PV capacity and prevent as much excess of energy as possible, benefiting from the lack of conversion efficiency to lower the costs.

Moreover, the main variables were the PV and converter installed capacity. Input PV rated capacities were 10 MW, 425 MW, 1050 MW, 2100 MW, 3200 MW, 4250 MW, 5300 MW, 6350 MW. Results for each of these attributes are compared in the following table (5-4), NPC is in billion dollars ($B).

Table 5-4: Simulation results for different PV sizes.

PV Capacity (MW)	PV production (GWh/year)	PV Penetration (%)	NPC ($B)	COE ($)	CO_2 Emission (MMt/year)
10	17.9	0.024	138	0.135	105.3
425	741.2	1.00	137	0.134	104.2
1,050	1,836.8	2.48	135	0.132	102.7
2,100	3,706.1	5.00	131	0.130	100.1
3,200	5,597.7	7.55	126	0.127	97.4
4,250	7,412.3	10.0	123	0.124	94.8
5,300	9,271.3	12.5	119	0.122	92.3
6,350	11,118.4	15.0	115	0.119	89.7

The table shows the results of different PV attributes, in the sight of these result increase in renewable fraction has the utmost importance. Along with the increase in PV capacity, renewable fraction increased too. increasing the PV capacity to 425 MW is faced by achieving 1% solar penetration, for 2,100 MW it was 5% and for 4,250 MW was 10%, but to achieve 15% renewable fraction the capacity had to be increased by at least nine folds to the capacity of Al-shagaya PV project (10 MW). For the target penetration the global solar intensity and solar PV output is provided in figure (5-5), which shows the reliability of the solar resource in Kuwait.

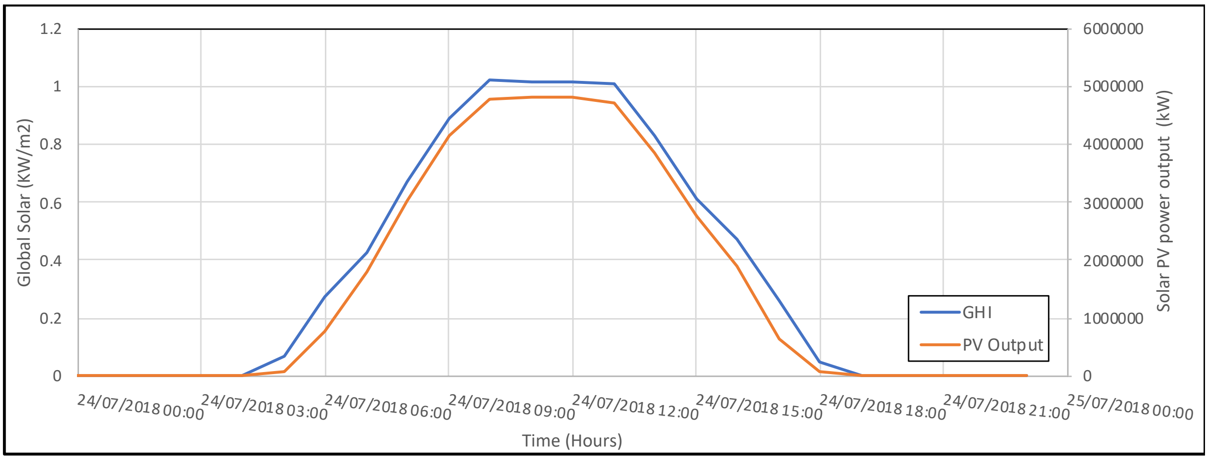


Figure 5-5:Global solar and solar PV output profile, 15% solar penetration.

The global horizontal intensity is associated with sunrises and sunsets, which explain its zeros and gradual values. Thus, the figure shows GHI behavior for a day in the summer, it is at its minimum at 4am and 7pm while it peaks at 10am and maintain its radiation 1pm. Solar PV power output follows similar behavior but there is a loss of radiation in due to PV modules reflectance, hence Solar power output is proportional to the solar incidence instead. Accordingly, the annual PV power production jumped to 11.1 TWh, increasing its share in the total energy production to 15% and reducing grid electricity purchases by the same amount (kWh) with only 0.0000385% excess in electricity. Minimum surplus energy was manged by choosing appropriate inverter capacity, the excess percentage is too low that can be neglected and assumed to be zero. table (5-5).

Table 5-5: Electrical related results for different PV attributes.

PV Penetration (%)	Grid Energy purchased (TWh/year)	Excess Electrical Energy	
		(MWh/year)	(%)
0.024	74.1	0	0
1.00	73.4	0	0
2.48	72.3	0	0
5.00	70.4	3756	0.005
7.55	68.5	2225	0.003
10.0	66.7	0	0
12.5	64.8	0	0
15.0	63.0	0	0

The small fraction of surplus energy is generated from renewables at low demand, this is considered as supply-demand mismatch solved by storages. However, at national scale the storage would be unnecessarily expensive. For the target penetration (15%) the global solar and solar PV output is provided in figure (5-5), which shows the reliability of the solar resource in Kuwait. However, at national scale the storage would be unnecessarily expensive. In general, simulations were done under minimum NPC and levelized Cost of Energy (COE) values, table (5-6).

Table 5-6: Financial costs based on PV capacity.

PV Penetration (%)	NPC ($B)	COE ($)	Capital Cost ($M)	O&M ($B/year)	O&M reduction (%)
0.024	138	0.135	7	10	-
1.00	137	0.134	297	9.9	1
5.00	131	0.130	1,410	9.5	5
10.0	123	0.124	2,960	9.1	9
15.0	115	0.119	4,370	8.6	14

NPC Behavior: as explained in section 5.1, NPC is the difference between the total costs and total incomes throughout the project's lifetime (25 years) and it depends on discount and inflation rate of the country. The major costs that can NPC behavior are installation costs and O&M costs. Due to the fact that cost of operation in renewables are higher than it is in fossil fuel power plants, it safe to assume an increase in NPC as more renewable penetration is achieved.

However, based on the results (table 5-6), higher solar PV contributions in the grid is associated with the lower NPC values. Suggesting that the cost ($/kWh) of conventional power production is higher than the cost ($/kWh) of solar/renewable power production. At first, this suggest a mistake in calculations, which in turn can be solved by either decreasing $/kWh of fossil fuels and/or increasing $/kWh of renewables.

The electricity cost ($0.135/kWh) sourced from the grid (conventional power plant) is an umbrella cost that contains price of oil and/or gas with profit margin included. But in actuality there is high possibility that MEW is buying the fuel at prime cost from KNPC. This claim can be supported by the high governmental subsidy for electricity, that goes up to 72% of the 0.0135/kWh. It also justifies the fixed price of electricity for the consumers ($0.039/kWh) despite the variable cost of electricity ($0.115-$0.135/kWh) mentioned in nongovernmental. Therefore, cost of electricity in these published is dependent on the oil market price. In turn it explains why the overall NPC decreasing when Solar share is increasing, figure (5-6).

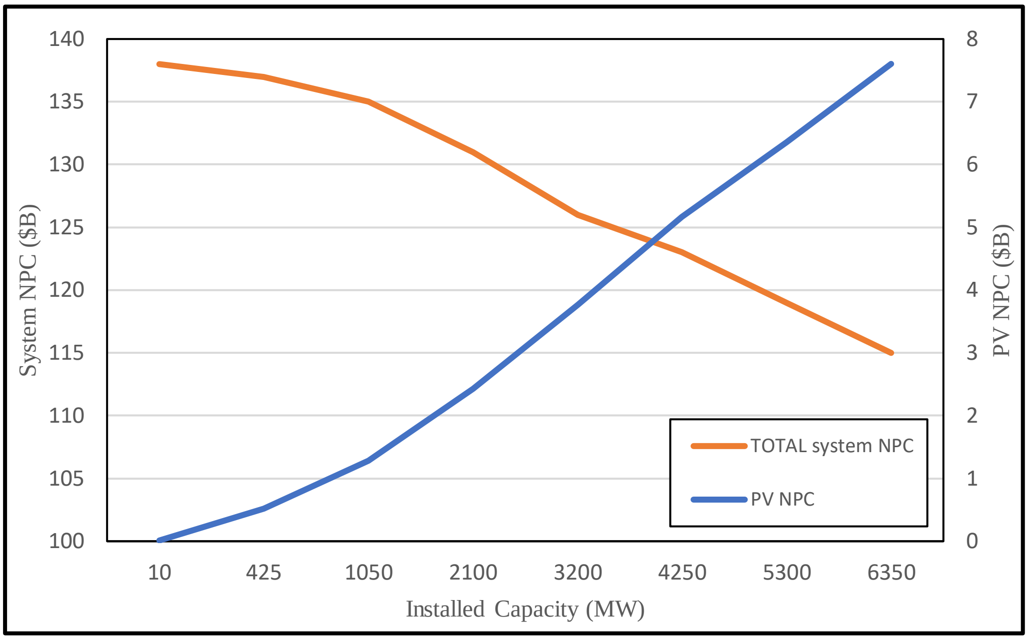


Figure 5-6: NPC behavior for solar PV system only and total (PV-grid) system.

Similarly, for Kuwait to achieve its target of 15% sustainability, they have to install 6,350 MW PV capacity. Investment of that size would have initial cost of $2.7B and nominal annual O&M cost of $8.6B. Meanwhile, the reduction in O&M annual cost reached 14% for the target solar penetration. The main contributor in the reduction is cost of operation, it decreases over projects lifetime. Therefore, the average cost of electricity generation decreased from $0.135/kW (for grid electricity only), to reach 0.119/kW (for solar fraction = 15%). By applying the 72% subsidy, the consumer price (cost of bill) would be $0.033/kWh. The reduction in the utility price is small relatively.

The overall project of introducing solar to the grid have higher savings at 15% penetration among other attributes. Since the discounted (table 5-6) and nominal (figure 5-7) NPC with solar energy system is lower than the grid only system, it is self-explanatory to have more savings at higher penetrations, which reach up to $23B$_{\text{dicounted}}$ and $31B$_{\text{nominal}}$.

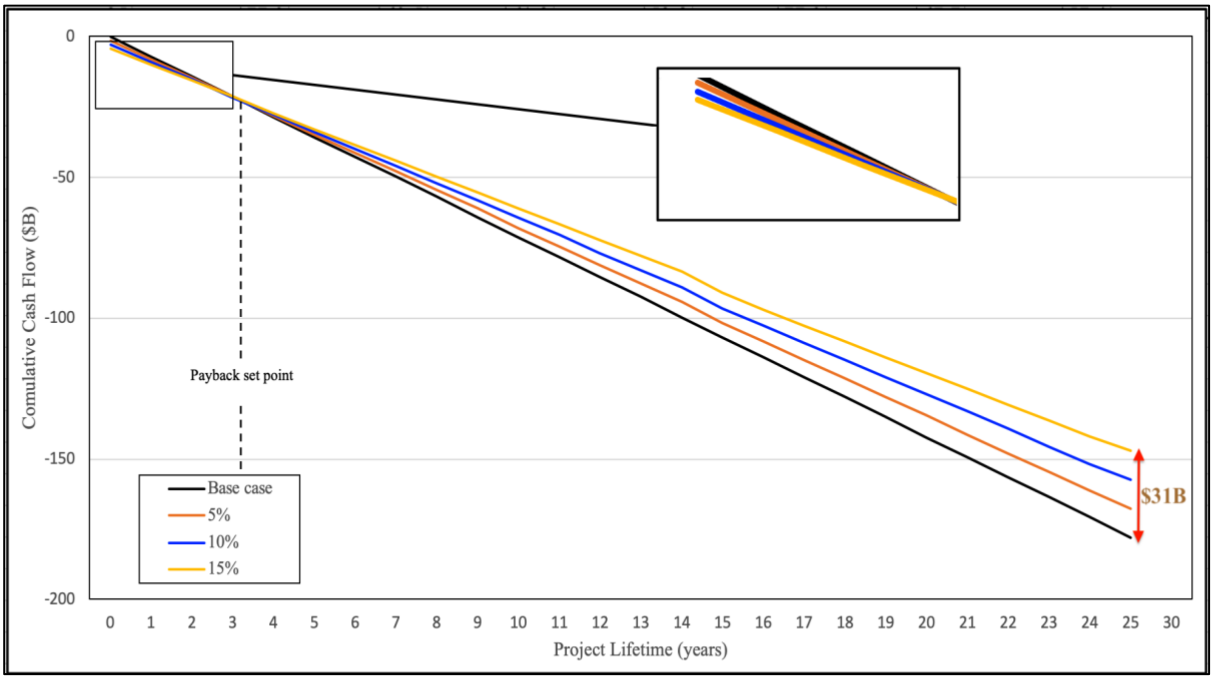


Figure 5-7:Cash flow for (solar PV-grid) system at different attribute in reference to base case.

The zoom-in view in the figure shows that achieving higher solar penetration requires higher capital costs but the overall cost of the system will be less, that is including the grid influence. But as for the solar systems of different attributes its cost will increase with the increase in solar PV capacity/penetration as demonstrated in figure (5-6). The payback occurs after the third year of project operation with 29.4% return of investment, which is one way or another is affected by the published cost of electricity in Kuwait.

Through increasing the capacity to 6,350 MW, another 15% was achieved, the 15% represents the reduction in the annual CO_2 emissions, about 7 million tonnes (Mt) of carbon is prevented from being released. The following figure (5-8) illustrates the reduction in carbon dioxide, sulphur dioxide and nitrogen oxide emissions as a result of higher renewable fraction/penetration.

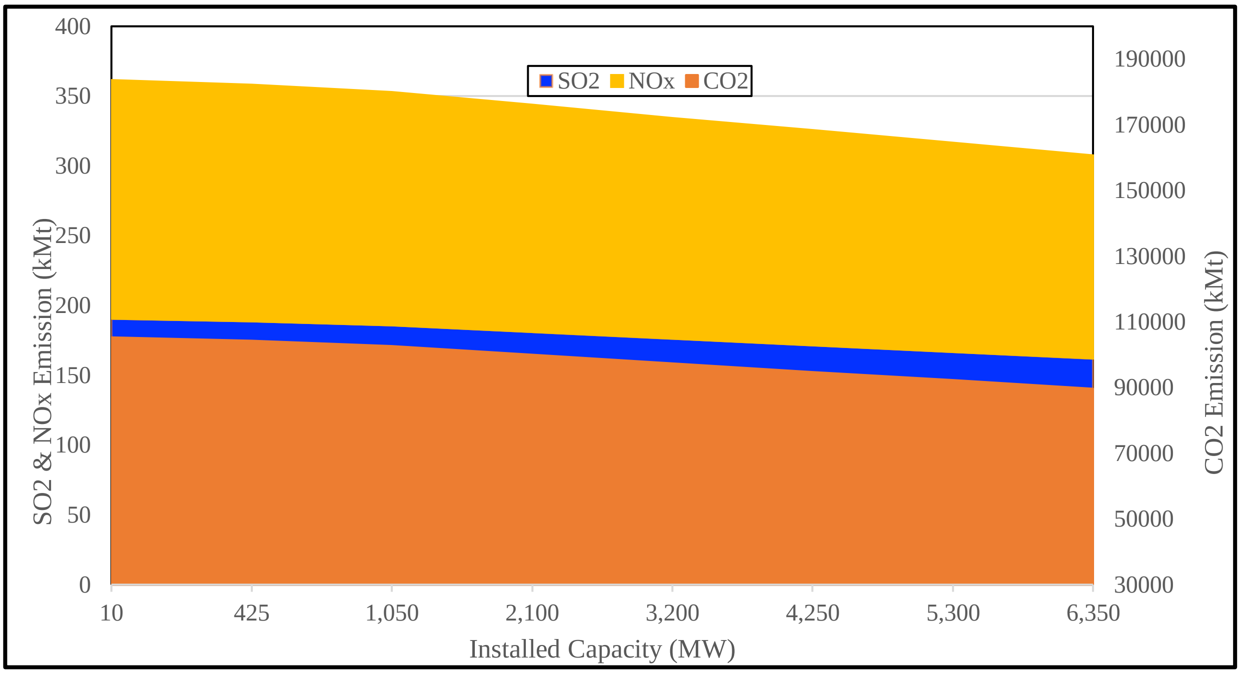


Figure 5-8: Mass of annual SO_2, NO_x and CO_2 emissions based on PV size capacity,

The highest reduction occurred for the carbon emissions follow by NO_x emissions. These are mainly emitted by the grid of conventional electric generations. the annual total amount of reduction in emissions was just over seven million tonnes correlated with the 15% PV fraction and PV power production of 11 TWh.

Power Station Size

Producing this amount of electric energy requires considerable space of flat land. For example, if each 1kW of installed PV capacity is produced from 4.4 m_2 (each panel is 0.4 kW and has an area of 1.76 m_2) then the area of the power station would have to be 28 km_2. Meaning PV power station with 6,350 MW capacity will take up only 28 km_2 and the required number of (0.4 kW) PV modules is 15.79 million units, assuming modules were placed flat (0°) on ground. By the same method of calculation, the size of the power plant to achieve 1%, 5%, 10% and 15% PV penetration are shown in table (5-7), for reference of the PV capacities table (5-4)

Table 5-7: size of PV power station.

PV Capacity (MW)	Area of PV Power Station (km2)	PV Modules ($\times 10^3$)
10	0.044	25
425	1.9	1,057
2,100	9.2	5,220
4,250	18.7	10,565
6,350	27.9	15,785

The size of power station is very important for assessing the feasibility of the renewables. Dedicating 28 km2 for PV technologies might be great achievement for sustainable engineers in terms of clean energy and less GHG emissions. However, the area is an only estimation of the minimum area needed. For example, the 2 GW 'Pavagada' solar project in India covers 52.5 km2 and costs over $2 billion. Thus, the area required for 6.35 GW solar project should be at least 4 times higher than the calculated area in table (5-7). Yet, this also depends on the simulation inputs of PV modules efficiency and other factors. Nevertheless, a project of that scale (triple the size of largest Solar project in the world) is considered to be very challenging to achieve and almost infeasible. Also, Kuwait has provided an area of 84 km2 for renewable projects which is not even close to the area required (Steensma *et al*, 2019, 2).

Therefore, in theory and by software analysis it was determined that feasibility of a 15% solar penetration depends on multiple factors. Based on simulation, PV systems offers the target solar penetration (%) at a year period. However, on monthly or even daily basis, the fluctuations in solar production might be an issue to its reliability. Moreover, the project would cover between 28 km2, which is less than the area that Kuwait prepared to date. Furthermore, the financial results from the estimated inputs are relatable to the investments of the current renewable projects in Kuwait, yet it should be expected to be higher in reality since the financial inputs were estimated and optimized for least cost. The O&M costs are about 4 times higher than the initial investments, which is a typical for solar PV (Fu e*t al*, 2018, 21). Therefore, 15% solar penetration feasibility depends on the governments dedication and definition of the penetration, because if they are aiming for daily 15% renewable penetration this will not be achieved by solar system only, hence, not feasible for solar power station applications otherwise (i.e. house integrated) it should be feasible.

5.3 Case 1: Scenario 2

The first simulation results were found for wind systems with installed capacity of 10 MW table (5-8), with 84 m hub height.

Table 5-8: Simulation result for 10 MW wind turbine.

Quantity	Capacity (MW)	Wind power production (GWh/year)	Wind Penetration (%)
5	10	17.4	0.0235

Building 10 MW wind power plant require installing five wind turbines. The annual power generation of such plant is around 17.4 GW/year, for which it is considered only a fraction of a percent of the total Kuwait energy generation of 74.1 TWh/year grid included. Moreover, the mean output for 10 MW wind power plant is 1.3 GW, that means turbines are operating at only 20% of the capacity. Also, it was found that renewable fraction and penetration are identical in AC system. Because the AC generative wind turbines are directly connected to the grid, hence the losses are minimised and loss of conversion is zero. The power production corresponds with 8,538 hours (353 days and 12 hours precisely) of operation time.

Energy production from the wind turbines are distributed throughout the day and all year long, which is expected based on high operational hours. The distribution of the power output provides insight on wind’s unpredictable behavior, the absence of clear pattern and uncertainty of wind for forecasting on hourly or even daily basis. However, wind turbine power outputs can be seen in brighter colors and higher concentration in summer months, in these months wind speeds are higher than the rest of the months figure (3-9). Raise in wind speed could be a resultant of higher temperature gradients in weather at these periods. Figure (5-9) presents the power output to the respect of wind speed.

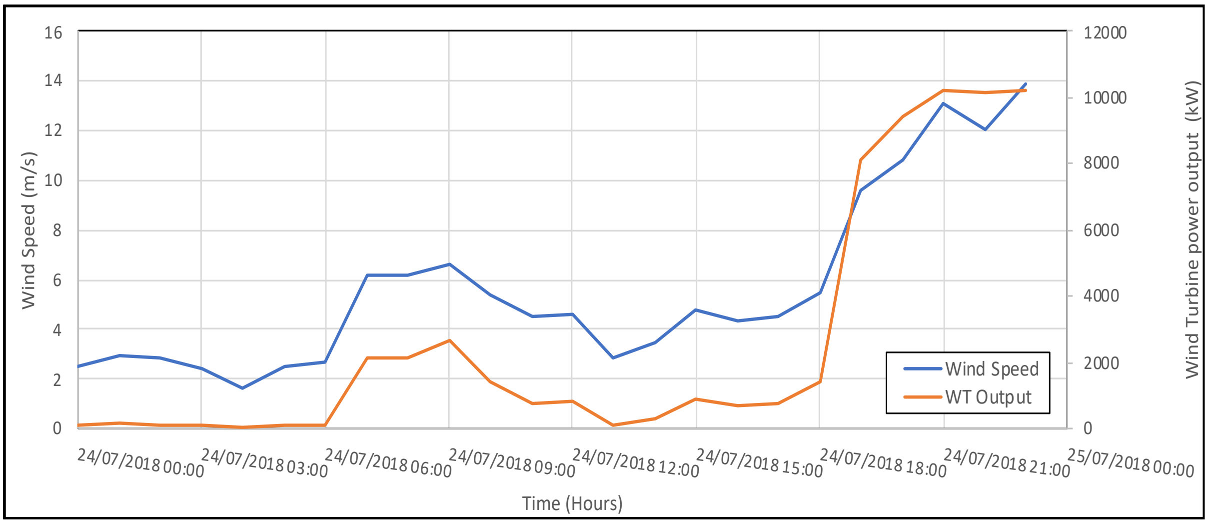


Figure 5-9: Wind turbine power output (kW) with respect to wind speed (m/s), 0.023% wind penetration.

Unlike solar generations, wind power generations have lower tendency to be in a pattern during the day. The power generation is nearly zero at the start of the day with wind speed below the cut-in speed. Once the wind speed exceeded 3m/s wind turbine started generating power and it remained proportional to the wind stream until the wind speed reaches 9m/s is when the power generation increase exponentially.

5.3.1 Increasing capacity

For this scenario, the capacity was increased by installing more wind turbines to achieve higher renewable fractions 15%. Based on the first scenario there is a rough estimation on the required capacity to reach 1%, 5%, 10% and 15% of the total power production from renewable resources. The amount of wind turbines required to achieve these targets are listed in table (5-9).

Table 5-9: Simulation results for different wind power plant capacities, Enercon E82 E2.

Quantity	Capacity (MW)	Wind Production (GWh/year)	Grid Energy Purchased (TWh)	Wind Penetration (%)
5	10	17.6	74.1	**0.0235**
213	426	730.2	73.4	**1**
1065	2130	3,650.5	70.4	**5**
2130	4260	7,301.3	66.7	**10**
3195	6390	11,027.0	63.0	**15**

According to the simulation results, in order to achieve 15% renewable penetration in the total power production, projects have to aim on installing wind turbines with total capacity of 6390 MW. The total power production of the wind turbines was measured to be 20% of the total installed capacity and according to EIA (2020) the typical range of capacity factor for wind turbines is 20% - 40%. Thus, the capacity factor from the simulation is considered to be low for utility-scale which explains the excessive need for wind turbines to achieve the 15%. But the wind power productions at different attributes are almost identical to the ones from solar system for the same attribute, table (5-4).

The cost of onshore wind turbines (and renewables in general) has been declining since the global markets started investing in these technologies. Currently, the capital cost of onshore wind turbines is averaged to be $1,750/kW capacity (EIA, 2020). That matches the capital cost from simulation financial results, shown in table (5-10).

Table 5-10: financial simulation results at different wind turbine capacity.

Installed Capacity (MW)	NPC ($B)	COE ($)	Capital Cost ($M)	O&M ($B/year)	O&M reduction (%)
10	138	0.135	17.5	10.00	-
426	137	0.134	746	9.9	1.0
2130	133	0.130	3,730	9.5	5.0
4260	127	0.126	7,460	9	10.0
6390	121	0.121	11,200	8.5	15.0

Installing more capacity for wind systems for higher renewable energy production fractions is associated with increase of capital cost, given each turbine cost $3.5M to install. The capital cost for 15% penetration was calculated to be $11.2 billion with a payback period of less than eight years, Figure (5-10).

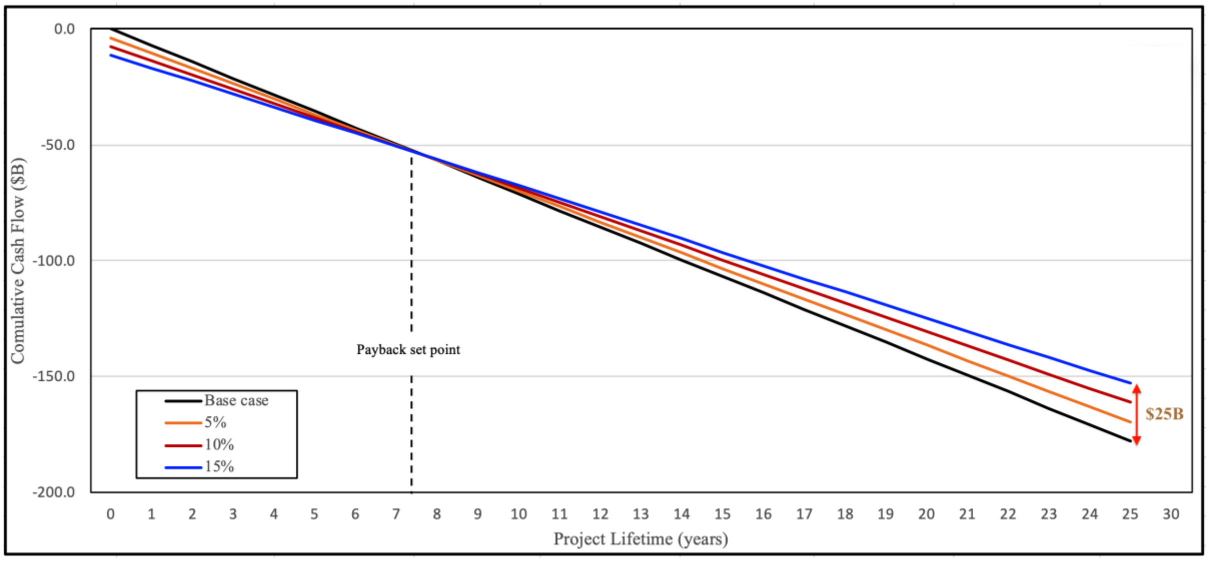


Figure 5-10: Cash flow for Wind project at different attribute in reference to base case

The total nominal NPC over the project lifetime (25 years) decreases for higher wind penetration in the power production, cause the 15% wind penetration to save $25B. Detailed explanation of NPC behavior is provided in 5.2.2 under "NPC Behavior". In simple the total NPC decrease when the renewables' NPC increases as illustrated in figure (5-11). That is mainly suggesting the cost ($/kWh) for electricity generation sourced from oil/gas power plants is higher than it is from renewable technologies. Hence, the $0.135/kWh (from fossil fuels) should be lower. However, since it was heavily referenced in the literature, it was assumed that it was based on fuel cost in global market. instead it should be prime cost of fuel.

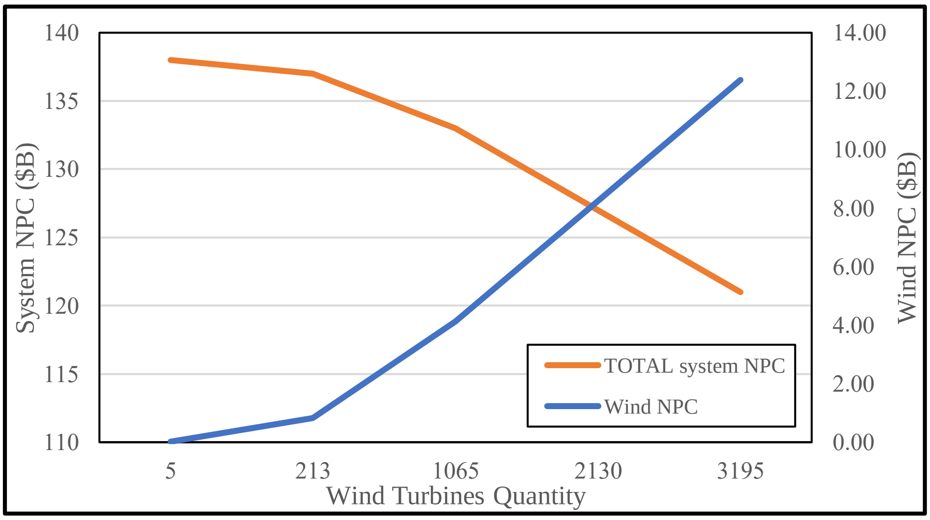


Figure 5-11: Discounted NPC behavior wind farm system only and total (wind-grid) system.

In contrary, Levelised COE is decreasing as it should the electricity network comes more independent for higher renewable penetration. Therefore, the cost of energy generation is cut by 10% from the conventional price ($0.135/kWh), to be 0.121/kWh for 85% grid dependance (15% wind penetration). Hence, electricity price for the consumers drops from 0.039/kWh to 0.035/kWh, which might be considered small reduction.

Also, shifting to clean energy generations reduce the impact on the environment and helps mitigate climate change. The GHG emissions reduces by at least 1.1 million metric ton for 1% of wind penetration, the amounts reduced by different wind penetrations in the grid are listed in table (5-11).

Table 5-11: CO_2, SO_2 & NO_x emissions at different wind penetrations (%).

Wind Penetration (%)	CO_2		SO_2		NO_x	
	Emission (MMt/year)	Reduction (MMt/year)	Emission (kMt/year)	Reduction (kMt/year)	Emission (kMt/year)	Reduction (kMt/year)
0.0235	105.3	<0.05	190.5	0.05	171.0	<0.05
1	104.2	1.1	188.6	2.4	169.5	1.5
5	100.1	5.2	181.0	10.0	162.7	8.3
10	94.8	10.5	171.5	19.5	154.1	16.9
15	**89.7**	**15.6**	**162.0**	**29.0**	**145.6**	**25.4**

Creating the project of 15% renewable penetration from wind turbines, would save Kuwait from a total mass of over 7.1 million tonnes of greenhouse gas emission per year. The percentage of reduction in the emissions are the same, but since the total emissions of CO_2 is in tens of million tonnes, the 15% percent reduction is translated into 7016 million tonnes, which is much higher the nitrogen oxide and sulphur dioxide emissions estimated at 14.9 and 30.4 thousand tonnes per year, respectively.

Sizing wind farm

Unlike Solar PV, wind farms require spacing of 3-9 times the rotor diameter. For example, wind turbines with 82 m rotor diameter requires 246 m spacing. The spacing is important for the wind to regain its kinetic energy after being scattered in the process of spinning the first wind rotor, Meyers and Meneveau (2012) concluded that the optimal wind farm spacing for wind to regain its energy is 15 times the rotor diameter for large wind turbines. However, that would result in excessive use of land, instead 246 m spacing at all directions is used. Therefore, building a wind farm in grid formation for 3195 turbines will approximately require 193 km$_2$ of area table (5-12);

$$Wind\ farm\ area = (3D_w \times 3D_l) \times spacing\ on\ width \times spacing\ on\ length$$

$$Wind\ farm\ area = (246 \times 246) \times 45 \times 71 = 193\ km^2 \text{ approximately}$$

Table 5-12: Area of land required for different wind farm sizes.

No. of turbines	5	213	1065	2130	3195
Formation	Straight	Grid			
Area (approx.) (km$_2$)	0.242	12.7	62	129	193

After reducing wind farm spacing, 15% renewable penetration by wind turbines might be achievable, however it still may not be the most feasible choice. Because of the spacing requirement in wind turbines, lower renewable fractions are more acceptable in terms of the land utilised such as 1% or 5% penetration. Unless Kuwait is willing to provide as much of its land as 193 km$_2$, Kuwait vision cannot be achieved by wind turbine only. However, it would contribute as much as 5 percent in the renewable energy generation network and remain as a viable option. The feasibility of wind penetration to be ranging between 1% and 5% (426 MW and 2.13 GW, respectively) coincides with future capacity of wind farms in Kuwait, as it was projected to be 1.5 to 4.5 GW. Note that Enercon E82 E2 is a better performance model than the actual wind turbines currently used in Alshagaya (Gamesa) it has higher capacity factor, more robust, directly connected to the grid and fast response to grid frequency.

One way to overcome land size issue, is to locate these installation site away from future residential or industrial project. for example, along the country borders from the west in straight formation, or it could replace old oil desalination site. But these suggestions require large high efficiency step-up transformers for longer electric transmission lines from wind farms to the consumers.

5.4 Case 1: Scenario 3

For the third scenario, HOMER was configured to have both solar and wind systems contributing towards the total energy generation figure (4-7c). After analysing the previous scenario, power productions were found to be almost identical for a given percentage of penetration. For example, the total power production of solar and wind systems at 15% penetration were 11,118.4 GWh and 11,027.0 GWh, respectively, the difference is negligible and can be considered insignificant. Hence, a power production at the same range should be obtained from third scenario simulation. Solar system to wind system ratio was assumed to be balanced (1:1) in terms of their installed capacity at any given penetration. both solar PV and wind turbine produce almost identical power magnitudes for a given installed capacity

Results of the Alshagaya representative simulation was found at first, it includes 10 MW capacity for each solar and wind systems which accounts for 0.05% of the total electricity generated. Based on literature the per capita electricity consumption was calculated for 4.6 million people. Also, the renewable electricity generation was assumed to be fully consumed, to find the per capita consumption from renewables (solar PV & wind turbine). table (5-13) shows the electric simulation results for renewable system.

Table 5-13: solar-wind system simulation results.

Renewable energy penetration (%)	Renewable source consumption (GWh/year)	Per capita consumption (kWh/year)		Grid sourced consumption (TWh/year)
		Renewables	Grid	
0.05	35	8	16109	74.1
1	739	161	15957	73.4
5	3,681	792	15326	70.5
10	7,359	1603	14522	66.8
15	11,087	2410	13696	63.0

The renewable electricity production has been recorded to have similar range of values (GWh/year) as the first and second scenario at any given penetration (%). However, there are slight variations which are not random nor caused by an error in the simulation. The variations are mostly factored to the small inefficiency (1.5%) in the inverter for solar PV systems, requiring a bit higher solar DC electricity production than the wind AC production to attain the same renewable fraction. Although the variations are in tens of GWh and they can be even higher for lower efficiency inverters. they seem to be negligible due to the noise and different losses in real power stations figure (5-12).

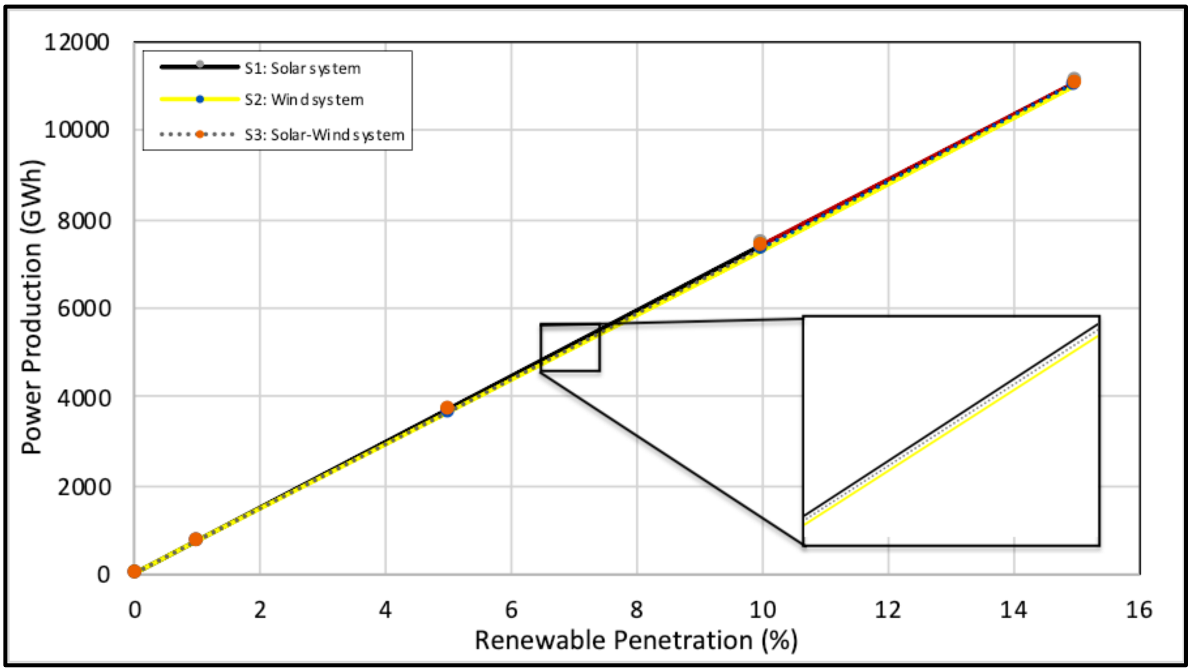


Figure 5-12: Power production variation among the configurations.

In simulation, Kuwait total electricity energy production is about 74.13 which is similar to the reported one (MEW, 2019), that over the total population of Kuwait generates the per capita value. Therefore, Annual electricity consumption (kWh) per capita are shown in figure (5-13), representing per capita consumption from renewables and conventional resources.

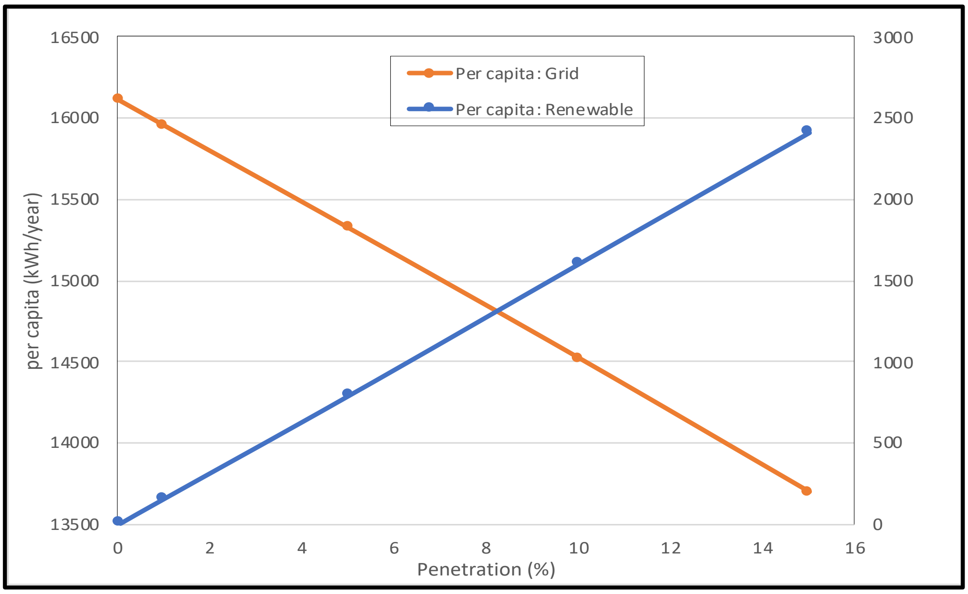


Figure 5-13: Renewable and grid per capita consumption (kWh/year).

Naturally the rise in electric load and consumption is a direct result of the harsh climatic conditions and of the rapid economic and construction growth in the country's private and public sectors. However, the rise in per capita average rate of consumption reflects the extent of luxury and abundance enjoyed by the people, meanwhile it plainly indicated aspects of waste and extravagance prompted and encouraged by the very cheap price of electricity. Nevertheless, to generate this amount of energy requires large amount of land and based on the previous scenarios it can be deduced that implementing solar PVs to attain any penetration will take less space table (5-7 & 5-12). Similar effect is shown in table (5-14), in which each percentage penetration is obtained by the half the space required for wind and solar (since balanced contribution was assumed for this scenario).

Table 5-14: The area of renewable power station at different attributes.

(RE Penetration 0.05%)			
Segment	Wind	Solar	Total renewable system
Area required approx. (km$_2$)	0.242	0.044	0.3
Renewable Energy Penetration: 1%			
Segment	Wind	Solar	Total renewable system
Area required approx. (km$_2$)	6.5	0.95	7.45
Renewable Energy Penetration: 5%			
Segment	Wind	Solar	Total renewable system
Area required approx. (km$_2$)	31	5	36
Renewable Energy Penetration: 10%			
Segment	Wind	Solar	Total renewable system
Area required approx. (km$_2$)	65	10	75
Renewable Energy Penetration: 15%			
Segment	Wind	Solar	Total renewable system
Area required approx. (km$_2$)	87	14	101

The size of the power stations might be considered as an issue because of its demand of land just like the previous scenario. The mains concern is the public impression to the news of four district equivalent size of land would be for renewable generation. Regardless, the feasibility is high for each of the systems (solar PVs only, wind turbines only and solar-wind). Especially since they can reduce the strain on conventional power stations by factor of 15%, in return for only 28-193 km$_2$ of land. If wind takes significant amount of land, then solar PV only (scenario 1) or solar-wind (scenario 3) systems would be more appropriate choice. However, renewable power production for the latter system is more distributed and causes a lot of excess energy which have to be exported (815 GWh/year). In comparison, solar and wind individual systems had surplus electricity that were recorded at 21 GWh/year and 18.5 GWh/year, respectively. Surplus energy can be useful or waste depending on energy management. In this regard both solar PV and solar-wind systems seems to be feasible. But the latter is more common to exist and because Kuwait is looking for diversification of energy sources it was decided to be more technically viable.

In Contrary, unlike power production the initial costs are at different ranges for solar PV and wind turbines, yet the other costs like O&M are the same. The, general budget for the investments to implement renewable energy in Kuwait was found to be in several millions USD for the initial cost to $10 billion for O&M costs. Main concept of these costs is correlated, after all to increase renewable penetration the initial cost increases in fraction of millions (due to higher installation of technology) meanwhile the O&M cost drops by hundreds to thousands of millions (due to renewable operating and maintenance being cheaper than fossil fuel power plants). Table (5-15) present similar behavior for the solar wind power station configuration.

Table 5-15: Financial results for third simulation for different sizes.

Installed Capacity (MW)	NPC ($B)	COE ($)	Capital Cost ($M)	O&M ($B/year)
20	138	0.135	87.5	10.00
426	137	0.134	525.5	9.9
2100	132	0.130	2,324	9.5
4260	125	0.126	4,636	9.0
6390	118	0.121	6,947	8.6

According to the simulation Kuwait will be able to recover the total investment within the first 6 years from project lifetime (25 years). ROI was found to be 9.2% and remains the same throughout the scenario despite the change in penetration, with simple payback of 4.7 years and discounted of 5.6 years. While the simple payback plainly counts the required years to recover the total cost through savings/revenue, the discounted payback accounts for the discount rate in each year, prompting more realistic estimation of the payback period. In figure (5-14), the simple payback is demonstrated by the turnover of the trendlines, before the payback set point the lines represents the initial cost, and after it represents the savings all with reference to a basic case.

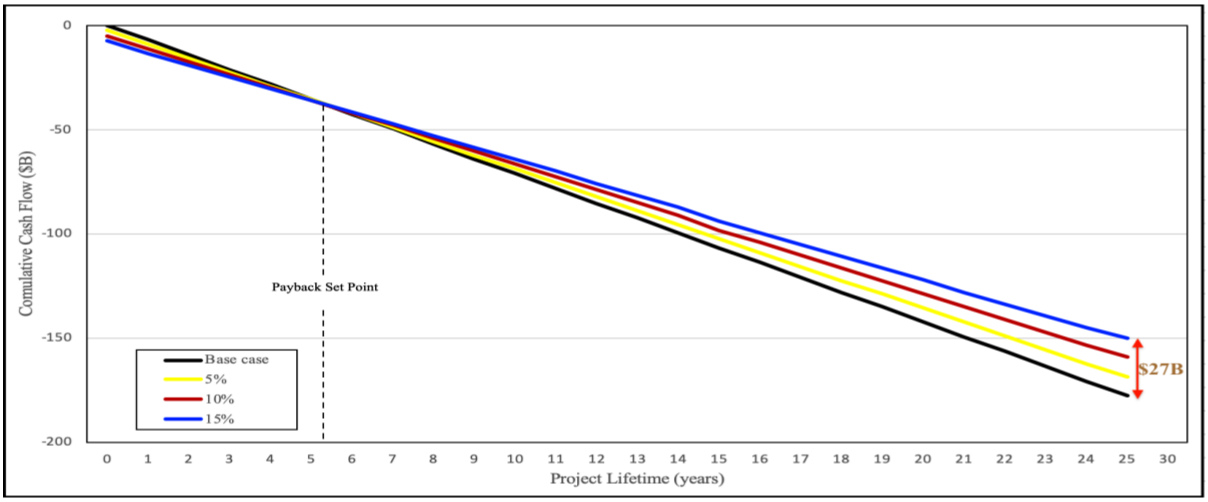


Figure 5-14: Cash flow (nominal NPC) for the project at different attribute in reference to base case.

The basic case (black) consists of conventional power plants only, zero initial cost and $250B total cost were assumed for it to represent the ‘reference’ to renewable costs. For instance, the 15% penetration trendline (red) had highest initial cost of $6.9B placing it in the bottom at first, around year 4.7 the initial costs were reclaimed, and revenue started accumulation at that point onward. Thus, by the end of the project’s lifetime Kuwait would be saving $27B by implementing renewable (solar PV-wind turbine) systems in comparison to the reference.

Technical feasibility decision: the challenges of size and money (if Kuwait is faced by one) could be overcome that determined the infeasibility of the systems were based on assumption of Power station application. Solar doesn’t have to be built for power stations, geverment could spread awareness and provide incentives for home/building integrated applications, in a way that each building has to implement PV panels for on their roofs and/or their car parks to lift 15% of the building’s energy demand. Accordingly, it is more possible to achieve the 15% solar penetration and the financial aspect will be at advantage from governmental and consumer point of view. From governmental point of view, it redirected part of the capital cost of installation onto the consumers and consumer will have 15% reduction in the annual bill.

Brief Scenarios Comparison

By comparing the findings from the three scenarios (grid-solar PV, grid-wind turbine & grid-solar PV-wind turbine) at 15% penetration table (5-16), it can be deduced that grid-solar PV-wind turbine configuration (scenario 3) is more suitable for Kuwait. The NPC in the table below is of renewables only for 25 years (excluding the grid) although ROI and COE include Grid effect.

Table 5-16: Comparison between three configurations at 15% renewable penetration.

Scenario	First	Second	Third
System	Solar PV	Wind Turbine	Solar PV - Wind turbine
Area approx. (km^2)	28	193	101
NPC ($B)	7.6	12.4	10.1
COE ($)	0.119	0.121	0.120
ROI (%)	26.9	9.0	9.2

Through comparison it is clear that wind is the worst option. It requires large amounts of land for spacing the turbines, has highest total NPC and have the least return of investment. On contrary, solar PV is the most suit among the options. It requires small space of land, has the least NPC and its ROI is high by far. However, each of the wind and solar is limited in a way. For example, PV depend on the sun time which limits it production of power to sunlight hours for high clearance index. whereas, wind turbines are capable of power production all day long, it helps providing 15% renewable penetration on a monthly or even daily basis. Combining the wind and solar seems to be the most suitable as a middle option. Combined, it would requires half the land of wind only 101 km^2, which is not much higher than the current project land area (84 km^2) and total NPC is in-between and its ROI is not as high as solar PV but the pay back will be after the 7th year of the project lifetime rather than 3rd year. therefore, third scenario is the most suitable.

5.5 Case 2: Scenario 4

In this scenario the technical, financial and environmental analysis will be presented separately and will be compared with Scenario 3. Since the both have the same system configuration (figure 4-7c).

5.5.1 Technical Aspect

From the previous section (4.6) the load profile had to be updated to investigate the feasibility of 15% renewable penetration for the year 2030 with 4% growth rate in the load profile, based on MEW (2019). As a result, the total power production/consumption in Kuwait increased by the same rate, to reach 77.1 TWh/year, representing the anticipation for year 2030. The energy production is broken into renewable production and grid dependent table (5-17).

Table 5-17:Kuwait's requirements for 15% penetration, 2030.

Total Capacity (MW)	Electricity Energy Production		Renewable Penetration (%)
	Renewable* (GWh)	Grid (TWh)	
443	770	76.4	1
2,216	3,844	73.3	5
4,433	7,702	69.5	10
6,650	11,538	65.6	15

*Renewable: Both wind and solar

More energy production is required to cover the imposed growth in demand, both grid and renewable generations were increase as a result. This was done to maintain the 15% penetration for year 2030, which is the main aim of this paper. Since Kuwait population and load demand were projected to grow at different rates, in which population growth is higher, per capita power consumption should be lower, figure (5-15). With the assumption of identical power production and consumption. The figure emphasise the difference in per capita consumption for the years 2020 and 2030, it is also governed by the per capita demand reduction throughout the 10 years gap. Although it is based on past information MEW (2019), this could be viable for the future in which appliances are slightly more efficient and people more aware of electricity value, which result in reduction of the individual consumption. MEW (2019) considered the reduction in demand growth rates an effect of the increase in electricity prices, the old consumer price which is $0.009/kWh was reconfigured in 2010s to $0.039/kWh. Similarly, if a demand growth was flattened, per capita consumption will be lower each year.

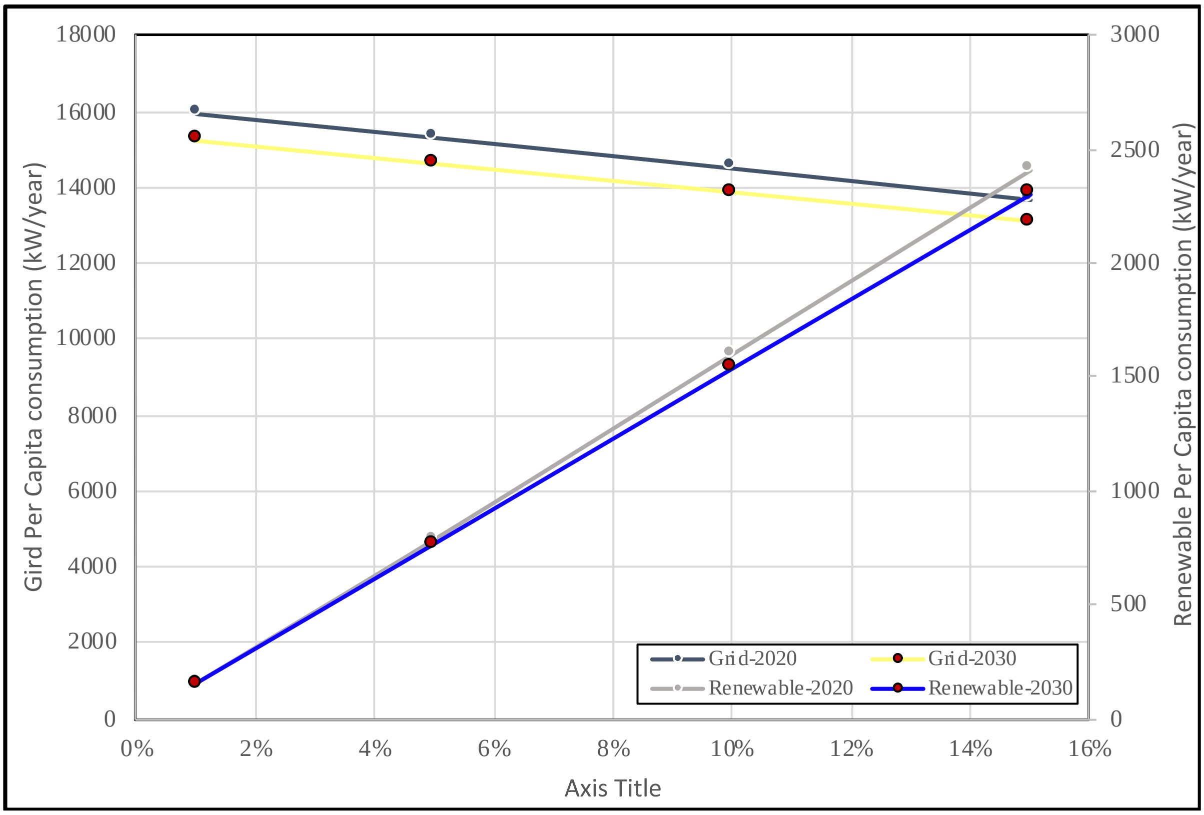


Figure 5-15: comparison of per capita electricity consumption for both renewables and grid separately for the years 2020 and 2030.

In addition, the increase in the total demand and the proportional increase in renewable size in order to maintain its penetration fraction requires more area for renewable projects. As presented previously there will be increase in demand by 4% including renewable sourced, thus, to cover the difference in demand power production is increased, hence, its installed capacity and module quantity were increased too. As previously mentioned, Solar-wind grid connected system provide higher reliability than the individual (solar / wind) when its grid connected, which explains the selection of this system configuration rather than solar PV grid connected power which had a requirement for smaller area to install in. Table (5-18) lists the area requirement of wind turbines and solar PVs in balance contribution of production (1:1).

Table 5-18: The new areas of renewable power station at different attributes

<table>
<tr><td colspan="4">Renewable Energy Penetration: 1%</td></tr>
<tr><td>Segment</td><td>Wind</td><td>Solar</td><td>Total renewable system</td></tr>
<tr><td>Area required approx. (km$_2$)</td><td>6.7</td><td>0.98</td><td>7.7</td></tr>
<tr><td colspan="4">Renewable Energy Penetration: 5%</td></tr>
<tr><td>Segment</td><td>Wind</td><td>Solar</td><td>Total renewable system</td></tr>
<tr><td>Area required approx. (km$_2$)</td><td>33</td><td>5</td><td>38</td></tr>
<tr><td colspan="4">Renewable Energy Penetration: 10%</td></tr>
<tr><td>Segment</td><td>Wind</td><td>Solar</td><td>Total renewable system</td></tr>
<tr><td>Area required approx. (km$_2$)</td><td>67</td><td>10</td><td>77</td></tr>
<tr><td colspan="4">Renewable Energy Penetration: 15%</td></tr>
<tr><td>Segment</td><td>Wind</td><td>Solar</td><td>Total renewable system</td></tr>
<tr><td>Area required approx. (km$_2$)</td><td>93</td><td>15</td><td>108</td></tr>
</table>

The needed area for the renewable project to achieve 15% penetration in the electricity production network is 108 km$_2$. In comparison, the currently designated land for renewable development in Alshagaya project (Phase II) is 84 km$_2$ which is 24 km$_2$ difference from the required for 15% penetration. For the same area (24 km$_2$), residential district can be large enough to accommodate considerable population in about 50,000 houses. However, 15% coverage of the electricity consumption despite the excessive use is also considered an achievement. Although the total area for the three phases of Alshagaya project is yet to be revealed officially. However, if it was less than 108 km$_2$, then it only means that this balanced configuration of solar PV and wind turbines is not viable and more appropriate configuration is to install a megawatt capacity of wind turbine for two megawatts of solar PV. This clearly suggest the equivalency of capacity factors (~20%), which in turn provide insight to the wind resource in Kuwait.

Moreover, Kuwait has moral obligation to achieve 15% by 2030. Suggesting the time limitation of achieving the project and the large need for manpower to install the massive amounts of renewables. 8.37 million solar PV panels is the least requirement for it to harness the solar energy and produce 7.5% of the annual power production while 1650 wind turbines need to be installed to produce the same power. Period of installation is proportional to Kuwait dedication in achieving its aim because based on the discussion of the previous scenarios (lower requirement) the time is very limited to install 6.65 GW capacity of renewables. important aspect associated with this is the cost, because the cost of labor (a segment of initial cost), to make the target penetration possible in time, will be much higher than $400/kW.

Feasibility decision: the main feasibility determinants are the availability of the land for renewable energy project construction and the time limit to achieve target penetration of renewables. since Kuwait has already prepared 84 km2 it has moved long steps toward it target and 24 km2 more should not be a reason to hold the project back. But in case Kuwait was limited on the current area of land or is looking to reduce the area needed, then increasing solar PVs in renewable ratio or incentives the Microgrid implementation of solar PVs, are methods to manage the space. In addition, time is a crucial determinant of feasibility for the 15% renewable penetration target by 2030. In reference to solar PV power station construction period, Saudi Arabia were able to install 300 MW PV within almost 2 years in Sakaka (Alves, 2008). Thus, by scaling up the project, Kuwait will finish installing 6,650 MW PV capacity (15% solar penetration project completion) by the year 2059, it is well past 2030. Therefore, Kuwait either have to triple the labor force or look for more time efficient energy generation (i.e. biomass).

5.5.2 Financial Aspect

Cost of renewable projects depends on renewable technology and the sized of rated capacity aimed to be installed. In this scenario the renewables are solar PV and wind turbines and the target installed capacity is 6650MW, to be able to cover 15% of electricity consumption. In table (5-19) is a list of the financial results based on the simulation.

Table 5-19: financial requirement for 15% RE penetration in Kuwait, 2030.

PV Penetration (%)	NPC ($B)	COE ($)	Capital Cost ($M)	O&M ($B/year)	O&M reduction (%)
1.00	145	0.134	533	10.3	1
5.00	139	0.130	2,727	9.9	5
10.0	132	0.126	5,373	9.4	10
15.0	125	0.121	8,075	8.9	15

In this scenario also, the reduction in the NPC is very clear and it is about $20B. However, the NPC in general is higher than the previous scenarios (Case 1). This is due to the imposed growth rate in the simulation, the base case for the year 2030 load profile require larger amount of electricity to be generated from conventional power plant (grid component), at $0.135/kWh. Cost of electricity production is assumed to be unchanged and is unaffected by inflation rates. Therefore, the COE values remain in the same range as the previous scenarios, despite the change in NPC. Essential factor in NPC calculation underwent value change, was the annual income from consumers purchases of electricity the increase in consumption lead to growth in the annual income. After it was $2.89/year, it grew to be $3.01B/year. in general, it is considered very low income for MEW from electricity, compared to the expenditures for the same sector.

Main source of expense is O&M annual cost which is about $9B/year for 15% renewable penetration, three times the income for the same year. This also suggest MEW is losing money every year although the loss is higher with lower renewables contributing in the electricity network, figure (5-16). Main cause of this conflict is the cost of electricity production that MEW have to cover for kWh ($0.135/kWh) is much higher than the average consumer price ($0.039/kWh). It is possible that there are aspects calculations did not account for, that created the decrease in NPC and the annual loss, but the most apparent ones are; the electricity production cost which should be lower and/or the consumer price which should be higher.

Although the average consumer price was officially stated by MEW (2019), the cost of production is not. But many publications were suggesting the cost is $0.135/kWh circa. As discussed beforehand, this cost could have included the global fuel cost instead of the prime cost of fuel, which MEW probably is purchasing at. That lays out Kuwait’s ability to subsidy the electricity and possibly profit.

Moreover, Capital cost is the initial cash flow that occur at the start of project. Kuwait is projected to spend $8.1B to install over 8 million PV panels (with inverters) and 1650 wind turbines. The chart in figure (5-16) illiterate the cash flow throughout the project lifetime for base case (grid only), 5%, 10% and 15% renewable penetration.

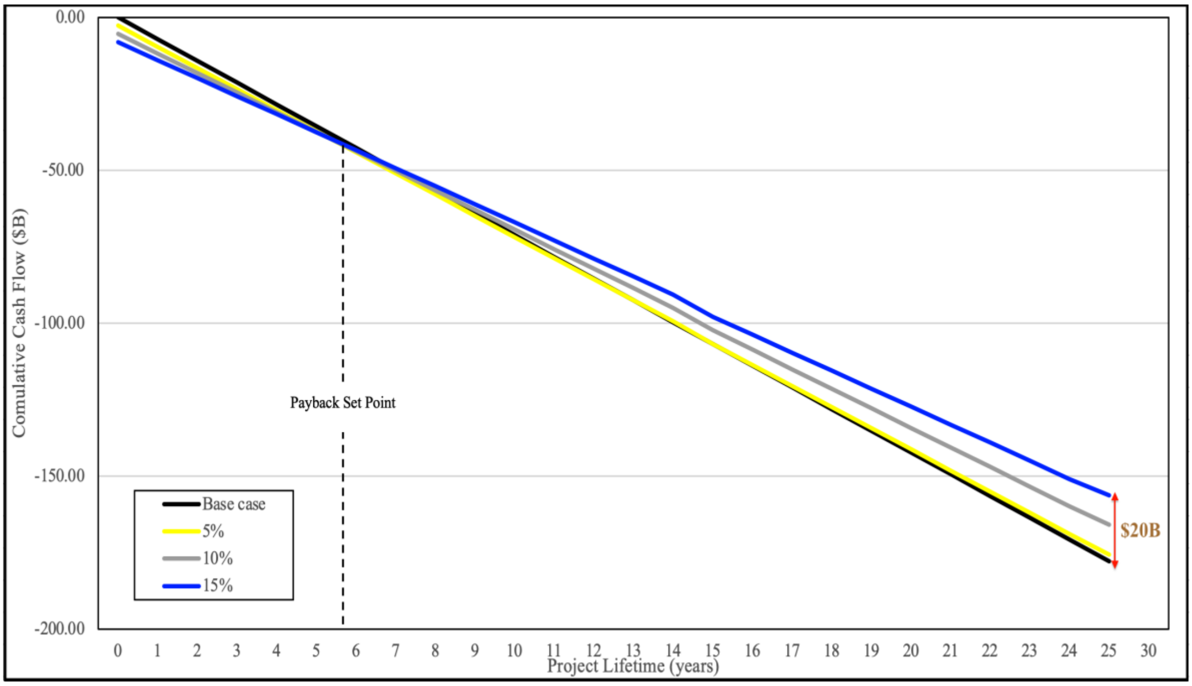


Figure 5-16: Cash flow for of the entire electric network.

It shows that there is a decrease in the NPC (lower losses) for higher penetrations of renewables. ROI of this scenario is 14.3% higher than scenario 3 and it has lower payback period about 5.5 years. After the sixth-year profits of the renewable system decreases the NPC of the total project. Along with the previously mentioned reasons of NPC reduction behavior, the levelised CEO of is lower, around $0.08/kWh.

Feasibility decision: assuming the validity of the calculations, Kuwait should be able to make high amount of investments considering its significant income from oil exports. It might priorities its projects, renewable projects can be achieved financially, nevertheless.

Noteworthy, there is considerable probability of inaccuracy in technical and financial assessments due to the fact that inputs are multi-sourced, and HOMER is for microgrid which create financial miscalculations. For example, the year load profile was scaled from a single day, multiple inputs (PV costs and wind turbine model) were estimated to closest available value/model and cost of electricity production on Kuwait is based on different publication but MEW have no official statement to this regard.

5.5.3 Environmental Aspect

This section will be brief since the is mainly focuses on the mass of GHG emissions, that are emitted by the grid of conventional power stations or the avoided using renewables. In this scenario both renewable and grid power production are higher than it was in previous scenarios for any given renewable penetration. Therefore, there will be larger GHG emissions in the base cause since the emissions are only associated with Grid power production while renewables have zero emission. The following chart demonstrate the CO_2 SO_2 NO_x emission behavior as the renewable contribution in the grid is increased, Figure (5-17). Increasing renewable contribution is correlated with decrease in grid dependance.

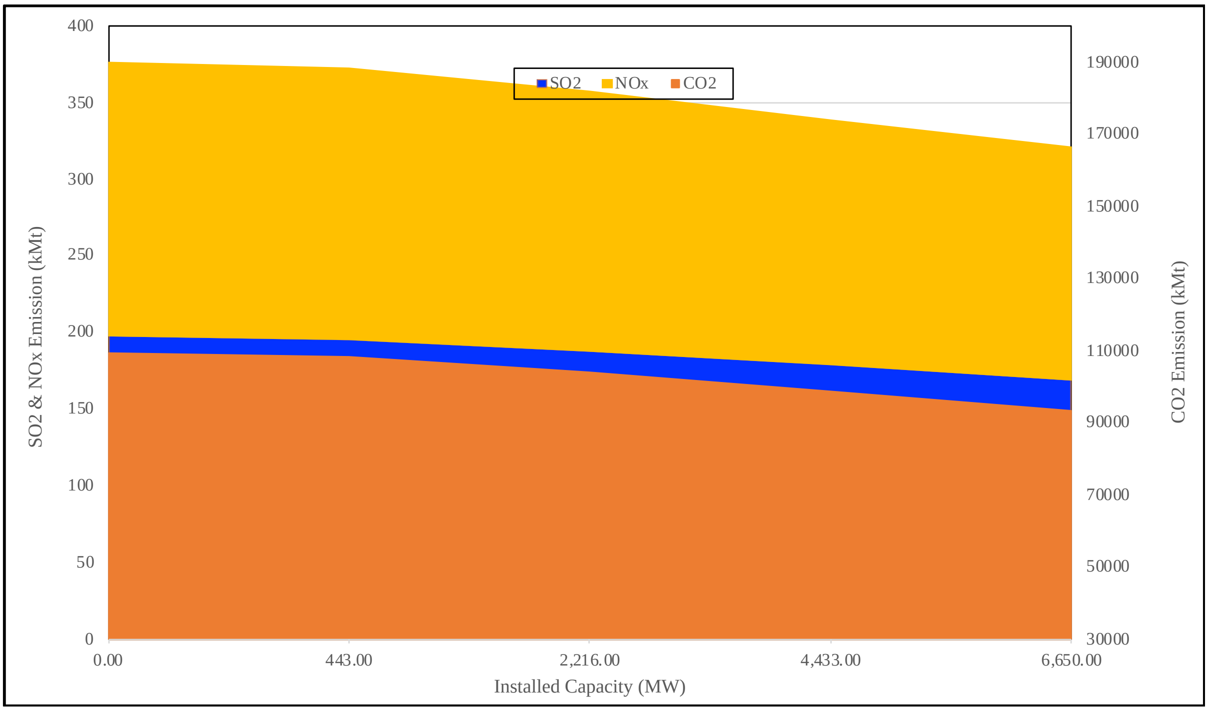


Figure 5-17: GHG emissions of the total system for different installed renewable capacities.

The total reduction of the three GHG emissions over the course of 25 years were found to be 16 MMt, 29 kMt and 26 kMt of CO_2, SO_2 and NO_x, respectively. the reduction in CO_2 is equivalent to ¼ of the population’s carbon footprint.

6 Conclusion & Future Work

In conclusion, the paper has reviewed Kuwait's current situation based on the literature. The review started with general information about Kuwait's of size and population. Then, it focused on its national economy and sources of income, climate state, and electricity energy supply and demand at national scale. It was found that Kuwait consumes 74.1 TWh/year and emits about 105 million Mt of CO_2 while financial aspects were not included for the lack of the fundamental information. The information were used to create an energy model, which then was used to prove that HOMER Pro simulation of the base case (Conventional power station/grid only) generates valid results. Therefore, Kuwait's electricity demand profile was created based on MEW's current statistics for a year period. Case 0 is a simulation of the base case which had valid results (national consumption: 74.1+0.1 kWh/year, CO2 emission: 105.3+0.1 MMt), emphasising on the viability of the created demand profile.

Thereafter, wind and solar resource potentials were investigated based on both literature and calculations, to find that Kuwait have abundance of solar energy and a decent potential for wind. Thus, Solar PV and wind turbine were promoted as subjects for the 15% renewable penetration feasibility analysis. Case 1 looked at three different configurations solar-grid, wind-grid, solar-wind-grid, capacity of the renewables in each of the scenario were increased to produce 15% of the total power and each scenario was concluded as follows;

Scenario 1 (Solar-grid): the capacity factor was 20% which is very close to its conversion efficiency (22.5%). PV Power station would be 28 km_2 and consist of at least 15 million 400W panels. Which is acceptable considering the scale, target solar penetration in power production and the fact that Kuwait have prepared 84km_2 for renewable projects. the project has large sum of capital cost but the NPC decreases which higher renewable penetration, reasons for NPC behaviors were discussed.

Scenario 2 (wind-grid): had similar capacity factor as solar PV which is slightly below average power production. Wind farms would cover 190±3 km_2 and consist of 3200 turbines. Which is a loss of land to only similar power electricity production as solar PV. Also, wind turbine requires larger capital cost and has higher NPC over projects lifetime.

Additional scenario was created since solar PV's power generation is limited on the daytime. Wind turbine can help distributing the production throughout the day. Solar-wind-grid concluded;

Scenario 3 (solar-wind-grid): is feasible (conditionally). The capacity of renewables in this scenario and the previous ones achieve similar renewable-grid fraction (penetration %). Renewable power station with balanced ratio of installed wind-solar technologies requires 101km$_2$ in total to achieve 15% fraction. This is well over the current available area (84km$_2$) but there is high possibility for increasing the area renewable projects. Otherwise it can be managed by partial microgrids. Also, it had less NPC than scenario 2

Since the third scenario was found feasible the load profile was changed to simulate the technical and financial requirements that in tuns maintain the 15% renewable penetration for the year 2030.

Scenario 4 (solar-wind-grid): 'New Kuwait' Vision is feasible (conditionally). The increase of power production is a result demand growth. Hence, area required for renewable project grew to 108km$_2$, which can be managed if Kuwait can provide the extra area or incentivising solar PVs for microgrid to accommodate the current available area. Another way to manage it is by breaking the balance and increase the PV to wind turbine capacity ratio since the both have similar capacity factor and PVs have higher kWh/m$_2$. The NPC was increase for the increase in demand but with Kuwait's financial state it is still reasonable. Therefore, finance and area feasibility are heavily dependent on Kuwait's governmental decisions regarding 'New Kuwait' Vision.

Future work, Kuwait's vision for sustainability is limited on 2030-35 and eventually it might be required to increase the renewable fraction in the grid to 30% by year 2050. Detailed financial analysis is required for the year 2030 vision. Also, solar resource in Kuwait have high potentials, solar heating and cooling system can be navigated. Finally, the wind potential was decent for on shore wind turbines, but its potential might be higher offshore or in Kuwait islands.

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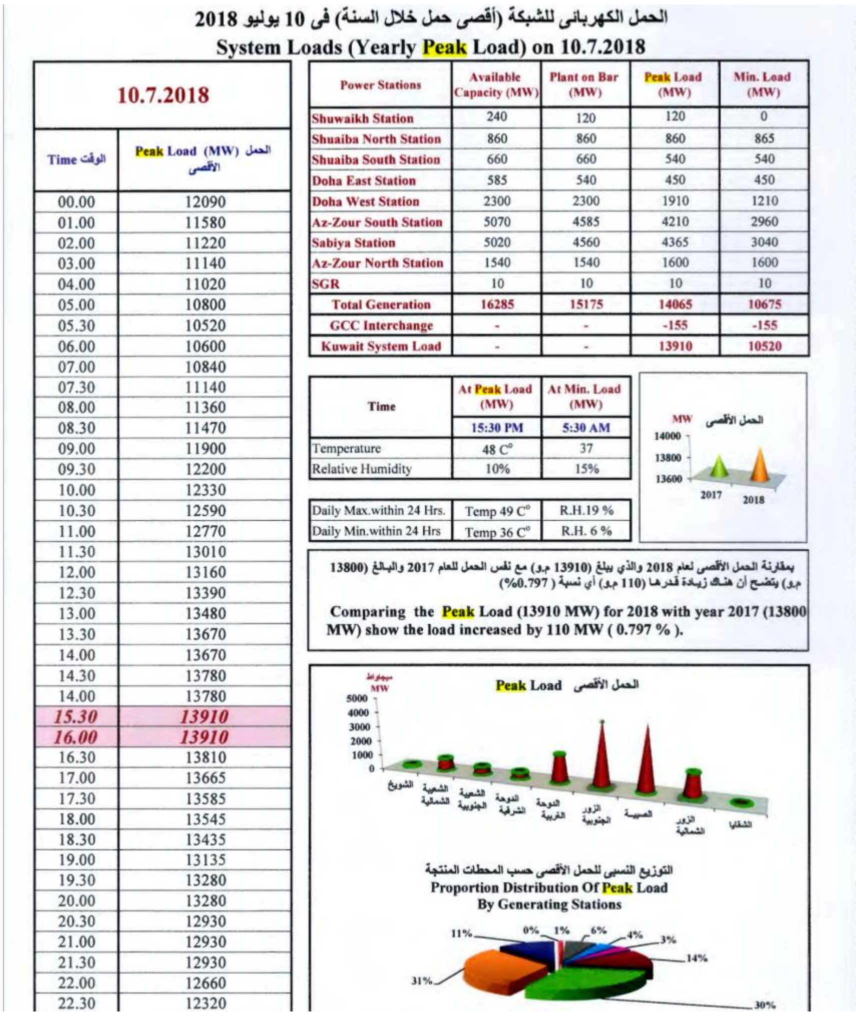
Appendix



الحمل الكهربائى للشبكة (أقصى حمل خلال السنة) فى 10 يوليو 2018

System Loads (Yearly Peak Load) on 10.7.2018

10.7.2018	
Time الوقت	Peak Load (MW) الحمل الأقصى
00.00	12090
01.00	11580
02.00	11220
03.00	11140
04.00	11020
05.00	10800
05.30	10520
06.00	10600
07.00	10840
07.30	11140
08.00	11360
08.30	11470
09.00	11900
09.30	12200
10.00	12330
10.30	12590
11.00	12770
11.30	13010
12.00	13160
12.30	13390
13.00	13480
13.30	13670
14.00	13670
14.30	13780
14.00	13780
15.30	*13910*
16.00	*13910*
16.30	13810
17.00	13665
17.30	13585
18.00	13545
18.30	13435
19.00	13135
19.30	13280
20.00	13280
20.30	12930
21.00	12930
21.30	12930
22.00	12660
22.30	12320

Power Stations	Available Capacity (MW)	Plant on Bar (MW)	Peak Load (MW)	Min. Load (MW)
Shuwaikh Station	240	120	120	0
Shuaiba North Station	860	860	860	865
Shuaiba South Station	660	660	540	540
Doha East Station	585	540	450	450
Doha West Station	2300	2300	1910	1210
Az-Zour South Station	5070	4585	4210	2960
Sabiya Station	5020	4560	4365	3040
Az-Zour North Station	1540	1540	1600	1600
SGR	10	10	10	10
Total Generation	**16285**	**15175**	**14065**	**10675**
GCC Interchange	-	-	**-155**	**-155**
Kuwait System Load	-	-	**13910**	**10520**

Time	At Peak Load (MW)	At Min. Load (MW)
	15:30 PM	5:30 AM
Temperature	48 C°	37
Relative Humidity	10%	15%

Daily Max.within 24 Hrs.	Temp 49 C°	R.H.19 %
Daily Min.within 24 Hrs	Temp 36 C°	R.H. 6 %

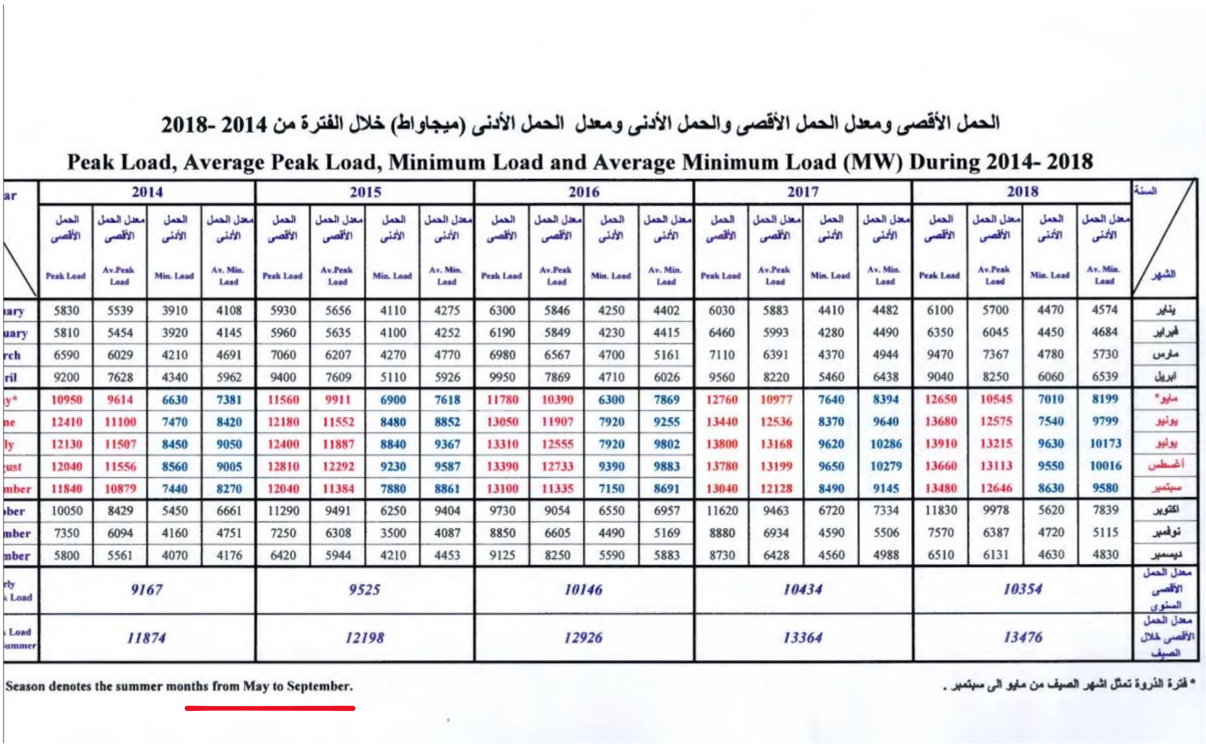
بمقارنة الحمل الأقصى لعام 2018 والذي يبلغ (13910 م.و) مع نفس الحمل للعام 2017 والبالغ (13800 م.و) يتضح أن هناك زيادة قدرها (110 م.و) أي نسبة (0.797%)

Comparing the Peak Load (13910 MW) for 2018 with year 2017 (13800 MW) show the load increased by 110 MW (0.797 %).

التوزيع النسبى للحمل الأقصى حسب المحطات المنتجة

Proportion Distribution Of Peak Load By Generating Stations

Figure 0-1: Average peak load (MEW,2019).



الحمل الأقصى ومعدل الحمل الأقصى والحمل الأدنى ومعدل الحمل الأدنى (ميجاواط) خلال الفترة من 2014 -2018

Peak Load, Average Peak Load, Minimum Load and Average Minimum Load (MW) During 2014- 2018

ar	2014				2015				2016				2017				2018				السنة
	الحمل الأقصى Peak Load	معدل الحمل الأقصى Av.Peak Load	الحمل الأدنى Min. Load	معدل الحمل الأدنى Av. Min. Load	الحمل الأقصى Peak Load	معدل الحمل الأقصى Av.Peak Load	الحمل الأدنى Min. Load	معدل الحمل الأدنى Av. Min. Load	الحمل الأقصى Peak Load	معدل الحمل الأقصى Av.Peak Load	الحمل الأدنى Min. Load	معدل الحمل الأدنى Av. Min. Load	الحمل الأقصى Peak Load	معدل الحمل الأقصى Av.Peak Load	الحمل الأدنى Min. Load	معدل الحمل الأدنى Av. Min. Load	الحمل الأقصى Peak Load	معدل الحمل الأقصى Av.Peak Load	الحمل الأدنى Min. Load	معدل الحمل الأدنى Av. Min. Load	الشهر
ary	5830	5539	3910	4108	5930	5656	4110	4275	6300	5846	4250	4402	6030	5883	4410	4482	6100	5700	4470	4574	يناير
uary	5810	5454	3920	4145	5960	5635	4100	4252	6190	5849	4230	4415	6460	5993	4280	4490	6350	6045	4450	4684	فبراير
rch	6590	6029	4210	4691	7060	6207	4270	4770	6980	6567	4700	5161	7110	6391	4370	4944	9470	7367	4780	5730	مارس
ril	9200	7628	4340	5962	9400	7609	5110	5926	9950	7869	4710	6026	9560	8220	5460	6438	9040	8250	6060	6539	ابريل
y*	10950	9614	6630	7381	11560	9911	6900	7618	11780	10390	6300	7869	12760	10977	7640	8394	12650	10545	7010	8199	مايو*
ne	12410	11100	7470	8420	12180	11552	8480	8852	13050	11907	7920	9255	13440	12536	8370	9640	13680	12575	7540	9799	يونيو
ly	12130	11507	8450	9050	12400	11887	8840	9367	13310	12555	7920	9802	13800	13168	9620	10286	13910	13215	9630	10173	يوليو
ust	12040	11556	8560	9005	12810	12292	9230	9587	13390	12733	9390	9883	13780	13199	9650	10279	13660	13113	9550	10016	أغسطس
mber	11840	10879	7440	8270	12040	11384	7880	8861	13100	11335	7150	8691	13040	12128	8490	9145	13480	12646	8630	9580	سبتمبر
ber	10050	8429	5450	6661	11290	9491	6250	9404	9730	9054	6550	6957	11620	9463	6720	7334	11830	9978	5620	7839	اكتوبر
mber	7350	6094	4160	4751	7250	6308	3500	4087	8850	6605	4490	5169	8880	6934	4590	5506	7570	6387	4720	5115	نوفمبر
mber	5800	5561	4070	4176	6420	5944	4210	4453	9125	8250	5590	5883	8730	6428	4560	4988	6510	6131	4630	4830	ديسمبر
rly k Load	*9167*				*9525*				*10146*				*10434*				*10354*				معدل الحمل الأقصى السنوى
k Load ummer	*11874*				*12198*				*12926*				*13364*				*13476*				معدل الحمل الأقصى خلال الصيف

Season denotes the summer months from May to September.

* فترة الذروة تمثل اشهر الصيف من مايو الى سبتمبر .

Figure 0-2: average peak load that was used for creating demand/load profile, (MEW, 2019).