Department of Mechanical and Aerospace Engineering

Designing a PV-Storage System for a Residential Community in Kuwait

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Copyright Declaration

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Signed: Shahzaib Ali Sheaikh Date: 2 September 2017

Abstract

The overall aim of this project is to access the feasibility of installing a PV-storage system to meet the electrical demand of a residential community in Kuwait. The system should be both technically and financially feasible and have high renewable fraction, reduce grid imports and CO_2.

During the course of the project an understanding into the current power generation system of Kuwait was gained. Kuwait has a 100% electrification rate and the demand of electricity is growing rapidly each other at a rate of 6%. The current generation capacity is barely able to meet the current demand. An absolute reliance on hydrocarbons in meeting the electrical demand has had negative effect with limited oil reserves and high CO_2 emissions. Future plans and policies were considered and a solution is proposed. For reliability and stability of the system, Kuwait needs invest in a more de-centralised and distributed energy system. This will not only help in achieving a much-needed energy mix but will also stabilise the cost of electricity production which varies with the prices of oil in the market. Furthermore, it will help in achieving the target of 15% energy from renewables by 2030.

In order for the successful completion of the project two methodologies were created: General methodology included background research and literature review that helped in better defining the scope of the project. Modelling methodology that included steps needed in order to achieve the stated aims and objective of the project. Detailed explanation of modelling methodology is given in the section 1.5.

A case study was undertaken for a community in Kuwait. Since the data regarding the electricity consumption was not available a demand survey was conducted. HOMER software was used for modelling and designing the PV-storage system for the community. Under the current situation it is not possible to install a large PV capacity without the help from the government due to high prices of the Renewable Energy Technologies (RET). A future scenario was considered with the introduction of Feed-in-Tariffs (FIT), increased grid purchase price and lower prices for RET. In the second scenario, it was found that the a 1389kW of PV and two FB 250-1000 vanadium batteries are able to meet 79% of the electricity demand of the community though renewables. Also, the COE of the system was $0.113/kWh even in the worst case financial scenario with grid export restricted. This was lower than the cost of electricity assumed for the year 2025. Making the system a more economically viable option. Furthermore, the CO_2 was reduced to 232,699 kg/year with the addition of storage system.

Capacities and limitation of the software are mentioned in the report. Future work regarding the project is also mentioned. Various analyses were conducted before selecting the final model for the community.

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I would like to thank Andrew Lyden for his availability and support with modelling software; HOMER Energy Pro, and Bartosz Soltowski who helped me in understanding LoadProGen and MATLAB for creating load profile of the community.

Last but not the least, I would like to thank my friends and family who supported and encouraged me during the course of this project.

Contents

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List of Abbreviations

RES-Renewable Energy System

RE-Renewable Energy

DSM-Demand Side Management

KISR- Kuwait Institute of Scientific Research

KFAS- Kuwait Foundation for Advancement of Sciences

NTEC- National Technology Enterprises Company

GHG-Green House Gas

Li-ion-Lithium Ion

EES-Electrical Energy Storage

ESS-Energy Storage System

MPPT-Maximum Power Point Tracking

DNI-Direct Normal Irradiance

FIT-Feed in Tariff

LF-Load Following

CC-Cycle Charging

LNG-Liquified Natural Gas

MENA- Middle East And North Africa

DER- Distributed Energy Resources

DES- Distributed Energy System

DOD-Depth of Discharge

SOC-State of Charge

RET-Renewable Energy Technologies

DG-Distributed Generation

KPC- Kuwait Petroleum Corporation

MEW- Ministry of Electricity and Water

Tesla PW2- Tesla 13.5kWh Powerwall 2.0

PV-Photovoltaic

FES- FLYWHEEL ENERGY STORAGE

CAES- COMPRESSED AIR ENERGY STORAGE

PHS- PUMPED HYDRO STORAGE

REB- Redox Flow Battery

VRB- Vanadium Redox Flow Battery

Equations Used

- Green Electricity Used (kWh/year), $E_{green}(\frac{kWh}{year})$

$$E_{green}(\frac{kWh}{year}) = Primary\ Load\ \left(\frac{kWh}{year}\right) - Import\ \left(\frac{kWh}{year}\right)$$

- Green Electricity Used (%), E_{green} (%)[i]

$$E_{green}(\%) = \left(\frac{Primary\ Load\ \left(\frac{kWh}{year}\right) - Import\ \left(\frac{kWh}{year}\right)}{Total\ Renewable\ Genration\ \left(\frac{kWh}{year}\right)}\right) x\ 100$$

- Fraction of Load Met from Green Electricity, F_{green} (%)[i]above

$$F_{green} = \left(\frac{E_{green}\ \left(\frac{kWh}{year}\right)}{Primary\ Load\ \left(\frac{kWh}{year}\right)}\right) x\ 100$$

- Increase in Green Electricity Use (%), $E_{green,Inc}$ (%)[i]

$$E_{green,Inc}(\%) = \left(\frac{E_{green,alternate\ system}\ \left(\frac{kWh}{year}\right)}{E_{green,inital\ system}\ \left(\frac{kWh}{year}\right)} - 1\right) x\ 100$$

- Fraction of the additional energy generation consumed locally (%), F_{add} (%)[i]

$$F_{add}\ (\%) = \left(\frac{E_{green,alternate\ system}\ \left(\frac{kWh}{year}\right) - E_{green,inital\ system}\ \left(\frac{kWh}{year}\right)}{Additional\ Energy\ Generated\ \left(\frac{kWh}{year}\right)}\right) x\ 100$$

Report Structure

Chapter 1: Includes a background section that covers the problems faced by electricity sector in Arab countries with increasing electricity demand and why many Arab countries are considering the development of RE sources and their integration into the existing grid. It also mentions the main reasons behind the irrational and drastic increase in electricity consumption. This section also includes a project scope that talks about the two options Kuwait should invest in, to achieve its 15% energy from RE by 2030. One of the options is used as the basis for this report and compared to other countries that have successfully adopted it. Reasons for selecting PV along with storage is also briefly explained. It is further explained in rest of the report. A brief description of centralised distribution and decentralised distribution system is included. Aims and objectives are also mentioned. Furthermore, modelling methodology is explained in this section

Chapter 2: Covers literature review. It explains the current generation capacity of Kuwait and the operation of utilities. Main reasons behind the rapid increase in electricity demand are given. Government policies and regulations are stated. Early warnings on power shortage and negative impact of hydrocarbons on the economy and environment is also highlighted. Reasons why the RE deployment still in nascent stages in Kuwait is also highlighted. Highest consuming sector of electricity is also mentioned.

Section also include all large-scale and small-scale renewable projects undertaken by Kuwait government and the aim of these are also mentioned.

Resource assessment is carried out and results were validated. Demand profile is created using LoadProGen and MATLAB. The software working is explained and the results were validated.

This section also includes the types and characteristic of PV and batteries. Explanation on the different types of ESS along with their application is given. Comparison of different types of batteries is done. Reasons for the selection of certain batteries is given along with their properties.

Explanation regarding location selection and community selection is given. HOMER capabilities are highlighted. Working and setup of components and resources of HOMER is also explianed in this section.

Chapter 3: HOMER modelling is carried out and reasons and assumption for each scenario is given along the way.

Chapter 4: A discussion of all the results from both the scenarios is done and also brief explanation and reasoning for each scenario and simulation is given.

Chapter 5: The final model is selected based on various simulations, explaining the reason for its selection, HOMER limitations are stated and future work required for improving the project is given.

Chapter 6: Economic analysis is done for the model selected and the financial advantage is stated and explained for such as system.

Chapter 7: Conclusion of the report, main results and recommendation for improvement is given.

1 Introduction

1.1 Background

Energy is an integral part for a country's growth. The International Energy Agency (IEA) has estimated that by 2035 the electricity sector will contribute more than half of the global increase in energy[ii]. In the developing countries, the demand for electricity is increasing rapidly. This is providing governments with great challenges to meet the increasing electricity demand, as most of the electricity it still generated using fossil fuels. The power generating industry is the largest producer of Green House Gas (GHG) globally. There is an increase concern about meeting the electricity demand without affecting the environment and climate, and reducing dependency on fossils due to depleting reserves. Many countries have already invested and installed large scale Renewable Energy (RE) projects which include solar and wind to meet part of the electricity demand. IEA in their annual report published in 2013 on "Exploring the Future of Global Energy" stated that the developing countries will not only benefit from the expected increase in electricity but will also be the highest contributors, with China contributing about 30%, Middle East 6%, South East Asia 8% and India about 13% by 2035[ii].

According to IEA in Middle East between 2013-2035 there is an expected 281 GW production of new electrical energy. Power generation from natural gas and oil is expected to be around 153 GW and 31 GW respectively. Renewable energy will play a major role with wind energy contributing 26G W, solar energy about 46 GW and nuclear energy about 7 GW[ii]. Middle Eastern countries such as Saudi Arabia, Qatar, Kuwait and others are considering building nuclear reactors while UAE has already starting building two out of four reactors to meet the growing electricity demand. It has been found that the electricity demand in Middle East countries increases at the rate of 6%-8% annually compared to global annual increase of 2.3%[ii].

The main contributor of increase in electricity demand are the economic and population growth. The economic growth in Arab countries is between 3%-4% annually which is similar to the global annual economic growth. This shows that economy and demography aren't necessarily the main contributor to the increase in electricity demand. However, Arab countries have a higher population growth rate than the global growth rate, and the households and apartments are the highest consumer of electricity in the Arab countries compared to industrial plants. This irrational consumption and increase in electricity demand at residential level is due to; improvements in living standards, wellbeing of individuals, high subsidies, lack of education towards rational consumption and failure of utility companies in effectively collecting monthly electrical bills[ii].

Since majority of electricity is generated using fossil fuels in Arab countries, some Arab countries are forced to import oil and gas to meet the demand. Kuwait signed a contract with Shell oil in 2009 to import Liquified Natural Gas (LNG), and also have been exploring ways in which Qatar can supply Kuwait with additional LNG. This reliance on oil and gas for production of electricity releases harmful GHG which affect both: the environment and the citizens. Furthermore, there are regular outages during summer due to the mismanagement in the power sector and lack of proper pre-planning for peak consumption[ii].

This thesis focusses on Kuwait which is a Middle East country, and like other Arab countries faces great challenges in meeting the increasing electricity demand especially in the residential sector which accounts for the highest electricity consumption. The government has started to investigate ways to improve the electricity generation and distribution, network development and reform policies for collection of bills and reducing subsidies[ii].

1.2 Project Scope

"The Stone Age did not end because we ran out of stones; we transitioned to better solutions" (Steven Chu and Arun Majumdar, Nature, August 2012)[iii].

Similarly, the oil dominance period will not end because we will run out of oil, but it will decline as we move towards a more sustainable future and adopt alternative options for energy. Countries like Kuwait whose economies are highly dependent on oil exports and meeting their energy demands through hydrocarbons must start diversifying its energy mix and adopt sustainable energy measures, or else its economy will be significantly affected[iii].

The oil demand is expected to decline in future, it is evident from the new policies that are targeted towards mitigation of GHG emissions which involves continuous development of energy efficiency measure that encourage the use of more clean sources of energy such as renewables, biofuels, nuclear and other. The IEA 2013 Energy Outlook and OPEC World Oil Outlook have predicted a decline of 5% to 6% global oil demand between 2010 and 2035[iii].

Renewable energy has a huge potential to meet our increasing electricity demand and decrease GHG emission. Kuwait has embarked on an ambitious journey towards achieving 15% of its electricity from RE by 2030[iv]. Although in long term it is important to focus on reducing the electricity consumption.

To achieve the target, Kuwait is in much need for private-public partnerships, which is always a shortcut to modernization of energy sector as it plays a major role in bringing infrastructure investment and provision for much needed infrastructure[iii]. Different policies and strategies can be adopted to attract private stakeholders. Middle East And North Africa (MENA) region demonstrates that both centralised and de-centralised systems are feasible.

There are currently two options that Kuwait should invest in. First is to adopt a system similar to Jordan that encourages widespread acceptance and diffusion of Renewable Energy System (RES), whilst encouraging residential and commercial installation. Government in Jordan is promoting a more de-centralised energy system as part of its rural and localism development agenda that aims at developing solutions meeting local electricity needs and involving local stakeholders from all sectors; rural/urban communities, local authorities, private organisations in the energy projects and investments[iii].

The second one focusses on large-scale projects, similar to Morocco, that has invested in a more centralised renewable energy system. Morocco’s efforts are in attracting a few sizeable primary projects, in addition to developing policies for Renewable energy system (RES) industrial sector and green growth. Even though there are certain strengths and advantages to this policy framework it also has its disadvantages due to sole focus on large scale projects[iii].

Currently, Kuwait is investing massively on large scale deployment of renewable energy projects (further details outlined in section 2.2) However, Kuwait Institute of Scientific Research (KISR) is encouraging the use of solar energy units for residential and commercial sectors (more details related to small scale renewable energy system installation is given in section 2.3). This will be supported by Kuwait government by introducing FIT and other incentives.

In this paper, the focus is on the use of solar energy (solar Photovoltaic) specifically for residential sector, since it’s the highest consumer of electricity, and analyses the feasibly of installing a community scale Photovoltaic (PV) to meet the electricity demand of the households. This is similar to the Jordan’s model of de-centralise system to meet the electricity demand of the community.

This type of de-centralise system will help Kuwait in achieving the Renewable energy (RE) target set, similar to UK, where the government introduced FIT in 2010[v] to increase the level of RE in achieving the target of 15% energy from renewables by 2020 from 2% in 2009[vi].

Adding a community scale PV doesn't necessarily guarantees significant reduction in imports or ensure high renewable energy fraction despite large renewable generation. The major issue with renewable energy or in this case PV is the mismatch of supply and demand. Even though Kuwait has a huge solar potential, solar energy is generated during the day time when the demand may not be high and during evenings when the PV is not generating it relies heavily on grid imports. Due to large amounts of energy generated during the day time when the demand may be low, results in surplus electricity being exported to the grid. Initially this will not be an issue with only one or few communities installing DER, but with more and more DER being installed and being integrated into grid, it can cause serious technical and economic issues. Technical issues include grid stability, power quality, reliability, voltage, frequency and control.

Solar PVs have an intermittent and unpredictable generation and without appropriate storage system during the time of high generation, electricity companies will have to rapidly increase the generation to compensate for the loss of solar energy during the evening (sunset). This can lead to duck curve which occurs due to high ramp rate and will be major problem for the grid operators in future[vii]. Addition of storage system can help solve this problem. However, currently the energy storage technologies are expensive, but with the advancement in technology and decrease in prices, it is certain that the storage system will play a vital role in future energy systems[viii, vii].

1.3 Centralised Generation to Decentralise Generation

Traditionally the electricity system was highly centralised with electricity generated at large facilities typically close to the source of fuel, transmitted over large distances and then distributed to end users. For many decades, this structure of energy network has largely remained unchanged despite the large losses during transmission. This is because of huge economic benefits of installing generation facilities near the source of fuels such as coal, hydro, oil etc outweighed the inefficiency that occurred due to distribution and transmission losses[ix].

Although the centralised system served well to meet out energy demand, however such a system is struggling to meet the increasing electricity demand as the society continues to develop. Some of the drawbacks of centralised system are:

Aging Equipment: There are number of components in the system that are in need for repair or replacement, the aging of equipment in power systems leads to interruption in power supply, this not only raises a concern about the grid reliability but also adds to the cost of maintenance[x].

Rural Electrification: The system also struggles to meet the demand in rural or remote areas. High capital is required to connect these areas by setting up substations and laying overhead wires. This also raises a concern about the economics in areas with little consumption. This is further amplified due to the losses that occur during transmission and distribution[xi].

Transmission and Distribution Costs: Almost 30% of the cost occurs from transmission and distribution. This huge amount of costs for transmission and distribution is due to losses such as lines losses and conversion losses [xi].

Other drawbacks of centralised system that feature fossil fuel based generation system in particular are environmental impact and efficiency as a significant amount of the energy is wasted during generation, transmission and distribution process[x].

Due to advancement in new alternative technologies, change in market polices, need of reducing GHG emissions and the reliance on fossils to meet out growing energy demand has led to exploring new possibilities to improve the energy performance of the system and the focus has shifted towards de-centralise generation. Decentralise generation system is further promoted due to the introduction of FIT and other incentives.

There are several advantages of de-centralise system as locally generated energy can[xiii] result in reduced transmission and distribution losses and lower the carbon emissions.

A lot of communities around the world have installed their own energy systems compromising of solar, wind and hydro. This helps in better management of the resources and meeting the local demand. Excess electricity produced can be sold to the grid. However, with more electricity going into grid from these decentralised renewables can affect the grid stability negatively due to harmonics, voltage and frequency variation as a lot of grid especially in the developing countries a quite weak and old.

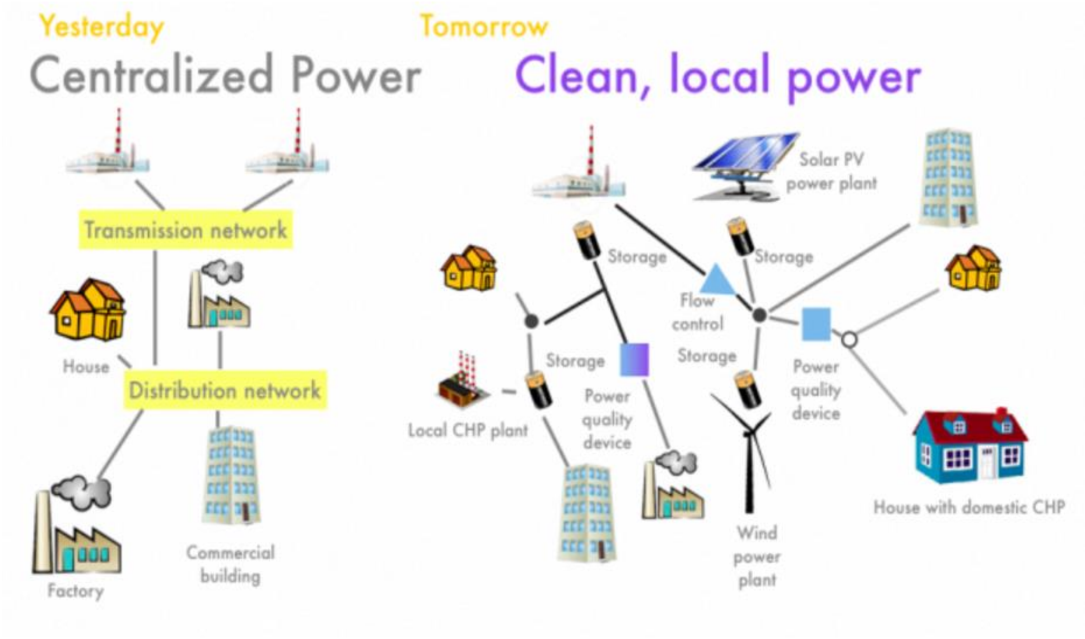


Figure 1: Centralised Generation System vs De-centralise Generation System[xiv]

Distributed Energy System

Distributed Energy System (DES) comprises of a wide range of generation sources, storage, control solutions and energy monitoring. They can be set up near the point consumption and can be tailored to meet the local demand. Given below is a picture that show different types of DES and their user applications[xv]. Various classes of DES are shown below in the figure 2 that include power generation, energy storage and distributed energy management systems.

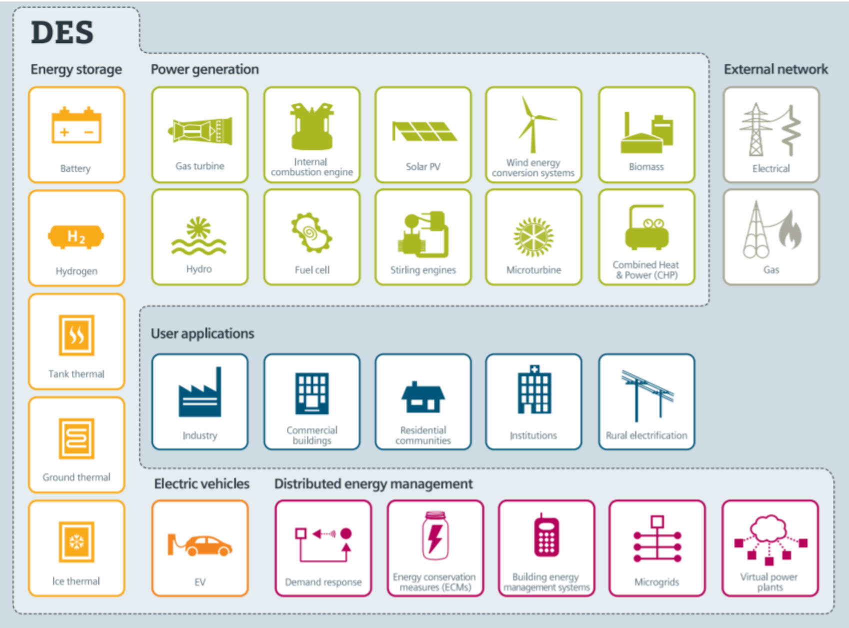


Figure 2: Various Classes of DES[xv]

DES and will play a major role in this energy transformation and help in meeting the future energy demands both economically and with reduce the GHG emissions. Also, DES technologies will help house and business owners better manage their resources and load, reduce the cost in addition to generating income from selling back to local utility and secure a reliable supply of electricity. DES will find application in rural and urban communities, industrial facilities, commercial buildings, institutions etc[xv].

Also, there are several benefits to DES[x , xv].

- There is an increased efficiency due to lower losses during transmission.
- There is far more flexibility to such as system for adding components and repairing. without disturbing the whole system.
- Improves security of energy supply and resilience.
- Reduced energy cost.
- Ensures energy for all as 17% of the world's population has no or little access to electricity and small DES systems can provide the opportunity for clean and reliable supply of electricity and improve the life quality.

Although the technology is available and has several economic, technical, social and environmental benefits but will not be solely controlled by the power companies and requires a collaboration between the utilities and customers to create a greener and a more reliable energy system[x].

1.4 Aim & Objectives

The aim of this thesis is to design and access the feasibility of PV and storage system for a residential community in Kuwait.

Objectives:

- Have a high renewable fraction, i.e. high load met from the renewable energy.
- Reducing the reliance on grid for electricity imports.
- Reducing the CO_2 emissions.
- The overall system selected must be both technically and financially feasible.

1.5 Modelling Methodology

As mentioned above the aim of the project is to develop a PV and storage system as source of electricity supply for a residential community in Kuwait. A number of steps are required to meet various objectives of the project.

1) The first step is to create an electricity demand profile for the community. Details regarding type of household selected in provided in section 2.7.
2) Climate of the selected location is assessed to study the renewable energy potential.
3) Software selection: It is important to select the right software for the project which will help in analysing the system in detail and help in aching the objective outlined. HOMER Energy Pro is selected in this case and reason for selection are given in section 2.8 and also throughout the report.
4) The location for the analysis is selected. The details regarding the location is provided in section 2.7.
5) Meteorological data is added
6) Components such as PV, inverter, storage are added and price for grid import/export and components is also set. Details regarding HOMER setup and prices are provided in section 2.9, 2.12, 3.1 and 3.3.
7) The most efficient model is selected and discussed based on emissions, renewable energy fraction, import/export, cost, area availability, tariff etc.
8) Two scenarios are considered to study the effects of certain financial and technical constraints on the system performance and final cost of running the system. These scenarios are explained in the modelling section 3.

2 Literature Review

2.1 Current Situation

Kuwait is a major exporter of oil and also one of the biggest consumers of its hydrocarbons to meet the rising electricity demand.

In 2008 Kuwait installed a 11.6GWe of electricity production unit[xvi]. Kuwait's total electricity fuel consumption was 14,000toe in 2008 representing 55% of Kuwait's total primary energy consumption[xvi].

From 2009 analysis it was estimated that Kuwait had a crude oil reserve of 104 billion barrels and 63 trillion cubic feet of natural gas reserves and in the same year oil accounted for almost 62% of its total primary energy supply. About 185 million barrels oil equivalent were used for primary energy consumption, and majority of it accounted for electrical power generation[xvi].

Electricity generation industry of Kuwait is a fully state-owned and is vertically integrated with the oil industry. It is operated by Ministry of Electricity and Water (MEW) which the sole provider of electricity and water in the country. MEW is responsible for producing, transmitting and distributing electricity. Kuwait Petroleum Corporation (KPC) provides the fuel for electricity production to MEW at no charge. Also, KPC maintains full control over the type of fuel that should be used for electricity generation since the availability of fuels is directly tied to the production and export schedules constraints resulting in MEW having limited visibility over different types of fuel available for production. This lack of control and visibility of the fuel types can be a major issue in long-term electricity production and future plant building given the challenges the country faces in meeting the current demand[xvi].

An article published in 2012 (Michael Wood and Osamah A. Alsayegh) stated that the total installed generation capacity was more than 12GW, out of which 55% included reheat steam, 20% non-reheat steam and 25% open cycle gas turbine plants[xvii].

A study conducted recently found that the installed capacity for electricity generation is barely able to meet the rising demand[xvi]. Over the past five decades electricity consumption has grown drastically from 380 million kWh to 45,234 million kWh between 1960 to 2008. Over the period between 1996 to 2008 the total electricity consumption doubled rising from 21 TWhe to 51.7 TWhe[xvi].

Peak load increased between 2006 to 2014 from 8900MW to 12719MW, with an average growth rate of 6% per year[xviii], as a result MEW is facing great challenges in meeting the growing electricity demand. First challenge faced is the large investments required to build new power plants and second is to have a rational and balanced use of electricity by taking necessary steps to reduce the amount of fossil fuel generated electricity demand[xviii].

A report published in 2012 (Michael Wood and Osamah A. Alsayegh) found, the base load was around 4500MW which accounted for about 40% of the total installed capacity. The average daily difference was about 1000MW between the maximum (3pm) and minimum load (4am), that is a difference of more than 8% of the total installed capacity. During evenings, even though the temperature drops the electric load remains the same as the afternoon due to the inefficient operation of A/C[xvii].

Kuwait is an extremely hot country with temperature exceeding 50 degrees Celsius during summer time and as it would be expected this would lead to a high electricity consumption for cooling purposes. However, the electricity demand in Kuwait is not just dependent on the weather since the weather is always extreme. An article published by Mohammad Ramadhan & Abdulhameed Hussain in “Kuwait Energy Profile for Electrical Power Generation” showed that electricity consumption also depends on several factors such as income, GDP, population etc[xix].

Some of the factors that led to drastic increase in the electricity consumption over the past decades are[xvi]:

- Growth in economic activities due to high oil revenues.
- Improvements in living standards.
- Widespread use of A/C.
- High growth rate in population due to arrival of expatriate labour. Between 2000-2009 there was 3.9% population growth per year.
- Rise in per capita consumption. Between 2000-2009 there has been an increase of 6.8% in the annual per capita consumption.
- Highly sustained, subsidised electricity prices.

The above factors lead to an accelerated rise in the electricity consumption, but electricity subsides played the major part which led to an irrational consumption and demand. Due to vast amounts of resources available electricity prices were highly subsidised. Historically, there was little gap between the cost of electricity and price of electricity, but this gap started to widen when the oil revenue started to come in. Until, 1953 the selling price of electricity was

27fils/kWh (9 cents/kWh) but with the oil revenue generated between 1953 and 1955 the selling price was decreased to 18fils/kWh (6 cents/kWh) and continued to gradually drop over the years. In 1966 Kuwait highly subsidised the electricity prices by 95% to raise public welfare and since than there has been a flat price of electricity of 2fils/kWh (0.7cents/kWh) for the residential sector. The selling price remained 2fils/kWh till date even when the cost of production in 1980 was 26fils/kWh (9 cents/kWh). In the mid 2000's the gap widened even further with the increase in oil prices in the international market and increase in LNG imports to fuel power sector. The current cost of production is 38fils/kWh (14 cents/kWh)[xx , xvi]. The prices were very low even by regional standards. Along with that there was a lack of public policy for conservation resulting in irrational consumption of electricity and waste of energy resources both in terms of efficient utilisation and allocation[xvi].

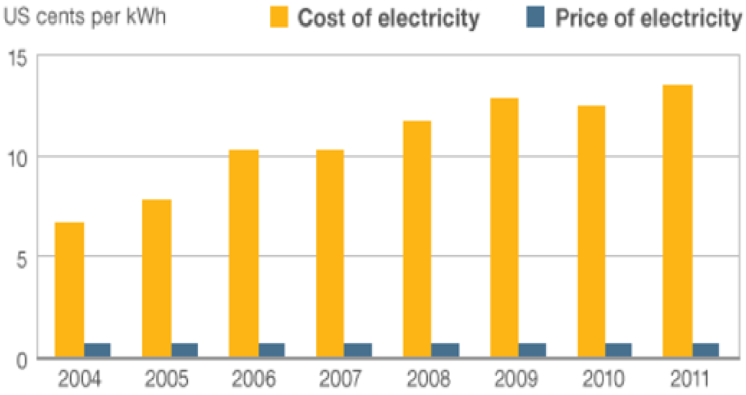
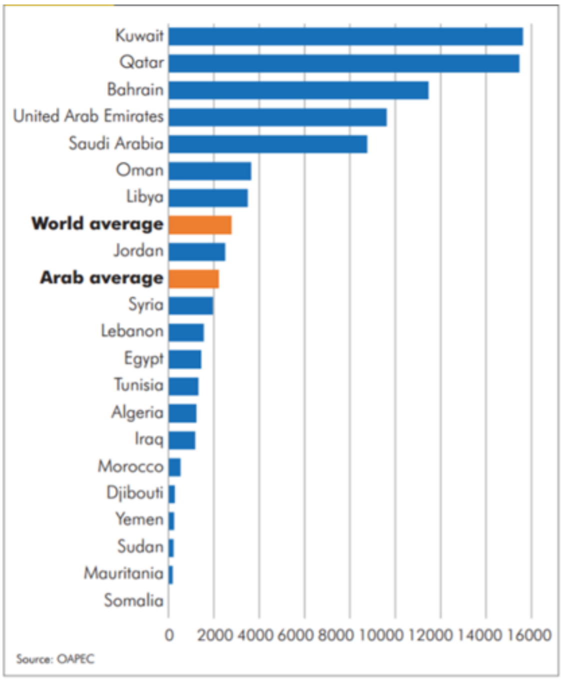


Figure 3: Gap Between the Cost and Price of Electricity in Kuwait [xx]

Kuwait has one of the highest per-capita electricity consumption in the world which is mainly due to the fact that the prices were highly subsidised. Also, majority of the electricity is produced using fossil fuels. This high reliance on fossil fuels has adverse impacts on the local environment through the emission of CO_2, Sox and NOx gases. Also, from Enerdata it was found that Kuwait has the third highest emission of CO_2 per capita (23.1 tCO_2/capita) in the world. Due to the importance oil plays in the country's economy it is in the best interest of country to investigate and explore other alternative sources of energy such as renewables for power generation. This will help the country lower their reliance on fossil fuels and prolong the expected life of its oil reserves and increase the export quality[xvi].



Source: OAPEC

Figure 4: Electricity Consumption kWh per Capita (2012)[xxi]

Until recently it was not possible to sell the idea of investing in renewable energy to decision makers in light of abundance of hydrocarbon resources[xvi]. Kuwait has always been highly dependent on oil for its electricity generation and with domestic electricity demand increasing at 6% per year and recent events such as shortages in electricity supply especially during the summer, surge of power at peak times and inability to meet the demand with the current generation capacity- with finite oil reserves and high CO_2 emission which affect the environment have convinced the government into exploring different options and diversifying the energy mix[xvii].

The authorities and Kuwait government are working on restructuring their energy policy and focusing on exploring the alternative energy options to satisfy the rising demand and considering changing the prices charged for electricity[xvi]. The country has started to invest heavily in areas of wind, nuclear and solar energy. This will not only reduce the dependency on fossil fuels but also create several white-collar jobs for Kuwaiti workforce and help achieve a low carbon economy. As one of the future goals set by the government is to reduce the CO_2 emission as well[xvi].

The main focus of Kuwait's government is meeting and reducing the electricity demand of residential sector. Residential sector in Kuwait accounts for 42.3% (figure 5) of electricity consumption. A/C in the buildings accounts for 70% of Kuwait's peak power consumption and 50% of the annual energy consumption[xviii].

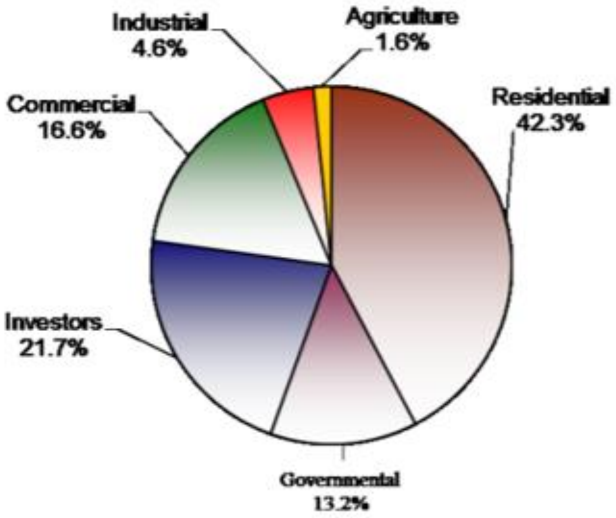


Figure 5: Distribution of Electrical Energy Consumption by end-use sectors, Kuwait [xviii]

Residential sector in Kuwait accounts for the bulk of electricity demand. Government is taking steps to reform and gradually eliminate the subsidy on the electricity. Initially raise in prices was met by strong opposition by the parliament and the bill was rejected forcing government to look into large scale awareness campaigns to control electricity demand[xvi]. The campaigns were not enough to help reduce the demand and finally electricity prices were raised for the first time in 50 years from 2fils/kWh (0.7cents/kWh) to 15fils/kWh (5cents/kWh). A 600% raise and subsidies dropping from 95% to 60% for residential sector. The new prices will be enforced from September 2017 onwards[xxii]. The government has a long-term plan of eliminating the subsidies. A study was conducted by the Oxford Institute for Energy Studies argued that Kuwait's electricity generation inadequacy was a result of highly subsidised electricity prices in the paper "Price Reform in Kuwait's Electricity and Water Sector". They developed a model to study the effect of eliminating the subsidies completely and compensating consumers with cash transfer so it doesn't affect their economic decision. Lower subsidies will force the users to consume electricity more rationally leading to a low consumption per capita in the future[xvi].

2.2 Path to RE Future

Kuwait has always been an advocate of renewable energy use in Middle-East since 1970. However, renewable energy in Kuwait is still in its nascent stages[xxiii].

Kuwait has embarked on an ambitious journey of supplying 15% (2000MW) of its energy demand from renewable energy by 2030. KISR and Kuwait Authority for Partnership Project (KAPP) are playing a major role in helping Kuwait achieve a low carbon economy. A major motivation behind Kuwait's increased interest and rapid growth in RE is the energy security and diversification of its energy system[xxiii].

Kuwait is a small country with an area of 17,820 m^2 and a population of around 4 million[xxiv] but has one of the world's highest electricity consumption per capita of 15,213kWh (2014)[xxv] and one of the highest carbon and ecological footprints.

Use of RE in Kuwait will assist the country in a transition to a low carbon economy and help in achieving a green and eco-friendly image in the world. Also, in the recent years Kuwait along with other Middle-East countries has received some of the lowest RE prices which has helped the country in further exploring the options for a large scale generation along with widespread availability of solar has strengthened its position in achieving a national energy mix[xxiii].

One of the most promising development was the start of 2GW Shagaya Renewable Energy park (Shagaya is to Kuwait as Masdar is to Abu Dhabi) in 2015 which is divided into three phases: the first phase is the construction of 70MW integrated renewable energy park (solar PV, solar thermal, wind). The second and third phase are projected to produce 93MW and 1000MW respectively. The project is estimated to cost 385 million dollars for the first phase and covers an area of 100km^2. Another one of promising projects is the construction of 280MW of Al-Abdaliyah integrated solar project[xxiii].

Figure 6: Shagaya, Kuwait [xxiii]

2.3 Pilot Projects

Kuwait has adopted aggressive steps for the development of renewables in order to achieve the objective of meeting the electricity demand, reducing its dependency on fossil to prolong its life and also cutting down the CO_2 emissions.

Kuwait's government and authorities have understood the importance of exploring different sources to diversify the energy supply especially for electricity in the residential sector.

The increase in residential electricity demand is a result of low prices along with low administered electricity system, coupled with rapid increase in income and prosperity. Variation in the temperature plays little effect on the residential electricity demand since the temperature has always been extreme in the region[xix].

Kuwait Foundation for Advancement of Sciences (KFAS) along with KISR, Kuwait's National Technology Enterprises Company (NTEC) and MEW have undertaken a pilot project to set PV cells to generate solar power in 150 houses. The PV will be able to generate electricity during peak times. The project is estimated to produce 2-3MW of power. On completion of the project 7,027 barrels of oil would be saved every year worth up to 221,000 Dinars ($ 784,718)[xxvi], [xxvii]. These units will be paid for by the government to assess the potential of solar power and measure the extent to which grid supply could be displaced. Also, through this the government's aim in providing a model for large scale initiatives and also help in implementing smart meters and develop FIT system. The FIT structure is currently being studied by the government.

KFAS also estimated 3000-4000MW of power could be produced if all the present and future buildings in Kuwait were fitted with solar power units, considering the peak demand during summer time is 13,000MW[xxvii].

Another project launched by KFAS includes installing PV solar units of 1MW capacity on two Union of Consumer Co-operative Society which will reduce a huge amount of import from the grid during peak times in the summer. The project is estimated to cost 12 million dinars (USD 40 million)[xxvii].

Another project undertaken by the KFAS was the installation of PV panels on carport of Zahara Co-op with a capacity of 752kW. The PV are estimated to generate a total of 1,273MW per year which is about KD 60,000 per year ($200,000) in monetary savings and avert at least 2000 tons of CO_2 annually[xxviii]. There are several other pilot projects being set up in Kuwait that include a 100kWp PV test platform. Also, a solar and wind to hydrogen plant that uses a 10kW PV panel and a 6kW wind turbine for the production and storage of hydrogen. These programs will help Kuwait in the energy resource assessment, allocation, development of polices and regulations. It will further help in development of RET through the assessment and evaluation of energy storage and RE for both grid tied and off grid systems[xxix].

2.4 Resource Assessment

2.4.1 Renewable Energy

In general terms, renewable energy can be defined as energy that is generated from ecological resources that are naturally replenished such as solar (solar thermal and PV), rain, wind, tidal, geothermal, biofuels and biomass. Renewable energy has proven to be a future solution in satisfying the growing energy demand around the world. Renewable sources such as solar, hydro, wind, wave, tidal and others have made a significant penetration in the global energy market[xxx].

Due to the interest in renewable sources and its applications over the previous decades have resulted in both: Cost reduction and technical advancements in terms of lifetime, efficiency, design, reliability[xxx].

The focus on this thesis will be on solar energy to generate renewable energy for Kuwait. Small pilot projects have already started in Kuwait featuring solar energy (PV in particular).

2.4.2 Solar Potential in Kuwait

The most predominant sources of renewable energy in Kuwait are in the form of wind and solar.

Since the paper focusses on solar energy it is important to assess the meteorological data to examine the feasibility of implementing the system. Previous renewable energy data of Kuwait shows that Kuwait has the potential to harness solar energy during summer times which account for peak time of the solar consumption in the year.

Long hours of sunlight per day and high solar radiation is important for solar energy generation. It is found that Kuwait has an annual sun hour of 9.2 hours daily and one of the highest solar irradiation levels in the world around 2100-2200 kW/m^2/year with an average insolation of

5.2kWh/m^2/day and diffused radiation of 1.6kW/m^2 where only 1 kW/m^2 is needed to activate the cell making Kuwait an ideal location for development of solar energy[xxiii , xxxi].

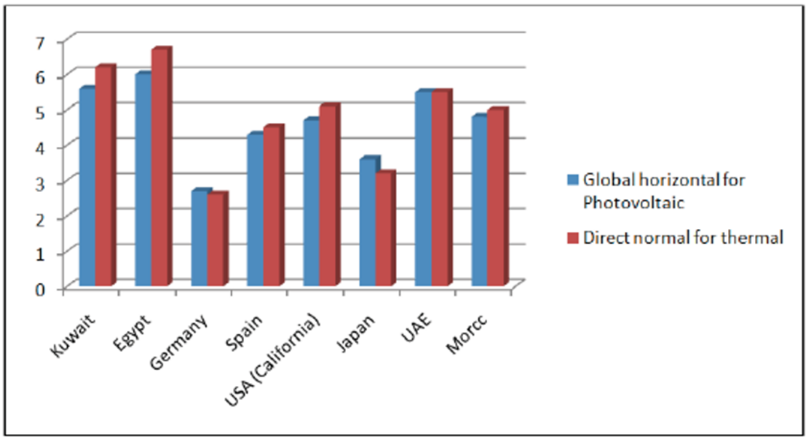


Figure 7: Global Horizontal and Direct Normal Solar Radiation [xxx]

The above figure 7 show's solar GHI and direct normal radiation for Kuwait compared to other countries.

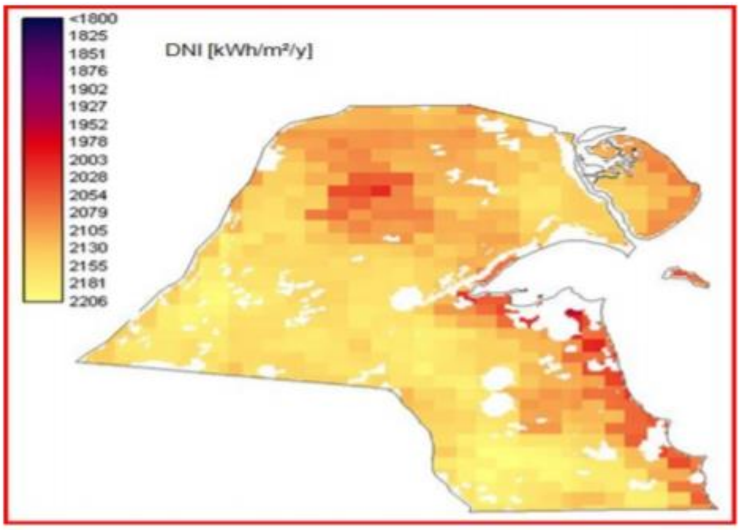


Figure 8: Solar Image Map, Kuwait [xviii]

As it can be seen from the map in figure 8 above that the yellow shaded area has the highest thermal solar radiation which covers a majority of the area showing that there are plenty of sites that are suitable for installation for solar energy[xviii].

Considering the 2 figures 7 and 8 above, highlights that Kuwait has a huge potential for utilising solar for electricity generation.

The below figure 9 and table 1 show the average monthly solar radiation and clearness index. This data was available in HOMER that uses NASA Surface Meteorology and Solar Energy data base. All the data regarding air temperature and solar GHI are monthly averaged values over a period of 22 years from 1983 to 2005.

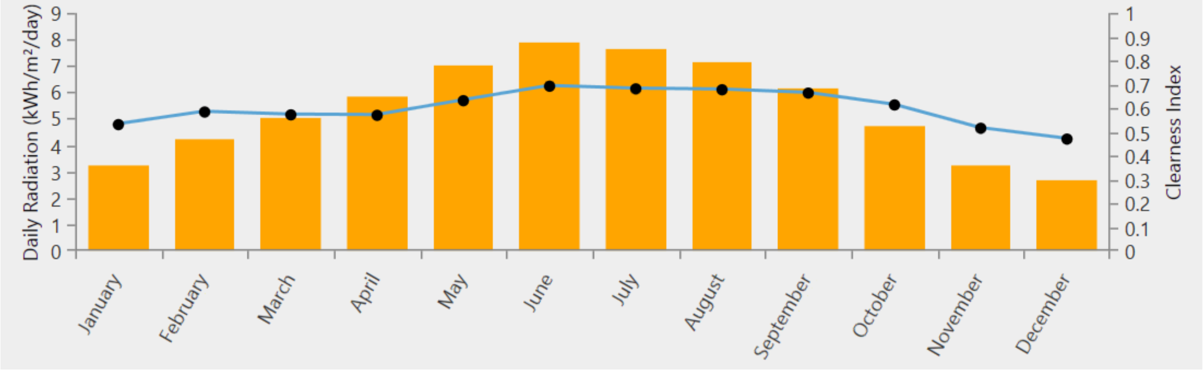
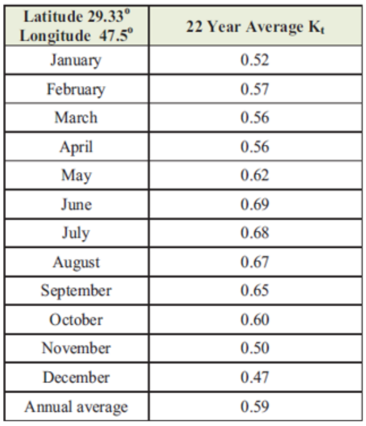


Figure 9: Solar GHI, HOMER

Month	**Clearness Index**	**Daily Radiation (kWh/m^2/day)**
January	0.531	3.200
February	0.584	4.230
March	0.572	5.050
April	0.570	5.840
May	0.631	7.010
June	0.692	7.890
July	0.681	7.640
August	0.677	7.130
September	0.663	6.160
October	0.613	4.720
November	0.515	3.240
December	0.479	2.650
Average	0.600 (recheck)	5.40

Table 1: Average Daily Radiation and Clearness Index, HOMER



Latitude 29.33° Longitude 47.5°	**22 Year Average K_t**
January	0.52
February	0.57
March	0.56
April	0.56
May	0.62
June	0.69
July	0.68
August	0.67
September	0.65
October	0.60
November	0.50
December	0.47
Annual average	0.59

Table 2: Monthly Averaged Clearness Index in Kuwait[xxx]

Table 1 shows the clearness index of Kuwait, downloaded by HOMER using NASA Surface Meteorology and Solar Energy data base and table 2 shows the clearness index from the report, “Maximum Power Point Tracking of PV Arrays in Kuwait”. From both the tables, it can be seen that the average clearness index is above 0.5, the value of 0.5 for any location indicates clear skies most days of the year[xxxi].

Kuwait has plenty of desert land that is unoccupied, a report published by Kuwait University demonstrates that 5 km^2 of area or 0.03% of Kuwait's land is adequate to generate 500MW of solar power[xxx].

VALIDATION

HOMER gives an annual average solar radiation of 5.40kWh/m2/day which is close to 5.20 kWh/m2/day as mentioned in the start of this section.

Also from table 1 and 2 it can be seen that the average monthly clearness index is similar.

2.4.3 Temperature

Form the figure 10 it can be seen that the temperature in Kuwait somedays reaches 50 degree celcius during the summer period of seven months with July being the hottest month of the year.

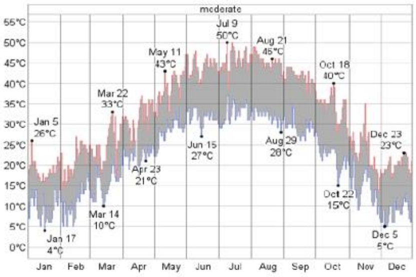


Figure 10: Temperature Variation in Kuwait[xxx]

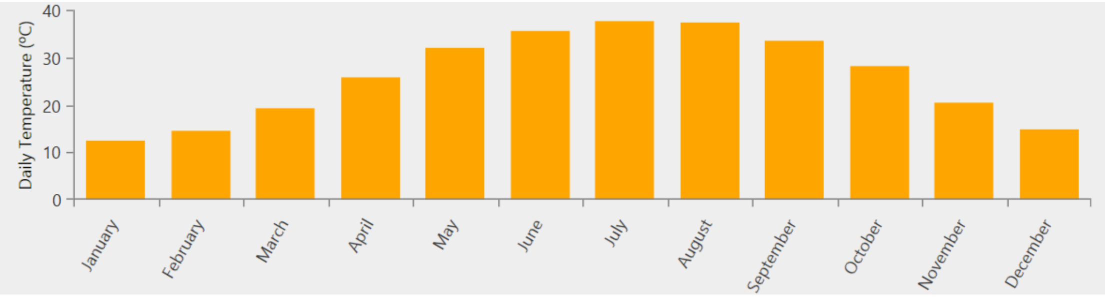
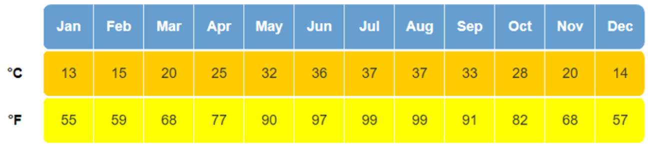


Figure 11: Average Monthly Temperature in Kuwait, HOMER

Month	Daily Temperature (ºC)
January	12.570
February	14.600
March	19.150
April	25.890
May	32.050
June	35.700
July	37.600
August	37.250
September	33.610
October	28.140
November	20.530
December	14.710

Table 3:Average Monthly Temperature in Kuwait, HOMER



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
°C	13	15	20	25	32	36	37	37	33	28	20	14
°F	55	59	68	77	90	97	99	99	91	82	68	57

Table 4:Average Monthly Temperature in Kuwait (Online)[xxxii]

VALIDATION

Table 4 show the average temperature in Kuwait on a monthly basis downloaded from internet, and table 3 or figure 11 shows the average monthly temperature in Kuwait from HOMER. Both the sources show similar average temperature values, hence the showing the reliability of data downloaded and used from HOMER.

2.5 Renewable Energy Technologies

2.5.1 PV System

A PV system generally consists of one or more solar panels that converts solar energy into electricity. It is made up of a PV module, electrical and mechanical components, electronic devices that regulate/modify the electrical output[xxx].

2.5.2 PV Arrangement

2.5.2.1 PV Cell

A PV cell is made up of a semi-conductor, usually silicon. The semi-conductor wafer has a positive side and a negative side. When the sunlight falls on the PV cell, a certain amount of energy is absorbed by the semi-conductor. This creates an electric field across the layer by knocking electrons loose and ultimately causing electricity to flow, generating direct current (DC). The direct current (DC) is converted into alternating current (AC) for use in buildings by an inverter[xxxiii].

The performance of a cell is measured by its efficiency of converting sunlight into electricity. Sunlight of certain energy is can of generate electricity, depending on how much energy is either reflected or absorbed by the material. Typically, most solar cells only have an efficiency of 15%, that is about one-sixth of the total sunlight striking the cell generating electricity[xxxiv].

2.5.2.2 PV Module

A PV cell generates a low voltage, of about 0.5V. To obtain the desired output several PV cells are connected either in parallel (higher current) or series (higher voltage). During night times, or in case of total or partial shading, reverse currents can occur which leads to power loss, overheating of the shaded cell or reduce the efficiency of the PV cell. Separate diodes are needed to avoid reverse flow[xxx].

2.5.2.3 PV Array

In certain cases, the power generated by a module is not sufficient enough to meet the demand/requirements of a home or a business. A PV array is a complete power generating unit made up of several PV modules[xxxv].

The desired voltage is achieved by connecting PV modules in series. Further, desired current is obtained by connecting these individual modules in parallel[xxx].

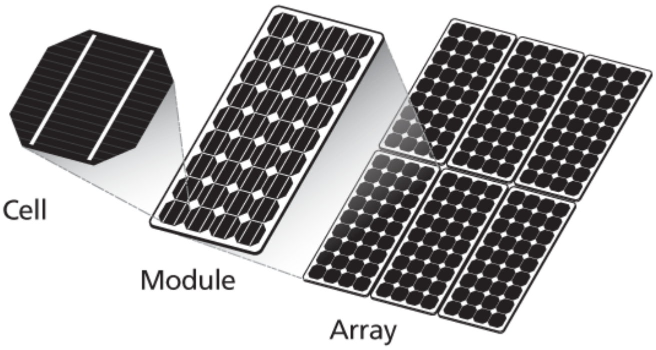


Figure 12: Three Types of PV Arrangements[xxxvi]

2.5.3 Types of PV Systems

There are two type of PV systems: Stand Alone and Grid Connected.

2.5.3.1 Stand Alone

Stand-alone PV systems or off grid PV systems are suitable for remote areas with no connection to utility grid because of high reliability and low servicing requirements. This kind of system generates and stores power independently off the grid. Although far less common the off-gird system has proven to be more cost effective than extending power lines. The electricity is generated by the PV panels and the excess electricity that is not being used is stored in the battery and used later during the day. PV output is not consistent all year long and is dependent on several factors, particularly on solar radiation. One of the biggest challenges of this system is to build system autonomy. Autonomy is required to provide a reliable supply of energy during periods of low radiation, adverse weather or unexpected increase in demand. Autonomy can either be achieved by over-sizing the PV system or battery storage, or adding a wind turbine in areas with high wind speed or other backup energy system such as a generator[xxxvii , xxx]. A block diagram of a stand-alone PV system can be seen below in figure 13.

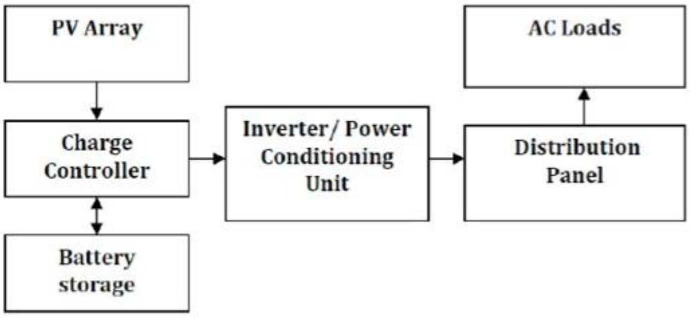


Figure 13: Blocked Diagram of a Stand-Alone PV System[xxx]

The main components of an off-grid PV system include an inverter that converts DC power to AC power, and also a charge controller that monitors the charge/discharge process of the battery in order to enhance the battery lifetime and performance[xxx].

2.5.3.2 Grid Connected

A grid connected PV is makes use of the existing electricity grid. They are simple in design and easier to install than a standalone PV system. The electricity is generated during day time and is either utilised on site or sold to the utility company. This type of system usually doesn’t require battery storage since at night time or when the PV output is lower than demand, electricity is imported from the grid. Although not required but some grid connected PV systems may have a storage system and can decide whether to sell excess electricity or store it. Also because of lower prices and technological advancement, there has been an increase in grid connected PV installation both in residential and commercial buildings. Grid connected PV systems can vary in size from rooftop panels on residential or commercial buildings to large arrays of PV modules that work as a generating station[xxx, xxxvii].

A block diagram of a typical Grid connected PV is shown below in figure 14 The most common components of a grid connected PV systems are: an inverter to convert DC power to AC power, a controller to adjust voltage and frequency deviations, metering device that measure the amount of power fed back to the grid or imported from the grid[xxx].

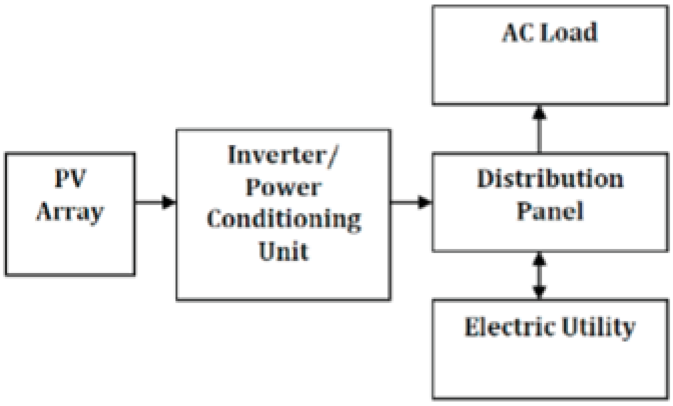


Figure 14: Block Diagram of a Grid-Tied PV System[xxx]

2.5.4 Characteristics of PV

Efficiency

It is expressed in percentage and is the ratio of maximum electrical power output to the radiation power input to the cell[xxxviii].

Effect of temperature

Performance of a PV cell is temperature dependent. The band gap of the semi-conductor decreases with an increase in temperature This decrease in band gap lead to increase in energy of the electrons hence lower energy is needed to break the bond. Open circuit voltage is affected mostly due to the increase in temperature as can be seen from the figure 15 below[xxxix].

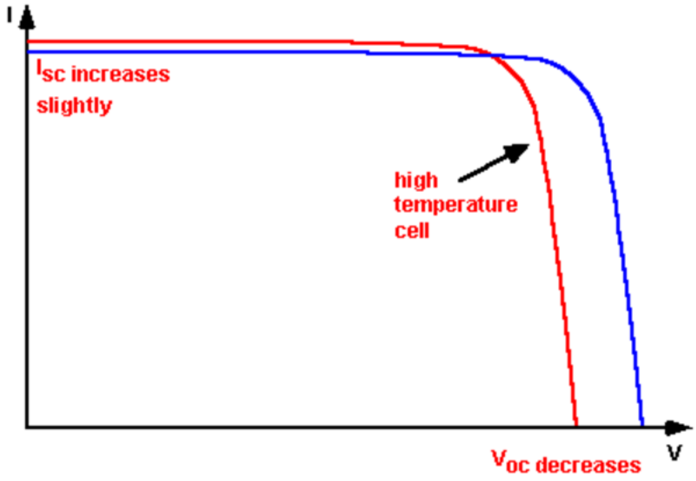


Figure 15: The Effect of Temperature on the IV Characteristics of a Solar Cell[xxxix]

From the above figure 15 it can be seen that with the increase in temperature the voltage decreases while the current increases. The efficiency of solar panels decreases with increase in temperature and reduces the PV output by 10%-25% depending on the installed location[xl].

To explain how the efficiency of the PV panel decrease with increase in temperature we use "Temperature Coefficient (pMax)". pMax can be found on the manufacturer manual and has a negative percentage, this explains the effect of temperature on the panel. Normally the PV panel is tested at 25°C. If the temperature coefficient is stated at -0.5%, it means that for every 1degree celsius increase in temperature the maximum power will decrease by 0.5%[xli].

2.6 Energy Storage

2.6.1 Classification of EES Systems

Sources of energy such as solar and wind have a huge potential to reduce our dependency on fossil fuels and reduce GHG emissions. However, wind and solar are intermittent sources of energy, and this variability of sources leads to reliability issues. Since the wind resource or solar resources may not be available all year long and also being site specific, there is an increased need for installing electrical energy storage with the RES to ensure reliability of the system. However, the installation of Electrical Energy Storage (EES) is also highly dependent on the economics and therefore it is important to take into consideration both economic and technical aspects and the impact on storage on the RES. Adding an EES to the RES although has several benefits, one of them being: it increases the renewable energy penetration in the system. However, it is important to consider the role of EES in relation to the overall electric system needs. This section deals with various EES available in the market[xlii].

Figure 16 shows the most common types of electrical storage systems: chemical, electrical, mechanical, electrochemical and thermal energy storage systems.

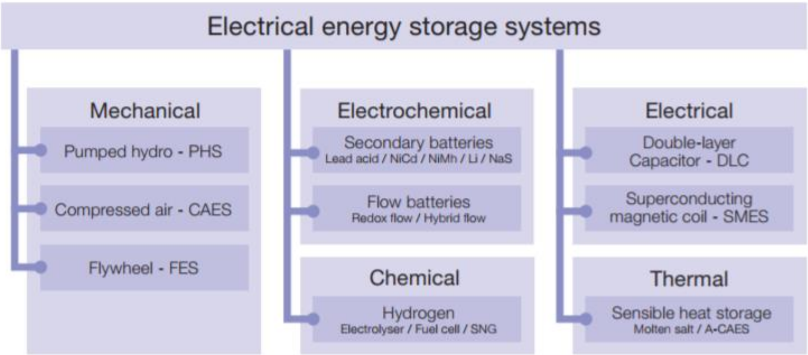


Figure 16: Classification of Electrical Energy Storage Systems According to Energy Form [xliii]

For this thesis only mechanical and electrochemical batteries will be considered.

Mechanical Batteries

2.6.1.2 Pumped Hydro Storage (PHS)

PHS uses two water reservoirs which are situated at different elevation levels. Water is pumped from the lower reservoir to the upper reservoir and the energy is stored in the form of gravitational potential energy. Water is pumped to the upper reservoir during off peak hours. During peak hours water flows back into the lower reservoir through a turbine and generator producing electricity[xliv].

PHS have an installed capacity of 120GW and represents almost 99% of the total installed electrical storage capacity. PHS system has a long lifetime, an efficiency between 70% to 85%, and practically unlimited cycle stability of installation. However, there are some drawbacks, the installation of PHS is dependent on specific topographical conditions and uses a large land area. Also, the cost of installation is not easy to estimate and are highly site specific[xliii].

Pumped Hydro Storage has a reaction time anywhere between few seconds to couple of minutes. They are principally used for large scale grid applications due to low energy density[xliv]. One of the key application of PHS is for energy management via time shift[xliii].

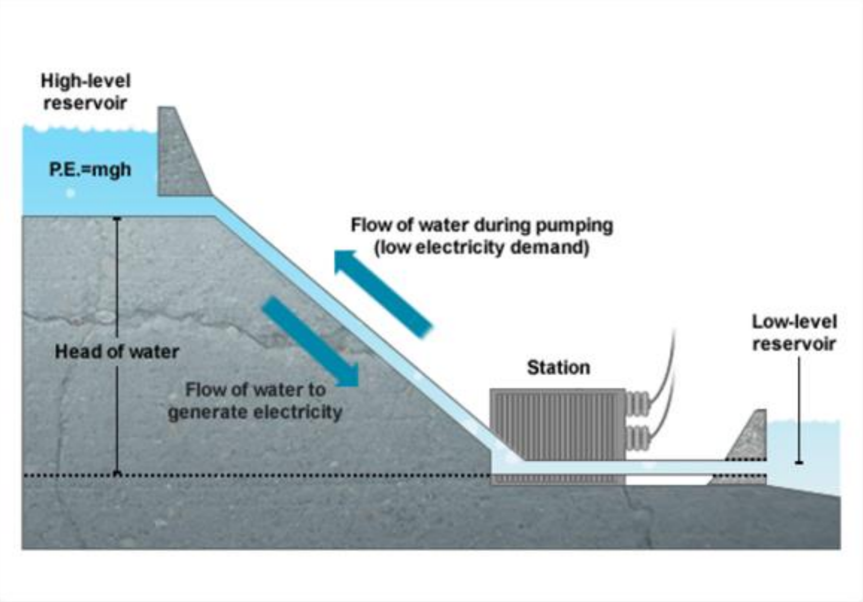


Figure 17: Illustration of Pumped Hydro Principle [xliv]

Summary of Characteristic of PHS can be found in appendix section A.

2.6.1.2 Compressed Air Energy Storage (CAES)

CAES is quite similar to the PHS in with regards to output, storage capacity and applications. However, the main difference is that instead of water being pumped up or down the two reservoirs in PHS, during low demand ambient air is compressed and stored under pressure in an underground cavern in a CAES. During high demand, the pressurised air is heated and expanded in an expansion turbine driving a generator to produce electricity. One major issue is the low round trip efficiency in the CAES, which can be less than 50% because of a process known as diabatic CAES[xliii]. Also, the system installation is site specific. There are several advantages of using a CAES system; the capital expenditure and operation expenditure are quite cost competitive, they are widely used in balancing energy and have large capacities[xlv, xliii].

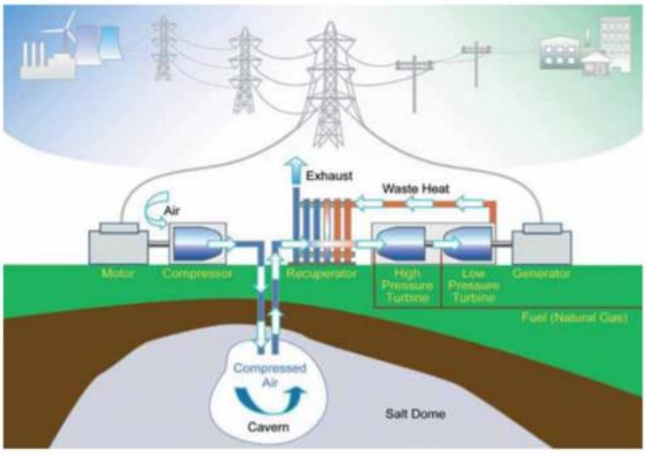


Figure 18: Underground CAES[xliii]

2.6.1.3 Flywheel Energy Storage (FES)

FES batteries also known as flywheel battery are a type of mechanical battery that stores energy in form of kinetic energy. When electricity is applied to the flywheel, the rotational speed increases allowing for more electricity to be stored. Electricity can be drawn by reducing the rotational speed of the flywheel. By maintaining a constant speed of the rotating body, the energy stored is maintained in the flywheel. There are several advantages of using FES; low maintenance, long life, high power density, 100% Depth of Discharge (DOD) and negligible environmental impacts. The major drawback of the technology is high self-discharge rate[xlvi, xliii].

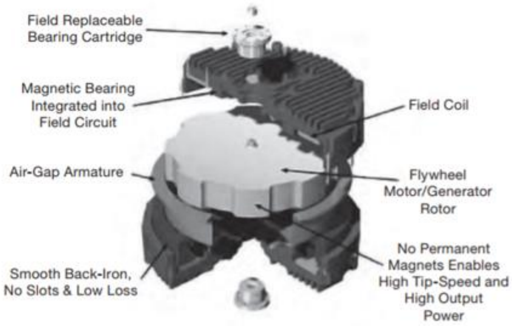


Figure 19: Flywheel Energy Storage [xliii]

Electrochemical Batteries

There are two major classification of electrochemical batteries: secondary battery and flow batteries. Most of the electrochemical batteries are quite mature and are widely used.

Secondary batteries: Lead Acid, Lithium Ion, Nickel cadmium and nickel metal hydride battery, sodium sulphur, sodium nickel chloride and Metal air battery.

Flow Batteries: Redox Flow Battery and Hybrid Flow Battery.

However, this section will only cover Lead acid, Lithium Ion and Flow batteries.

2.6.1.5 Lead Acid Battery

Lead acid batteries have been used commercially since the 1890s. They are applicable in both mobile as well as stationary systems. They are widely used as emergency power supply systems, stand-alone system coupled with PV, mitigation of output fluctuation from RE such as wind, and starter batteries in vehicles. Lead acid batteries were widely used as storage purpose in grids between 1910 to 1945[xliii].

Lead acid batteries are the most well researched storage device and available at low cost. A typical lead acid battery has a lifetime of 6 to 15 years with a cycle life of about 1500 cycles at a DOD of 80%, and have a cycle efficiency between 80% to 90%. They have a moderate cost/performance ratio and are easy to recycle. However, there are a few drawbacks to this technology: they discharge only 50% to 70% of the rated capacity, have low energy density, and are not environmentally friendly due to the use of lead, which is a hazardous material[xliii].

2.6.1.6 Lithium Ion Battery

Lithium ion batteries are widely used as a storage technology in portable equipment and Mobile applications. There are several advantages of using a Lithium Ion (Li-ion) battery due to low maintenance, low self-discharge rate compared to nickel- cadmium, high energy density and very high efficiency of 95%-98%[xliii]. Despite many advantages and its application in wide range of areas, there are still significant drawbacks to this technology. Li-ion batteries are fragile and require special protection circuit for safe operation, and are very expensive. Another issue with the Li-ion battery is that they require a storage temperature of 15°C[xlvii] because they are thermally unstable and may decompose at high temperature, releasing oxygen which can ultimately lead to thermal runaway[xliii].

There are still challenges to large scale development of these batteries but Li-ion battery is still in developing stages and research is being carried out to enhance the performance of the battery: such as lifetime, safety and ability to perform at elevated temperature. With the reduction of cost in future Li-ion batteries will find its application in various storage areas [xliii, xlvii].

Flow Battery

Flow batteries are also rechargeable batteries, but unlike secondary batteries where energy is charged and discharged in electrodes, in flow batteries energy is stored in chemical species that are dissolved in electrolyte and usually separated by a membrane[xlviii]. Originally it was designed by NASA as an electrical energy storage for long-term space flight but due to advancement in technology theses are gaining popularity in a wide range of stationary applications for storing several MW of power for hours and days[xliii].

There are two types of Flow Batteries Redox Flow Battery (REB) and Hybrid Flow Batteries, but we will focus on REB, in particularly Vanadium Redox Flow Battery since these are used in the HOMER modelling.

2.6.1.7 Vanadium Redox Flow Battery (VRB)

Unlike other redox flow batteries (REBs) which stores energy in two different tanks that are separated from the cell stack and have various chemistries with different elements such as iron/chromium and zinc/bromide, in VRB there is only one element in both the tanks, vanadium. Using only vanadium has a major advantage, since vanadium has the ability to exit in several states it overcomes the problem of cross-contamination degradation which is a major issue with REBs that use two different element[xlix]. Sulphuric acid is used as an electrolyte. Also in REB, the tanks can be sized according to the application which makes it easier to scale up the energy capacity than other traditional sealed batteries[xlix].

There are several advantages of using a VRB: higher cell voltage, energy density can be increased by increasing the concentration of vanadium[l], offers high energy efficiency, long cycle life (> 5000 deep cycles), low self-discharge rate, can store energy up to several MW, and because of no toxic or hazardous substances used, it makes them safer and environmentally friendlier[xlix].

However, there are certain drawbacks to this technology; crossing of metal ions cannot be completely avoided over the membrane (this results in loss of energy), membranes are subjected to fouling, have small operating temperature window, and due to the presence of highly acidic and oxidative condition they require expensive polymer which adds to the cost making it less economical[xlix].

Due to their large capacities, they are finding use in large power plants that have a high penetration of RE such as solar and wind to average out the production and levelling out supply/demand [lxxxi]. Also, because of their ability to completely discharge (0%) makes them suitable for solar and storage application[li].

Due to its immense potential in large scale applications research is being carried to prevent ion-exchange, develop lower cost membrane and lower the overall cost of the system.

2.6.2 Applications of Energy Storage

There are several criteria that need to be considered before selecting an energy storage system to improve both the technical and economical performance. Before we discuss the criteria for selecting energy storage is it is important to learn areas where energy storage has been successfully installed. Given below (figure 20) is a diagram that illustrates the application of energy storage.

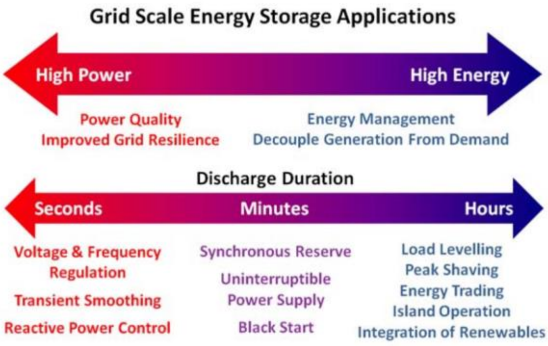


Figure 20: Energy Storage Applications [lii]

The above figure 20 can be further elaborated and the requirements are laid out as shown in the figure 21 below. The voltages specified in the figure 21 below are based on UK electricity grid and vary from country to country depending on the national network. However, this is just to explain the various application and requirements of ESS in grids[lii].

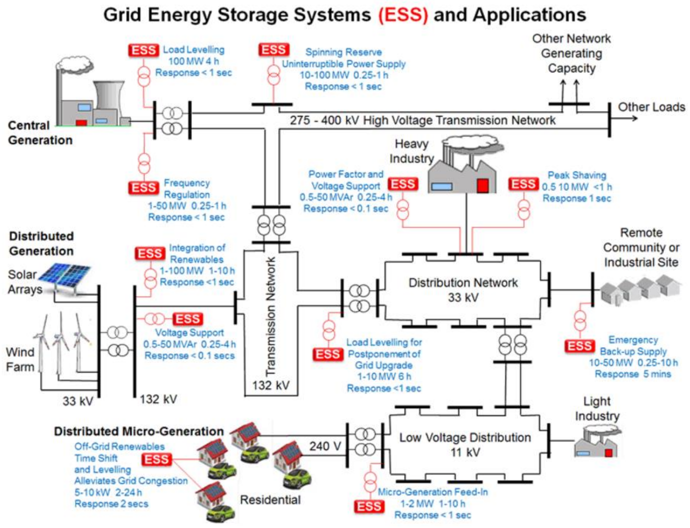


Figure 21: Application of Energy Storage and Requirements (For a Typical UK Electricity Grid) [lii]

As mentioned above, energy storage has its application in various grid tasks. Given below in figure 22 is chart that shows the type of battery used in performing three main grid tasks: UPS, T&D Grid Support and Energy Management. The characteristics and suitability of energy storage is expressed in terms of discharge time and power rating[lii]. Further figure 23 shows the uses of EES in grid based on duration and frequency.

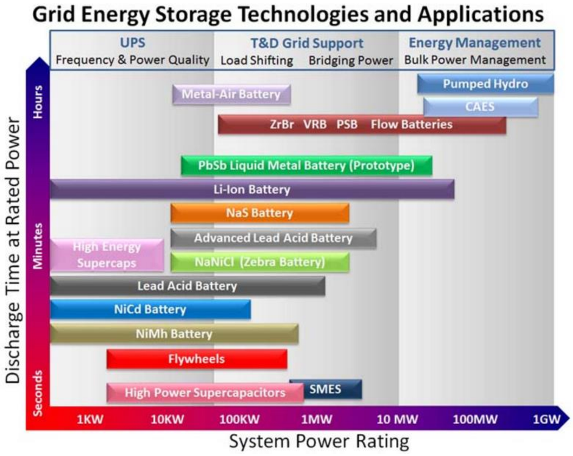


Figure 22: Application of Energy Storage for Various Tasks and Properties [lii]

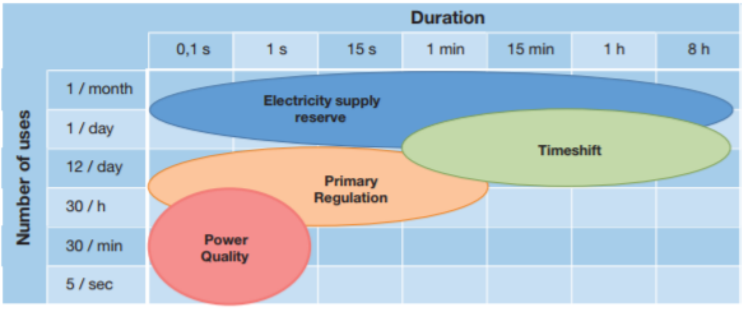


Figure 23: Use of EES based on duration and duration [xliii]

The table below 5 summaries all the key notes for the storage technologies and applicaions mentioned in section 2.6.1 and 2.6.2.

Energy Storage Type	Advantages[lii]	Disadvantages[lii]	Application[lii]	Efficiency[liii]
Lithium Ion Battery	High energy densities Good cycle life High charge/discharge efficiency Low Maintenance Low self-discharge	Expensive Thermally Unstable Intolerance to long duration deep discharges	Power quality Frequency regulation Bulk storage	80%-90%
Lead Acid Battery	Mature technology Cheap Moderate battery life High recycled content	Limited DOD Low energy density Large footprint High maintenance	Load levelling and regulation Spinning reserve Grid stabilisation Island grid	50%-95%
Redox Flow Battery	High energy storage capacity Long cycle life High cell voltage High DOD	Immature technology Complicated design Lower energy density Low charge/discharge efficiencies	Ramping Peak Shaving Time Shifting Frequency regulation Power quality Bulk storage	65%-75%
Flywheel	Proven potential for utility scale application Long cycle life	Rotor tensile strength limitations Limited energy storage time	Load levelling Frequency regulation	80%-90%

	High peak power Rapid response Low Maintenance High Power Density Negligible environmental impact	High frictional losses High self-discharge rate	Peak shaving and off-peak storage Transient stability	
PHS	Mature technology Large Capacity Effective cycle cost Long lifetime	Geographically limited Environmental impacts High overall project capital cost Poor round trip efficiency	Energy management Backup and seasonal reserves Regulation service also available through variable speed pumps Bulk storage	75%-80%
CAES	Better ramp rates than gas turbine plants Established technology	Geographically limited Environmental impact Low round trip conversion efficiency Slower response time than flywheels or batteries	Energy management Backup and seasonal reserves Renewable integration Bulk storage	65%-75%

Table 5: Summary of the Energy Storage Technologies

After considering applications, advantages and disadvantages of various energy storage technologies it was concluded that PHS and CAES storage systems were not feasible in Kuwait due to the geographical conditions. Flywheel technology was not considered due to its limited storage time, high frictional losses and high self-discharge rate.

2.6.3 Characteristics of Batteries

The most common characteristics used to advertise batteries are long life, deep cycle, fast charge, high energy etc. Performance of a battery is not just limited to these or the battery design. The performance of the battery is dependent on the environmental conditions that it operates under. This section outlines the key characteristics of batteries that need to be taken into consideration and how they are affected with varying operation conditions[lix].

Type and Chemistry

There are two types of batteries that are available in the market: Primary battery and Secondary battery.

Primary battery, also known as dry cells. These are not easily rechargeable and are disposed of after being discharged[liv].

Secondary batteries are rechargeable batteries and can be recharged by applying a reverse current since the electrochemical reaction is reversible. These types of batteries are commonly used as energy storage device due to their high-power density and high discharge rate[lv]. The most common battery chemistries are lithium, nickel and lead.

Temperature Dependence

Battery performance can be severely affected by the temperature. This is based on the theories of kinetics. The electrolyte may freeze at lower temperature resulting in lower voltage with increasing discharge. On the other hand, chemicals may decompose at higher temperature or result in reduced battery capacity due to unwanted reversible reactions[lvi].

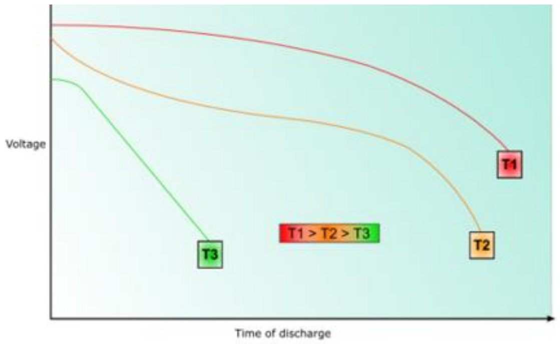


Figure 24: The Effect of Temperature on Battery Technology [lvi]

Depth of Discharge (DOD) (%)

It is the percentage of battery capacity that has been discharged[lvii].

State of Charge, (SOC) (%)

It is the expressed in percentage and represents the current state of battery capacity (0%=Empty, 100% is fully charged)[lvii].

CycleLife

It is the number of charge/discharge cycles that can be completed before the battery fails. Cycle life if dependent on several factors such as rate and depth of discharge, humidity, temperature and DOD. Cycle life of a battery decreases with higher DOD[lvii].

Specific energy (Wh/kg)

Specific energy density is used to define the capacity of the battery. It is calculated as the product of specific capacity and operating voltage in one full discharge cycle[lvi].

Power Density (W/L)

It is the maximum power that can be drawn per unit volume [lvi].

Self-Discharge

It is a determination of "shelf life". It defines at what rate would a battery lose its energy while sitting on a shelf due to unwanted internal chemical reactions, ultimately reducing the stored charge of the battery. It is dependent on the temperature and the chemistry of the battery[lviii]. Lead Acid battery have a self-discharge rate of 4%-6% per month and Li-ion of about 2%-3% per month[lix].

2.7 Location Selection

Kuwait is a small country with a total area of 17,820 km^2. As it can be seen from the below figure 25, majority of Kuwait's population is situated on the east side of the country shown in red circle.

Figure 25: Map of Kuwait (Goole Maps)

A better representation of the red circled area is given in figure 26 below.

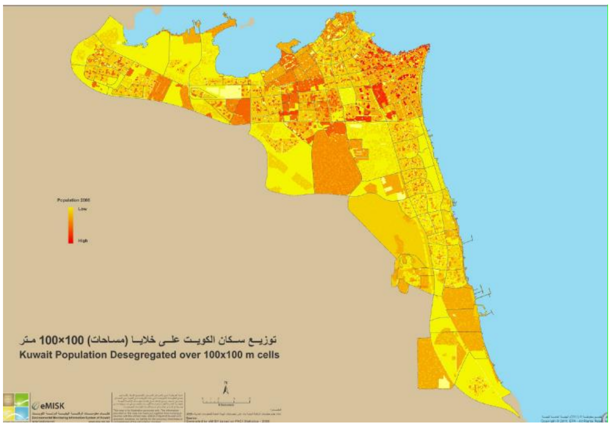


Figure 26: Population Density, Kuwait[lx]

For this thesis, the area selected was Abdullah Al Mubarak Al Sabah, Block 2, 48 households were studied to understand the electricity consumption pattern and create the demand profile and find the optimum solar PV and storage system as source of electricity supply for these households. The household type selected for this project are apartments. This is because no data regarding the electricity consumption pattern was available online that could be used for HOMER modelling. Therefore, it was important to conduct a demand survey and I was able to get in touch with the residents of the building and they provided me with the necessary data. The method used for collecting data is explained in the section 2.10. According to the national housing authority Kuwait, more than 50% of the housing units are apartments. Other housing units include traditional dwellings, villas, annexes, shacks and other marginal dwellings[lxi]. The modelling used in thesis is not limited to the apartments, these were selected to conduct the HOMER modelling due to the availability of data. The model can be applied to other housing types as well.

The block 2 is circled in red in the figure 27 below.

Figure 27: Community Under Study (Red) and Unoccupied Area (Blue) (Google Maps)

Another reason for the selection of this area is because of large amount of unoccupied area. The area circled with blue in the above figure 27 is about 14km^2 as found out using WebPlotDigitizer.

Another reason for the installion of PV in this area is because its not listed as a protected area, seen from the figure 28 below.

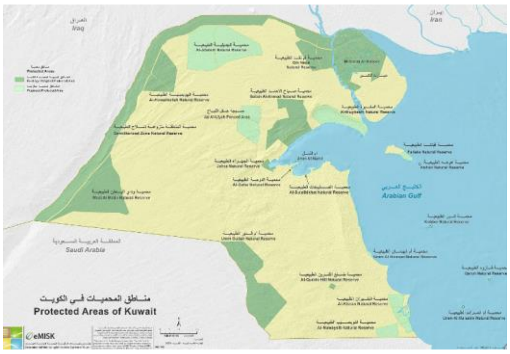


Figure 28: Protected Area Kuwait [lxii]

2.8 HOMER Capabilities

HOMER is a microgrid optimization software used by many professionals; engineers and researchers for designing and analysing both grid connected and off grid power systems[lxiii].

HOMER provides the user with option of various components that can be selected based on the requirement of the project such as wind turbines, Solar PV, biomass, hydro, storage system etc. Although HOMER has built in demand profiles for various sectors such as residential, commercial, industrial and community it allows for importing of self-constructed load profiles. Also, HOMER provides reliable resource data (wind, solar, temperature) as it's downloaded from NASA Surface Meteorology and Solar Data Base.

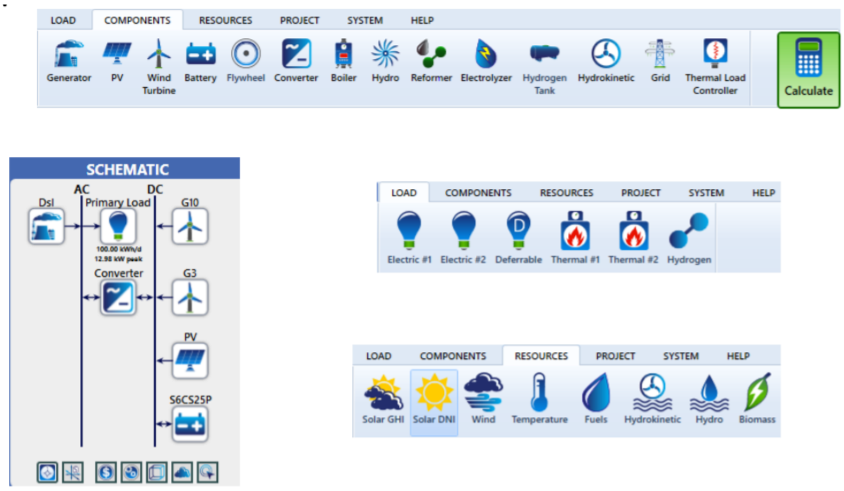


Figure 29: User Inputs, HOMER [lxiv]

The software's takes into account various inputs such as load, equipment price, equipment performance, resources, grid purchase prices, sellback price to give the most cost-effective system by analysing several systems in minutes. Below is a HOMER analysis layer[lxiv]:

- Sensitivity Analysis- Uncertain inputs such as prices, weather, loads
- Optimisation-LCOE, resilience, maximum renewables and reliability.
- Simulation- Time varying loads and resources require chronological analysis for the entire year.

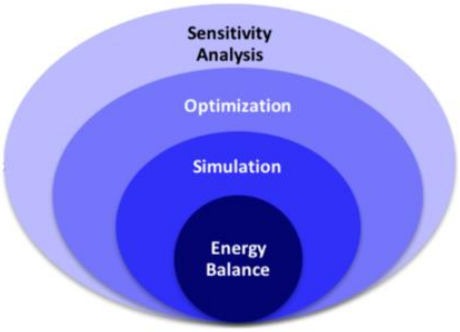


Figure 30: HOMER Analysis Layers [lxiv]

HOMER take into account both the engineering and economics aspects of the system to give the best configuration[lxiv].

It also provides detailed, simulations results, chronological simulations and allows economic comparisons of different systems.[lxiv]


Simulation Results

System Architecture: PV (2 kW) Diesel (15 kW) Converter (7 kW)
Generic 10kW (1) Surrette 6CS25P (12 strings) Cycle Charging

Total NPC: $211,555.00
Levelized COE: $0.4112
Operating Cost: $9,326.70

Production	kWh/yr	%
PV	3,235	6.67
Diesel	21,689	44.70
Generic 10kW	23,593	48.63
Total	48,516	100.00

Consumption	kWh/yr	%
AC Primary Load	36,500	100.00
DC Primary Load	0	0.00
Total	36,500	100.00

Quantity	kWh/yr	%
Excess Electricity	6,389.3	13.2
Unmet Electric Load	0.0	0.0
Capacity Shortage	0.0	0.0

Quantity	Value
Renewable Fraction	40.6
Max. Renew. Penetration	1,599.8

Return on investment (%)	12.2
Internal rate of return (%)	12.0
Simple payback (yr)	6.81
Discounted payback (yr)	8.64

Figure 31:Simulation Results ,HOMER lxiv

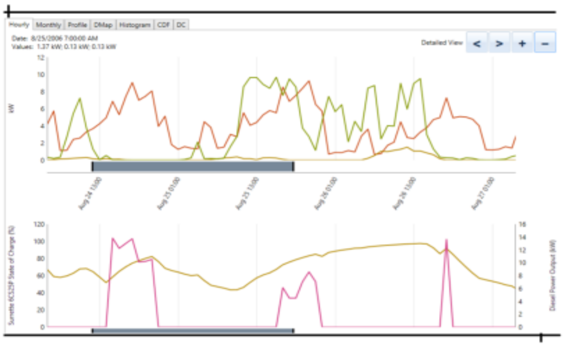


Figure 32: Chronological Simulation, HOMER[lxiv]

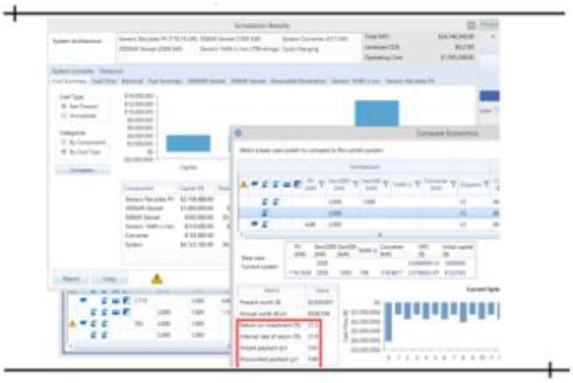


Figure 33: Compare Economics, HOMER [lxiv]

Other software’s that could have been used is MERIT which is a renewable energy planning tool that deals with supply/demand matching[lxv]. Alternatively, RETScreen which is a clean energy management software could be used. Both are hybrid renewable energy modelling tools. RETScreen is used by professionals to assess the technical viability of the project and to identify in early stage if the project is financially viable[lxvi]. However, these were not selected since it provided with only basic technical and financial analysis whereas HOMER allows for various detailed sensitivity analysis and modelling to achieve the desired results.

2.9 HOMER Setup

2.9.1 Components

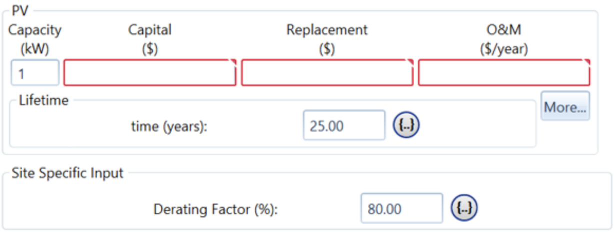
2.9.1.1 PV

A generic PV model was selected for HOMER modelling with an efficiency of 13%. There are various types of solar panels in the market. Apart from simple flat PV panels, there are concentrated PV cells (SVP and HCVP) or PV panels with solar tracker. For this thesis, it was decided to use a flat PV panel because of simplicity of its design and also these are well researched and established technology.

For the modelling of PV system in HOMER various inputs required, but the most import ones are cost, lifetime of PV and derating factor.

The time and derating factor was set at default value. The cost is divided further into capital cost, replacement cost and O&M cost. The capital cost includes the cost of PV panels, wiring installation, mounting hardware, tracking system, control system (MPPT)[lxvii].

The cost for PV used are given in section 3.1 and 3.3.


PV

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1			

Lifetime

time (years): 25.00

Site Specific Input

Derating Factor (%): 80.00

Figure 34: PV Setup Window

HOMER calculates the PV array output using the following equation:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right]$$

Equation 1: PV Array Output Equation [lxvii]

Where, [lxvii]

Y_{PV}= Rated PV array capacity [kW]

f_{PV}= PV derating factor [%]

$\bar{G}_T$= Sokar radiation incident in the PV array [kW/m2]

$\bar{G}_{T,STC}$= incident radiation at standard test conditions [1 kW/m2]

α_P= Temperature coefficient [%/^{o}C]

T_c= PV cell temperature in current time step [^{o}C]

$T_{c,STC}$= Cell temperature of PV under standard test conditions [25^{o}C]

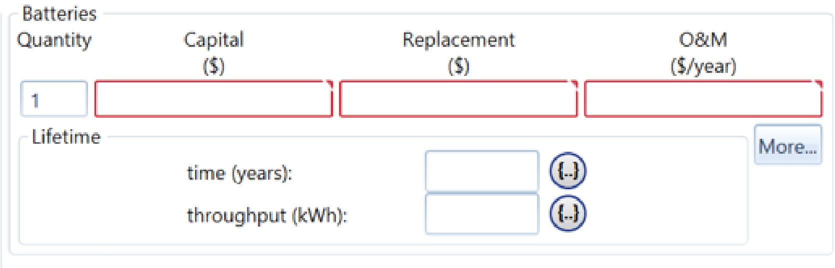
The equation was simplified further, since it was decided to not include the effect of temperature on PV array in for this thesis, setting a value of zero for temperature coefficient of power. The new equation used by HOMER to calculate the PV array output is:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right)$$

Equation 2: Simplified PV Array Output Equation [lxvii]

2.9.1.2 Battery

Five different types of batteries are used in this project. These batteries were selected from HOMER library. Most of the information regarding the battery were already available in the HOMER data base such as lifetime throughput float life, efficiency, SOC and voltage. These were provided by the manufacturers. The only changes made were to the cost of battery.



Quantity: 1

time (years):

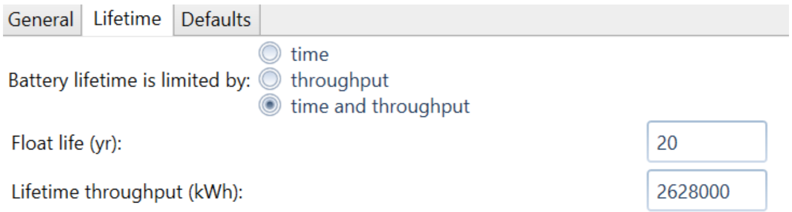
throughput (kWh):

Figure 35: Battery Setup Window

The capital cost of battery includes the initial purchase price of the battery and installation cost. The cost set for all the battery types is provided in section 2.12.

Further the lifetime of the battery in HOMER is determined by two parameters: Float time (years) and Lifetime throughput (kWh). Depending on the available data either one or both can be selected to limit the battery life. Selecting [lxviii]:

- Float time means the energy storage unit selected will need replacement after the length of time specified.
- Lifetime throughput means that the storage unit selected will need replacement after the specified amount of energy cycles through it.
- Float life and lifetime throughput means that that the storage unit selected will need replacement when either one of the values is reached first.



Battery lifetime is limited by: ○ time ○ throughput ● time and throughput

Float life (yr): 20

Lifetime throughput (kWh): 2628000

Figure 36: HOMER Lifetime Specification Battery Window

For Gildemeister 30kW-100kWh CELLCUBE® FB 30-100, redT 20kW-300kWh Energy Storage and Discover 2VRE-6200TF-U both float life and lifetime throughput were used, whereas for Gildemeister 250kW-4hr CELLCUBE® FB 250-1000 and Tesla 13.5kWh Powerwall 2.0 only float life was used. This is because of the availability of data from both HOMER library and manufacturers website.

Furthermore, there are two kinds of batteries available in HOMER: Idealized Storage Model and Kinetic Battery Model.

Idealized Storage Model

Is a simple energy storage model that allows independent sizing of energy and power. Also, a flat discharge cycle is assumed in this model[lxix].

Kinetic Battery Model

Is a more complicated energy storage model and has two-tanks. The first tank represents the available energy that is accessible for direct current conversion and the second tank represents the bound energy which is not easily available for use. A representation of the model is given below in figure 37[lxx].

Figure 37: Kinetic Battery Model [lxx]

2.9.2 Resources

2.9.2.1 Solar GHI

The output for flat PV array is calculated using global horizontal irradiation (GHI). HOMER calculates GHI as [lxvii]:

$$GHI = Beam\ radiation\ (DNI) + Diffuse\ Irradiance + \ Ground\ reflected\ radiation$$

2.9.2.2 Clearness Index

Clearness index is used to define the clearness of the atmosphere. It is the fraction of solar radiation that makes it through the atmosphere and strikes the surface of the earth. It has can have a value between 0 to 1. The value is higher (example 0.75) under clear and sunny conditions and low (example 0.25) during cloudy condition[lxvii].

The clearness index is calculated by HOMER using the following equation:

$$K_T = \frac{H_{ave}}{H_{o,ave}}$$

Equation 3: Clearness Index Equation [lxvii]

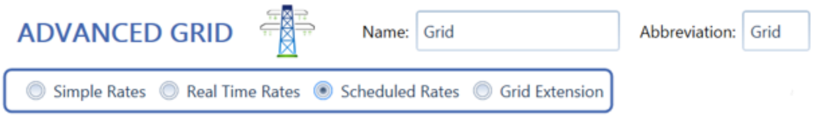
Where,[lxvii]

k_t=Clearness index

H_{ave} = is the monthly average radiation on the horizontal surface of the earth [kWh/m^2/day]

$H_{o,ave}$ = is the extraterrestrial horizontal radiation (radiation on a horizontal surface at top of earth's atmosphere) [kWh/m2/day]

2.9.3 Grid


ADVANCED GRID

Name: Grid

Abbreviation: Grid

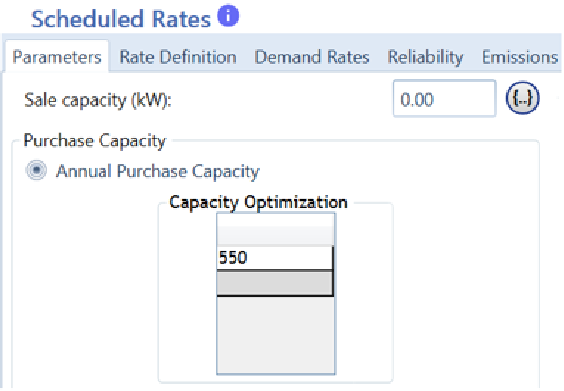
○ Simple Rates ○ Real Time Rates ● Scheduled Rates ○ Grid Extension

Figure 38: Grid Setup Window

There are four ways of specifying the grid: Simple rates, Real time rates, Schedule rates, and Grid extension [lxvii].

Simple rates= Allows to specify a constant power price, sellback price.
Real time rates= Allows to define prices on an hourly basis by importing formatted text file with time series data.
Scheduled rates= permit different prices at each time of day and month of the year.
Grid extension= Will compare the cost of a grid extension with the cost of each standalone system configuration in the model.

For our model "schedule rate" method was selected, as it allows for not only setting different grid purchase or sellback price but also allows to alter the purchase and sell back capacity which is required for different simulations in this project.



Sale capacity (kW): 0.00

Purchase Capacity

● Annual Purchase Capacity

Capacity Optimization

550

Figure 39: Scheduled Rates Capacity Setup Window

2.10 Demand Profile

Information regarding the electricity demand for households in Kuwait was not available. Several articles were referred that studied the electricity consumption pattern in Kuwait's households along with official government records such as Ministry of Electricity and Water (MEW) but none of them had data regarding electricity demand per household. Also, electricity bills were not available. This is mainly due to the inefficiency of billing by the utility companies.

This system has also contributed to the irrational consumption of electricity in the households. Kuwait has shifted its focus and is looking into reforming the energy policy and billing method. Also, the introduction of smart meters at residential sector is being considered.

Although the official MEW website has a link for electricity consumption bills but there was no data available. The data is not available to general public and a request has to be made to the officials to acquire such data which wasn’t possible for this thesis.

The demand profile was constructed from carrying out an extensive survey on 48 households of two and three bedroom. The survey focused on all appliances owned and time of operation during the weekdays and weekends for different months and quantity of each appliance.

Given below is the list of most common appliances owned and power rating for each:

Appliance	Power Rating (W)	Appliance	Power Rating (W)
1.5 Ton Split Air Conditioning	2000	TV	339
Window AC	1500	Video Games (Xbox, PS)	70
Fan	100	Cordless Phone	3
Extractor Fan Toilet	55	Mobile Charger	4
Extractor Fan Kitchen	55	Blender	300
Washing Machine	700	Fluorescent Tubes	32
Fridge	300	Hair Dryer	1500
Freezer	300	Heater	1500
Geyser	2000	Laptop	100
Iron	1100	Desktop	100
Toaster	1100	Broadband Equipment	10
Electric Frying Pan	1500	Microwave	800
Vacuum Cleaner	1400	Shaver	13

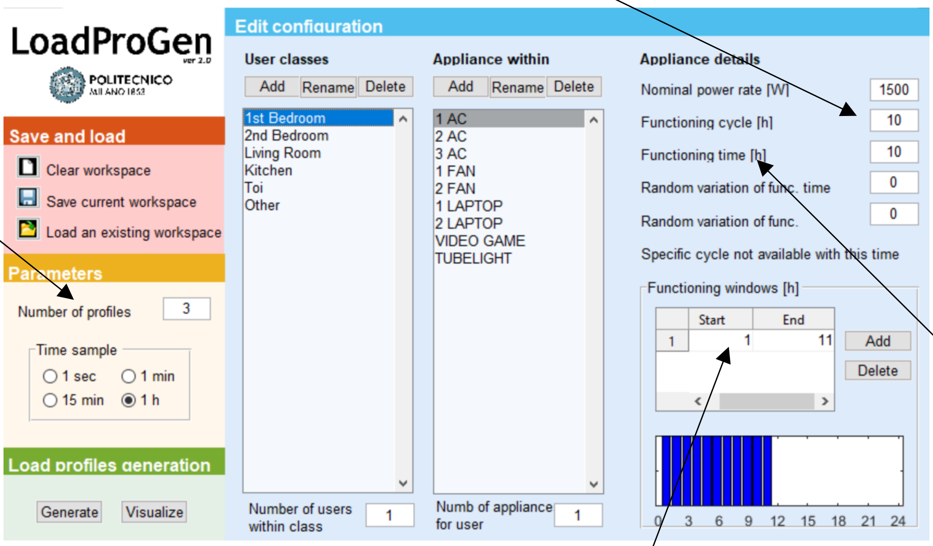
Table 6: List of Electrical Appliances and Power Rating

Once the data was gathered the load profile was constructed using 2 software's: LoadProGen and MATLAB.

Given below is an example for a weekday load profile constructed for the month of July for a 2-bedroom house using LoadProGen. Working of the LoadProGen and how it generates the load profile is explained in the figure 40 below. More information regarding the working of the software can be found in "The Handbook of LoadProGen" [lxxi].

Functioning Cycle: Series of instant in which the appliance was considered ON at the nominal power

Number of Profiles: Generates different load profiles based on input value. 3 profiles mean 3 different profiles would be generated.



Number of profiles 3

Time sample
○ 1 sec ○ 1 min
○ 15 min ● 1 h

User classes: 1st Bedroom, 2nd Bedroom, Living Room, Kitchen, Toi, Other

Number of users within class 1

Appliance within: 1 AC, 2 AC, 3 AC, 1 FAN, 2 FAN, 1 LAPTOP, 2 LAPTOP, VIDEO GAME, TUBELIGHT

Numb of appliance for user 1

Nominal power rate [W] 1500

Functioning cycle [h] 10

Functioning time [h] 10

Random variation of func. time 0

Random variation of func. 0

Specific cycle not available with this time

	Start	End
1	1	11

Functioning Time: Total amount of time the appliance was used in a day

Figure 40: LoadProGen Working

Functioning Window: Start and End time for the appliance

LoadProGen creates load profile for different time samples; 1sec, 1min, 15mins or 1hour. The time sample of 1 hour was selected since HOMER also used 1-hour time sample for the load.

Once the functioning time, functioning window, functioning cycle, and power rate were added for all the appliances, the load profiles were created and visualised.

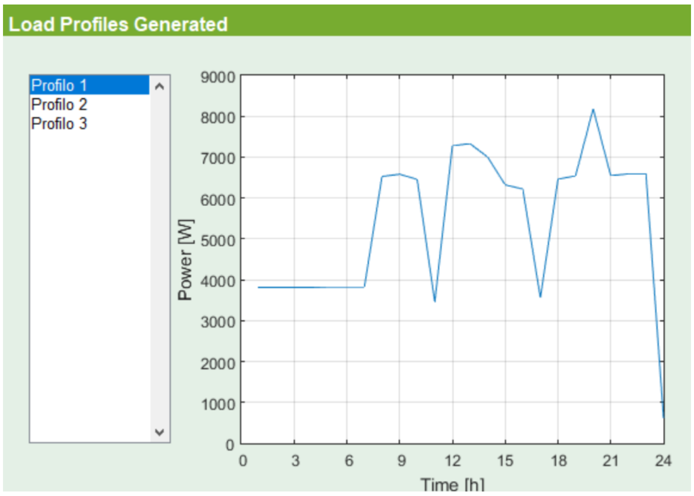


Figure 41: Load Profile for a weekday in July

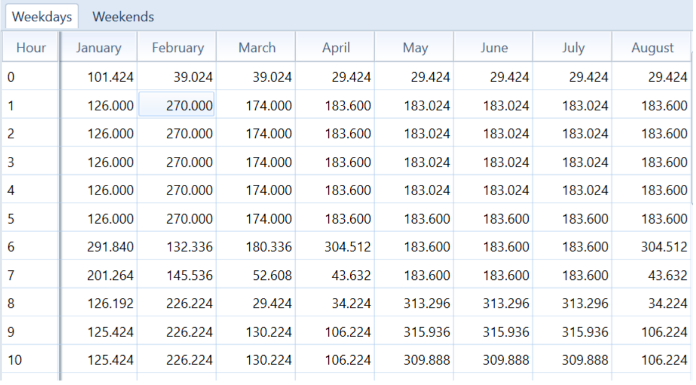
Figure 41 is a simple load profile generation for a single house but a similar method was used to create a yearly load profile of the all the 48 households.

<u>Validation of Results</u>

From the results obtained from the software it was found that the average power consumption of a 2-bedroom household was 2900kW. This value is justified since an article published by Kuwait Times 30th March 2016 stated that the average power consumption by 2-bedroom house was around 2700kW per month. The value quoted in the Kuwait Times was provided by MEW[lxxii].

2.11 HOMER Electric Load

Using the LoadProGen, load profile for each month, both weekdays and weekend was created separately and added to HOMER as shown below:

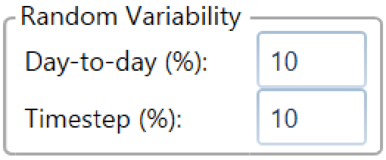


Weekdays | Weekends

Hour	January	February	March	April	May	June	July	August
0	101.424	39.024	39.024	29.424	29.424	29.424	29.424	29.424
1	126.000	270.000	174.000	183.600	183.024	183.024	183.024	183.600
2	126.000	270.000	174.000	183.600	183.024	183.024	183.024	183.600
3	126.000	270.000	174.000	183.600	183.024	183.024	183.024	183.600
4	126.000	270.000	174.000	183.600	183.024	183.024	183.024	183.600
5	126.000	270.000	174.000	183.600	183.600	183.600	183.600	183.600
6	291.840	132.336	180.336	304.512	183.600	183.600	183.600	304.512
7	201.264	145.536	52.608	43.632	183.600	183.600	183.600	43.632
8	126.192	226.224	29.424	34.224	313.296	313.296	313.296	34.224
9	125.424	226.224	130.224	106.224	315.936	315.936	315.936	106.224
10	125.424	226.224	130.224	106.224	309.888	309.888	309.888	106.224

Figure 42: HOMER Electrical Load Profile Data

Random Variability for both Day to day (%) and Time step (%) was set as 10%.



Day-to-day (%): 10

Timestep (%): 10

Figure 43: Random Variability

The seasonal profile created by HOMER on the basis of input is given below:

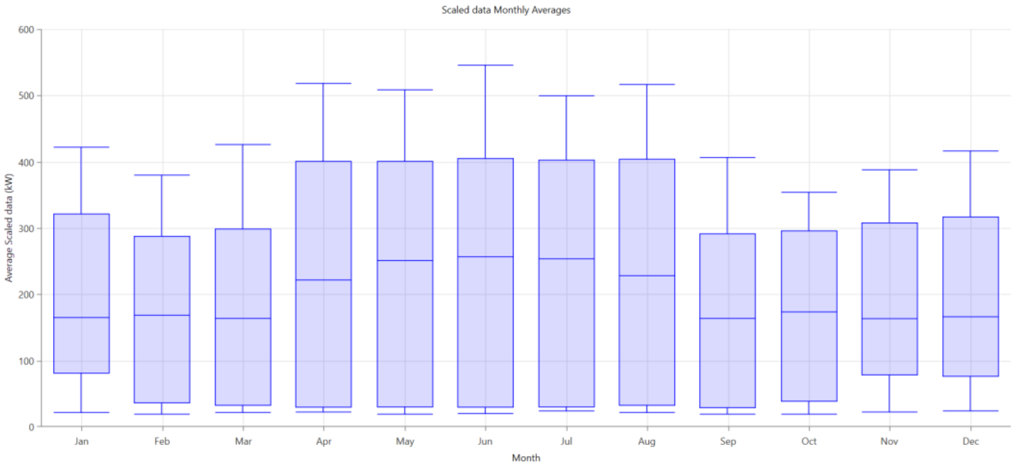
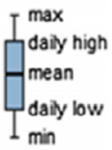


Figure 44: Seasonal Profile, HOMER

Figure 44 is used by HOMER to explain the load for each month in terms of maximum, daily high, mean, daily low and minimum. The maximum and minimum indicates the maximum and minimum primary load respectively for the month. Mean, daily high and daily low indicate the average, maximum and minimum primary load respectively for an average day[i].



July was found to be the peak month with peak load of 546kW.

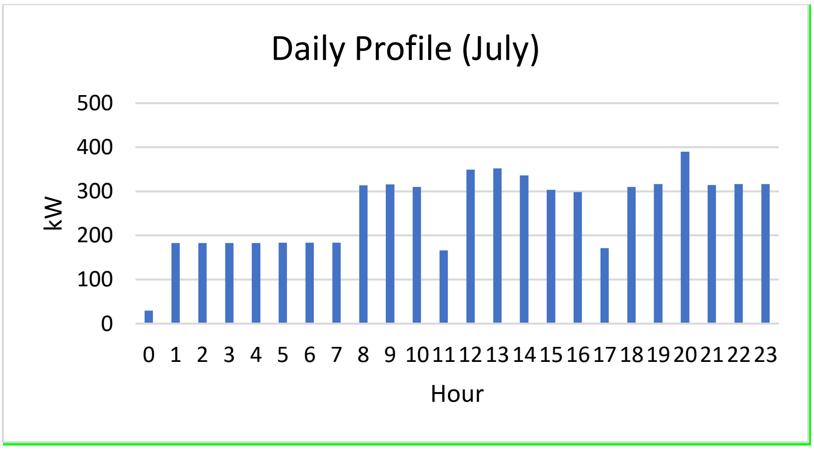


Figure 45:Average weekday Load Profile for the Month of July, HOMER

Figure 45 is a weekday load profile graph for the month of July. The peak load is at 8pm of 390kW with a daily average of 258kW.

Daily load profile for all the months is given below in figure 46.

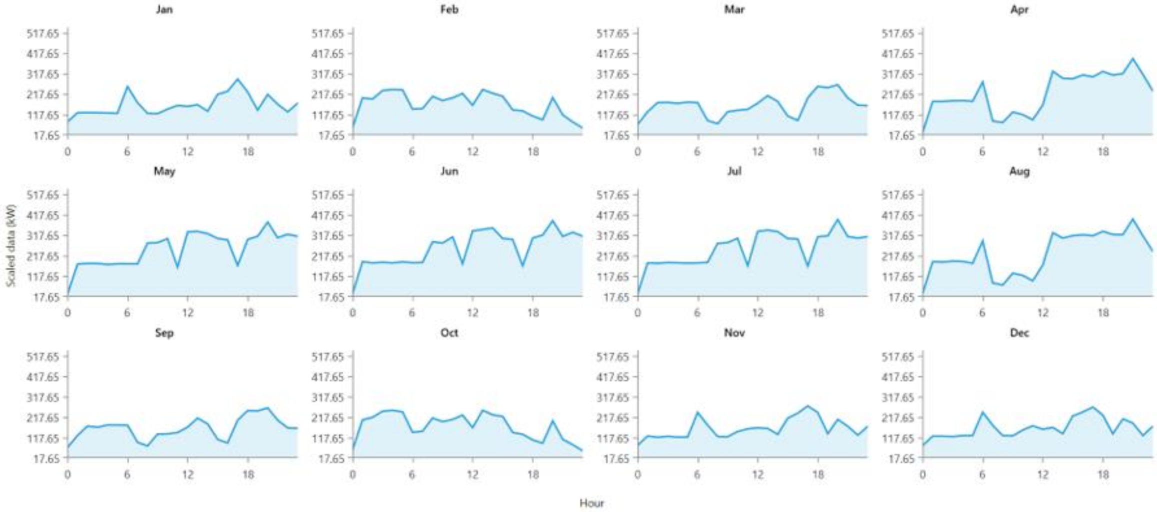


Figure 46: Scaled Data Daily Profile, HOMER

2.12 Battery Storage Technology

This section explains the different types of batteries considered for Kuwait.

2.12.1 Lead Acid Battery: Discover 2VRE-6200TF-U

Discover 2VRE-6200TF-U was selected from HOMER data base, it is a tubular flooded lead acid battery. This type of battery was selected because of its reliability and superior deep cycle performance for different applications such as residential, industrial and commercial. RE series battery types also provide a more reliable energy storage for stationary back-up, wind, solar, off-grid or grid-tie renewables energy applications. Discover tubular flooded RE series battery are tested and verified and have high performance even under high temperature environment; unstable power network installation, also has maximum efficiency per discharge-charge cycle and low cost per cycle[lxxiii].

Figure 47:Discover 2VRE-6200TF-U Battery [lxxiv]

The cost used are for the year 2025. This is because the scenario that considers storage is a future scenario in 2025. The future cost for Discover 2VRE-6200TF-U was not available but since chemistry of the battery is tubular flooded lead acid battery, IRENA published a document that predicated the cost for flooded lead acid battery till 2030. The price for 2025 was taken as capital cost and price for 2030 as replacement cost. The capital cost for new flooded lead acid battery for 2025 was found to be $99/kWh and the replacement cost as $77/kWh[lxxv]. Since there was no data available for O&M the cost was assumed as $10/year.

The table below show the battery properties and cost:

Property	Value
Nominal Voltage (V)	2
Nominal Capacity (kWh)	6.06
Round Trip Efficiency (%)	85
Minimum State of Charge (%)	20
Max. Charge Current (A)	652.5
Max. Discharge Current (A)	1,173.99
Nominal Capacity (Ah)	3029.968
Float Life (Years)	20
Lifetime Throughput (kWh)	8660
Capital Cost ($)	599.00
Replacement Cost ($)	466.20
O&M Cost ($/year)	10

Table 7: Discover 2VRE-6200TF-U Battery Properties

The minimum state of charge is 20%, giving a usable nominal capacity of 4.848kWh (0.8*6.06). Apart from the costs, data regarding the battery in table 7 was already available in HOMER library. It was checked against the manufacturers website to validate the data. The mechanical specification for Discover 2VRE-6200TF-U battery is given in appendix section B.

2.12.2 Lithium-Ion Battery: Tesla 13.5kwh Powerwall 2.0

Tesla 13.5kWh Powerwall 2.0 was selected from HOMER data base. It is a next generation energy storage battery for residential application launched by Tesla on October 2016. Compared to Tesla Powerwall 1.0 it had a higher storage capacity of 13.5kWh and had an integrated inverter that lowered the cost of production[lxxvi]. The Tesla Powerwall battery can either be floor or wall mounted both indoors and outdoors. It's a recharge battery and uses Li-ion NMC (Lithium Nickel Manganese Cobalt Oxide) chemistry. Th NMC is the new generation Li-ion recharge battery used for high power applications. NMC cells have a high current rate and high capacity rate. They also have a have a higher energy density, long cycle life and lower cost compared to other Li-ion batteries such as LICoO2[lxxvii].

Another advantage of using Powerwall 2.0 is that not only is it able to store electricity generated by solar panels but also draw electricity from the grid when the utility grid rates are lower. They even ensures homeowners with backup power in the event of outage[lxxviii].

However, installation of such a product with large storage capacity still poses an economic challenge despite its low cost and high performance[lxxvi].

Figure 48: Tesla 13.5kWh Powerwall 2.0 Battery [lxxix]

The cost used are for the year 2025. This is because the scenario that considers storage is a future scenario in 2025. The future cost for Tesla 13.5kWh Powerwall 2.0 was not available but since chemistry of the battery is NMC, IRENA published a document that predicated the cost for NMC Li-ion battery till 2030. The price for 2025 was taken as capital cost and price for 2030 as replacement cost. The capital cost for new Li-ion NMC battery for 2025 was found to be $244/kWh and the replacement cost as $176/kWh[lxxv]. Since there was no data available for O&M the cost was assumed as $10/year.

The table below show the battery properties and cost.

Property	Value
Nominal Voltage (V)	350
Nominal Capacity (kWh)	13.5
Round Trip Efficiency (%)	90
Minimum State of Charge (%)	10
Max. Charge Current (A)	20
Max. Discharge Current (A)	20
Nominal Capacity (Ah)	38.60
Float Life (Years)	10
Lifetime Throughput (kWh)	67500
Capital Cost ($)	3,294
Replacement Cost ($)	2,376
O&M Cost ($/year)	10

Table 8: Tesla 13.5kWh Powerwall 2.0 Battery Properties

The minimum state of charge is 10%, giving a usable nominal capacity of 12.15kWh (0.9*13.5). Apart from the costs, data regarding the battery in table 8 was already available in HOMER library. It was checked against the manufacturers website to validate the data. The mechanical specification for Tesla 13.5kWh Powerwall 2.0 battery is given in appendix section C.

2.12.3 Vanadium Redox Flow Battery

VRBs are rechargeable flow batteries that store chemical energy making use of the ability of vanadium ions to exist in several different states. VRB have short response time, higher energy density and long cycle life. VRBs can be stored for long durations whilst maintaining a ready state due to its limited self-discharge characteristic[lxxx]. Short response time make them suitable for UPS applications or in frequency regulation application.

Also, because of large capacities possible for VRB they are well suited for use in large power storage applications. They assist in averaging out the production of highly variable renewable energy generations for sources such as solar and wind. They also help generators cope with large surges in demand and levelling out supply/demand[lxxxi]. They have the ability to fully cycle and can maintain a minimum state of charge of 0% making them ideal for the use in solar storage application where batteries are empty at the start of the day and fill up depending on the weather and load. Li-ion or lead acid batteries operate between 20% to 100% giving only a maximum usable capacity of 80%. Below 20% there is possibility of damaging the battery.

Three types of VRB batteries were considered:

- Gildemeister 30kW-100kWh CELLCUBE® FB 30-100.
- Gildemeister 250kW-4hr CELLCUBE® FB 250-1000.

- redT 20kW-300kWh Energy Storage.

The cost used are for the year 2025. This is because the scenario that considers storage is a future scenario in 2025. The future cost for Gildmeister and redT was not available but since chemistry of the battery is vanadium, IRENA published a document that predicated the cost for vanadium battery till 2030. The price for 2025 was taken as capital cost and price for 2030 as replacement cost. The capital cost for vanadium battery for 2025 was found to be $183/kWh and the replacement cost as $125/kWh[lxxv]. Since there was no data available for O&M the cost was assumed as $2.5/year.

2.12.3.1 Gildemeister 30kW-100kWh Cellcube® FB 30-100

Property	Value
Nominal Voltage (V)	48
Nominal Capacity (kWh)	100
Round Trip Efficiency (%)	64
Minimum State of Charge (%)	0
Max. Charge Current (A)	583.33
Max. Discharge Current (A)	911.46
Nominal Capacity (Ah)	2,083.33
Float Life (Years)	20
Lifetime Throughput (kWh)	2628000
Capital Cost ($)	18,300
Replacement Cost ($)	12,500
O&M Cost ($/year)	250

Table 9: Gildemeister 30kW-100kWh CELLCUBE® FB 30-100 Properties

The minimum state of charge is 0 %, giving a usable nominal capacity of 100kWh. Apart from the costs, data regarding the battery in table 9 was already available in HOMER library. It was checked against the manufacturers website to validate the data.

2.12.3.2 Gildemeister 250kW-4hr Cellcube® FB 250-1000

Property	Value
Nominal Voltage (V)	700
Nominal Capacity (kWh)	1240
Round Trip Efficiency (%)	70
Minimum State of Charge (%)	0
Max. Charge Current (A)	289.85
Max. Discharge Current (A)	441.30
Nominal Capacity (Ah)	1,769.00
Float Life (Years)	20

Capital Cost ($)	226,920
Replacement Cost ($)	155,000
O&M Cost ($/year)	3,100

Table 10: Gildemeister 250kW-4hr CELLCUBE® FB 250-1000 Properties

The minimum state of charge is 0 %, giving a usable nominal capacity of 1240kWh. Apart from the costs, data regarding the battery in table 10 was already available in HOMER library. It was checked against the manufacturers website to validate the data. The mechanical specification for Gildemeister 250kW-4hr CELLCUBE® FB 250-1000 energy storage is given in appendix section D.

Figure 49: Gildemeister 250kW-4hr CELLCUBE® FB 250-1000 Battery [lxxxii]

2.12.3.3 redT 20kW-300kWh Energy Storage

Property	Value
Nominal Voltage (V)	96
Nominal Capacity (kWh)	300
Round Trip Efficiency (%)	75
Minimum State of Charge (%)	0
Max. Charge Current (A)	208
Max. Discharge Current (A)	208
Nominal Capacity (Ah)	3,125
Float Life (Years)	20
Lifetime Throughput (kWh)	876000
Capital Cost ($)	54,900
Replacement Cost ($)	37,500
O&M Cost ($/year)	750

Table 11: redT 20kW-300kWh Energy Storage Properties

The minimum state of charge is 0 %, giving a usable nominal capacity of 300kWh. Apart from the costs, data regarding the battery in table 11 was already available in HOMER library. It was checked against the manufacturers website to validate the data. The mechanical specification for redT 20kW-300kWh energy storage is given in appendix section E.

Figure 50: redT 20kW-300kWh Energy Storage [lxxxiii]

2.12.4 Control Setting For Storage

There are two types of controls in HOMER: Load Following (LF) and Cycle Charging (CC). These don't have an effect on the HOMER optimisation process unless storage systems are included. Under LF strategy surplus energy from the renewables is used to charge the batteries and no extra cost is added for charging the battery and they are discharged whenever it's the cheapest option. Under CC strategy the batteries are charged using the electricity from the grid/generator. Normally this kind of strategy is used in situations where there are different peak and off-peak electricity grid prices and batteries are charged during off peak time, this adds to the cost. In this project LF strategy is used[lxxxiv].

3 HOMER Modelling

HOMER allows for variable inputs that help in defining the system and uses optimizer to generate an optimum configuration based on the input values. Two scenarios are considered to show the effects of the PV and storage system in meeting the electricity demand.

Optimisation was carried out for each scenario with different financial and technical parameters under the current scenario (2017) and future scenario (2025).

3.1 Scenario 1

Scenario 1 takes account of the current situation. It is further divided into two scenarios; Grid Open and Grid Restricted.

As mentioned in the section 2.3 about different PV pilot projects in Kuwait, both in residential and commercial sector these are experimental projects to evaluate the feasibility of implementing small DG systems (PV in this case). It assesses the potential of PV to generate sufficient energy to meet the demand during the day time or a part of it, reducing the grid import, cost and impacts on the overall system. For that reason, some PV panels are restricted from exporting excess electricity to the grid which has to be curtailed and other are allowed to. These PV installation projects are paid by the government and household owners can join the program for free. Only a limited number of such projects are being carried out and there are several criteria's that are needed to be met before installation. Hence not all house owners can get paid for PV system installed. By doing so the government aims at studying the electricity consumption patterns in these households for future, which will allow them in introducing smart meters, FIT and other incentives for the installation of renewable energy system at residential level. According to the MEW, FIT's are currently being studied and will be introduced in the coming years to the public. This will help them in generating income from selling excess electricity generated by the system to the grid, diversify the energy mix, move towards a greener and low carbon economy and ultimately assist the country in achieving its target of producing 15% electricity from renewables.

The purpose of carrying out 2 analyses with similar constrains with the exception of grid export is to show how it affects the production, renewable fraction, CO_2 emissions, converter size and overall performance of the system both technically and financially.

The current grid purchase price as of August 2017 is $0.007/kWh, but new prices are going to be enforced September 2017 onwards. Therefore, for the 1st scenario the grid power price of $0.05/kWh is set. Since there is no FIT, grid sellback price is set at $0/kWh.

Default discount rate and inflation rate were set. The project lifetime was set at 25 years and annual capacity shortage of 0%.

Discount rate	8%
Inflation rate	2%
Project Lifetime	25 years
Capacity Shortage	0%

PV panel characteristics

A generic PV panel is selected. The characteristics of the PV panels are stated below:

PV	Price	Characteristic
Capital [lxxxv]	$1500/kW	/
Replacement [lxxxv]	$1200/kW	/
O&M [lxxxvi]	$19/kW/year)	/
Efficiency	/	13%
Life Time	/	25 years
Derating Factor	/	80%

Table 12:PV Panel Characteristics

Converter Characteristic

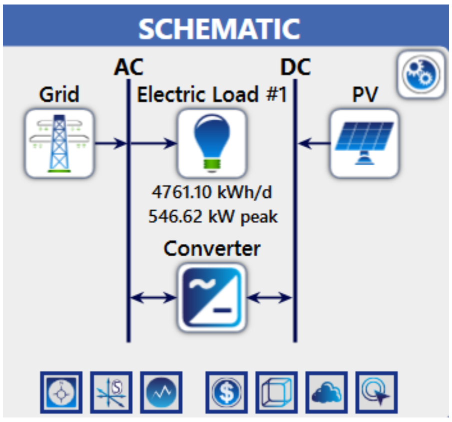
The O&M for the converter was not found online so was assumed to $10/year.

Converter	Price
Capital [lxxv]	$250
Replacement [lxxv]	$230
O&M ($/year)	$10
Lifetime	15 years

Table 13: Converter Properties

Inverter	
Efficiency	95%
Rectifier	
Relative Capacity	100%
Efficiency	90%

Table 14: Inverter & Rectifier Characteristics



Model configuration

3.1.1 Scenario 1: Grid Restricted

For this scenario, the grid export was restricted and a value of 0kW was set. The aim of this scenario is to get the best configuration that has the maximum renewable energy fraction, financially feasible and a lower CO_2 emission.

Another adjustment made was to the PV optimiser. Majority of Kuwait's pilot projects were installed on rooftop of the buildings and the total rooftop area of the building considered in this thesis is 1100m^2. This can accommodate 150kW PV system considering that area required for 1kW is 7m^2 [lxxxvii] the search space was modified from 150kW to 2000kW, and optimisation was carried out.

3.1.1.2 Simulation Results

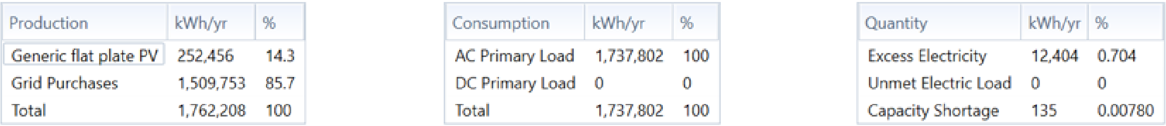
HOMER selected the best configuration based on NPC as:

PV (kW)	Converter (kW)	COE ($)	NPC ($)	Fraction Of Load Met By Green Electricity (%)	Excess %
150	100	0.0569	1.28M	13.1	0.491

Table 15: HOMER Results

Electrical

It can be seen that the AC load is 1737802kWh/year, the total generation is 1762208kWh/year out of which 14.3% is supplied by the PV panels and 85.7% is imported from the grid. With the 150kW of PV excess electricity is only 12,404kWh/year which means that almost 90% of the energy generated by PV is consumed locally.



Production	kWh/yr	%
Generic flat plate PV	252,456	14.3
Grid Purchases	1,509,753	85.7
Total	1,762,208	100

Consumption	kWh/yr	%
AC Primary Load	1,737,802	100
DC Primary Load	0	0
Total	1,737,802	100

Quantity	kWh/yr	%
Excess Electricity	12,404	0.704
Unmet Electric Load	0	0
Capacity Shortage	135	0.00780

Figure 51: Electrical Data

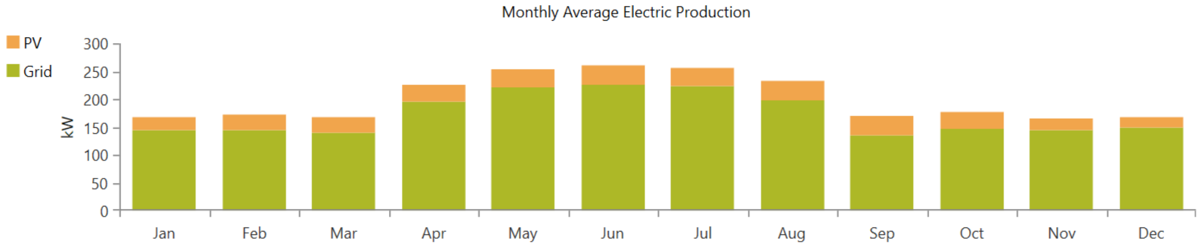


Figure 52: Individual Components Average Production

Generic flat plate PV

The 150kW of PV panel operates for 4387 hours/year has a total output of 252,456kWh/year with a mean output of 28.8kWh/year. It can also be seen that the PV output throughout the year is quite consistent.

Quantity	Value	Units
Rated Capacity	150	kW
Mean Output	28.8	kW
Mean Output	692	kWh/d
Capacity Factor	19.2	%
Total Production	252,456	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	149	kW
PV Penetration	14.5	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0802	£/kWh

Figure 53: Generic Flat Plate PV Electrical Data

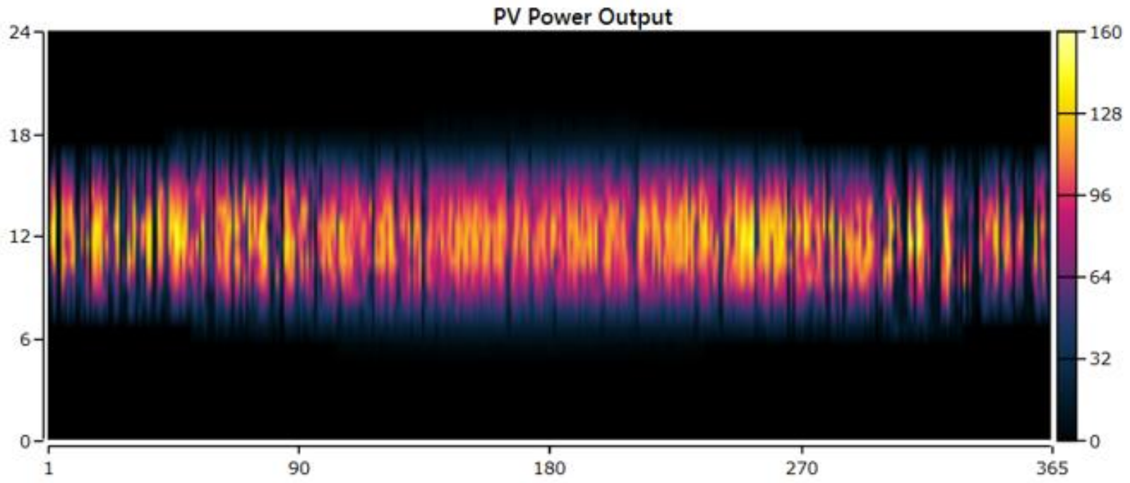


Figure 54: Illustration of PV Power Output (150kW)

Addition of more PV

As it can be seen from the above figure 51 the grid purchase is 1,509,753 kWh/year. From table 16 below it can be seen that the fraction of load met by PV is only 13.1%. The aim of the Kuwait government is to reduce the reliance on grid and meet maximum electricity demand from locally generated RE, solar PV in this case and reduce CO_2 emissions. There is not much excess and almost

90% of the energy generated is consumed on the site. Additional PV capacity was added to demonstrate the amount of load that can be met from RE and how much the import from the grid can be reduced. Alternately batteries can also be added but in current situation it's not economically feasible. This will be investigated in the second scenario. The grid export is still restricted in this scenario.

PV size was increased to 300 kW, 450 kW, 600 kW, 750 kW, 900 kW, 1050 kW, 1200 kW and 2000 kW. Various converter sizes were considered to get the most appropriate results with high RE fraction and low grid import. Converter sizes are important and must be aligned with the size of PV since more energy can flow through the converter which affects the consumption of electricity coming from the renewables. Converter size should increase with the increase with PV size allowing more energy output and reduced grid import.

PV (kW)	Converter (Kw)	COE ($)	NPC ($)	Fraction Of Load Met By Green Electricity (%)	Excess %
150	100	0.0569	1.28M	13.1	0.491
300	172	0.0651	1.46M	23	4.505
450	312	0.0754	1.69 M	30.84	9.776
600	312	0.0851	1.91 M	35	17.268
750	312	0.0955	2.14 M	37.41	24.593
900	312	0.106	2.38 M	39	31.120
1050	375	0.118	2.65 M	41.15	36.358
1200	344	0.129	2.89 M	41.88	41.373
2000	328	0.189	4.25 M	44.52	58.926

Table 16: Impact of Increased PV Capacity on the System

The above table 16 shows the fraction of load met by the PV of different sizes with minimum excess %, NPC and COE. It can be seen that as the PV size increases, excess % increases substantially since the gird export is prohibited and excess electricity cannot be used onsite or exported, so a large amount of useful energy is curtailed which doesn't allow the PV to reach its full potential.

Also, the converter size decreases as the PV capacity increases from 1050kW. This is because after a certain level increasing the converter size has almost negligible effect on the fraction of load met by green electricity %, excess % but significantly increases the COE and NPC of the system. This is shown below with an example of a 2000kW PV system and an 800kW converter. This increases the NPC by $200,000 and COE by $0.009 and fraction of load met by the green electricity only increase by 0.78% and excess decreases by 0.126%.

PV (kW)	Converter (kW)	COE ($)	NPC ($)	Fraction Of Load Met By Green Electricity (%)	Excess %
2000	800	0.198	4.45M	45.3	58.8

Table 17: HOMER Result

Other objective of the Kuwait government is to reduce the reliance on grid and reduce CO_2 with the installation of renewable energy systems, the table below presents the import and CO_2 emissions.

PV (kW)	Converter (kW)	PV Generation (kWh/year)	PV Penetration %	Import (kWh/year)	CO2 Emissions (kg/year)
150	100	252,456	14.5	1,509,753	954,164
300	172	504,911	29.1	1,3369,57	844,957
450	312	757,367	43.6	1,200,104	758,466
600	312	1,009,823	58.1	1,129,403	713,786
750	312	1,262,279	72.6	1,087,660	687,401
900	312	1,514,734	87.2	1,060,012	669,928
1050	375	1,767,190	102	1,022,551	646,252
1200	344	2,019,646	116	1,009,899	638,256
2000	328	3,366,076	194	964,021	609,262

Table 18: Impact of Increased PV Capacity on Imports and CO_2

The total AC load is 1,737,802kWh/year. From table 18 it can be seen that the PV capacity of 1050 kW, 1200 kW and 2000 kW generate sufficient energy that can satisfy the electricity demand but the fraction of load met by the green electricity is low because of the variation of solar output during the day and hour.

PV (kW)	Green Electricity Used (%)	Green Electricity Used (kWh/Year)	Fraction Of Load Met By Green Electricity (%)
150	90.33	228049	13.1
300	79.39	400845	23
450	71	537698	30.84
600	60.25	608399	35
750	51.51	650142	37.41
900	44.75	677790	39
1050	40.47	715252	41.15
1200	36.04	727903	41.88
2000	22.99	773781	44.52

Table 19: Impact of Increased PV Capacity on the System

From table 19, as it is expected that with the increase of PV size the amount of green energy used would increase from 228049kWh/year to 773781kWh/year and so would the fraction of load met by the green electricity but the percentage of green electricity used compared to the total PV generation decreases significantly from 90% to 23%.

Additional Capacity (kW)	Additional Energy Generated (kWh/year)	Fraction Of Additional Energy Consumed Locally	Import Decrease (%)	CO_2 Emission Reduction (%)
+150	252,455	68.45	11.45	11.45
+300	504,911	61.32	20.51	20.51
+450	757,367	50.22	25.19	25.19
+600	1,009,823	41.80	27.96	27.96
+750	1,262,278	35.62	29.79	29.79
+900	1,514,734	32.16	32.27	32.27
+1050	1,767,190	28.29	33.11	33.11
+1850	3,113,620	17.53	36.15	36.15

Table 20: Impact of Increased PV Capacity on the System

It can be seen from table 20 as the PV capacity decreases the imports and CO_2 emission decrease at the same rate. However, with the increase in PV capacity from 150kW to 2000kW the fraction of additional energy consumed locally decreases from 68.45% to 17.53%, this highlights the limitation of solar energy penetration.

The best results were obtained based on COE, NPC, RE fraction, CO_2, import, export and excess. Considering the current economic conditions, the best system configuration is 150kW PV with a 100kW converter.

3.2 Grid Open-Allowed Export

For this scenario, the grid export was permitted and a value of 999,999kW was set. The aim of this scenario is similar to the one above, to get the best configuration that has the maximum renewable energy fraction, financially feasible and lower CO_2 emission. Also, in this scenario the converter size made a significant difference, with the option of selecting a bigger converter meant that more energy could flow through which impacts the consumption of energy coming from the renewables. As the converter size increases more energy can be exported. Imports, CO_2 emissions can be further reduced and also leads to higher fraction of load met by green energy.

As in the above case with grid export being restricted the fraction of load met by green electricity was significantly limited. This scenario shows the impact on the system in the event of grid export being permitted and how the fraction of load met from green electricity, CO_2 emissions and excess changes.

HOMER Results

PV (kW)	COE ($)	NPC ($)	Excess %
150	0.0577	1.30	0
300	0.0649	1.51	0
450	0.0689	1.69	0.956
600	0.0739	1.99	0.0817
750	0.0791	2.32	0
900	0.0801	2.57	0.112
1050	0.0816	2.81	1.17
1200	0.0842	3.06	3.71
2000	0.0892	4.75	0.804

Table 21: HOMER Results

PV (kW)	Converter (kW)	PV Generation (kWh/year)	PV Penetration %	Import (kWh/year)	Export (kWh/year)	CO_2 Emissions (kg/year)
150	156	252,456	14.5	1,501,875	3906.332	946,716
300	312	504,911	29.1	1320635	62499.13	795,142
450	312	757,367	43.6	1200104	163755.4	654,972
600	500	1,009,823	58.1	1120180	340056.8	493,038
750	750	1,262,279	72.6	1072905	534267.8	340,418
900	750	1,514,734	87.2	1042672	741388.4	190,411
1050	750	1,767,190	102	1019963	929883.9	56,930
1200	750	2,019,646	116	1002038	1076519	-47,072
2000	1500	3,366,076	194	950104	2377126	-901,878

Table 22: Impact of Increased PV Capacity on the System

The PV penetration % and PV generation for the above selected PV sizes remain the same. However, in this scenario grid export is permitted which allows us to choose a bigger converter. A bigger converter allows for energy exchange thereby increasing the fraction of load met by the green electricity and reducing the grid import. The CO_2 emissions are also significantly decreased compared to the scenario with grid export restricted.

PV (kW)	Green Electricity Used (%)	Green Electricity Used (kWh/Year)	Fraction Of Load Met By Green Electricity (%)
150	93.45	235927	14
300	82.62	417167	24
450	71	537698	31
600	61.16	617622	36
750	52.67	664897	38
900	45.89122579	695130	40
1050	40.6203634	717839	41
1200	36.43034472	735764	42
2000	23.40107591	787698	45

Table 23: Impact of Increased PV Capacity on the System

Additional capacity (kW)	Additional Electricity Generated (kWh/year)	Fraction Of Additional Electricity Consumed Locally	Import Decrease (%)
+150	252,455	71.79101226	12.07
+300	504,911	59.76716689	20.09
+450	757,367	50.39762757	25.41
+600	1,009,823	42.47972169	28.56
+750	1,262,278	36.37891178	30.58
+900	1,514,734	31.81495893	32.09
+1050	1,767,190	28.28428183	33.28
+1850	3,113,620	17.72120554	36.73

Table 24: Impact of Increased PV Capacity on the System

However, with the increase in PV capacity from 150kW to 2000kW the fraction of additional energy consumed locally decreases from 71.79% to 17.72%, this highlights the limitation of solar energy penetration. The grid import significantly decreases from 12.07% to 36.73%.

3.3 Scenario 2

Scenario 2 takes account of the future scenario of 2025. Unlike scenario 1, scenario 2 has higher grid price and a sellback price is introduced.

As already mentioned in the earlier sections 2.1, that Kuwait government is looking into reducing the subsides on the electricity prices and have decreased the subsidy from 95% to 60% for September 2017. The debate on further reduction is also being considered but this will be a gradually process with the introduction of other compensatory measures to the public so that doesn't affect their economical decision.

The current cost of electricity production is 14cents/kWh, and from the figure 3 it can be seen that the cost of electricity production increase by 2cents/kWh in the past 8 years and the cost of electricity production doubled in the last 13 years from 7cents/kWh in 2004 to 14cents/kWh in 2017. This depends on the prices of oil. For this scenario, it is assumed that the cost of electricity production will be 16cents/kWh by 2025. This is a rough estimation and is selected on the basis that cost of the cost of electricity production increased by 2cents/kWh in the past 8 years.

This scenario assumes that the subsidies are further reduced to 40% by 2025 and grid power price of $0.096/kWh is set and a grid sellback price is assumed to be $0.052/kWh. This is because the cost of electricity production from solar is estimated to be 4-6cents/kWh by 2025[lxxxviii], also in 2014 Japan's Toyota Tsusho offered to set up a solar RE power plant in

Kuwait and sell the electricity generated from to MEW at $0.0776/kWh[lxxxix]. Considering the present and future prices a sell back price of $0.052/kWh is assumed.

Grid exports are permitted in this scenario. Default discount rate and inflation rate were set. The project lifetime was set at 25 years and annual capacity shortage of 0%.

Discount rate	**8%**
Inflation rate	2%
Project Lifetime	25 years
Capacity Shortage	0%

PV panel characteristics

A generic PV panel is selected. The characteristics of the PV panels are stated below:

PV	**Price**	**Characteristic**
Capital [lxxxv]	$800/kW	/
Replacement [lxxxv]	$600/kW	/
O&M	$12/kW/year)	/
Efficiency	/	13%
Life Time	/	25 years
Derating Factor	/	80%

Table 25: PV Panel Characteristics

Converter Characteristic

The O&M for the converter was not found online so was assumed to $8/year with a life time of 15 years.

Converter	**Price**
Capital [lxxv]	$100
Replacement [lxxv]	$80
O&M ($/year)	$8

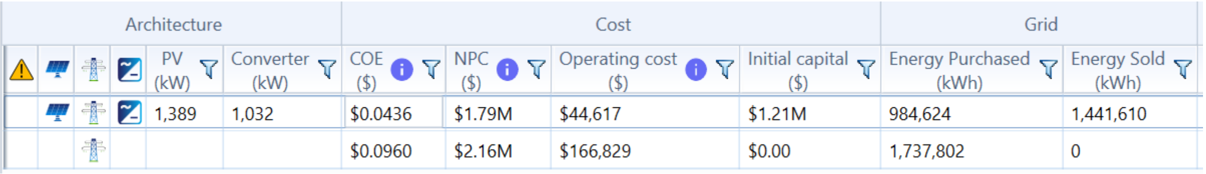
Table 26: Converter Cost

Inverter	
Efficiency	95%
Rectifier	
Relative Capacity	100%
Efficiency	90%

Table 27: Inverter and Rectifier Characteristics

3.3.1 Simulation Results

Based on the input values HOMER selects the best configuration with the lowest NPC.



Architecture						Cost				Grid	
⚠				PV (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Energy Purchased (kWh)	Energy Sold (kWh)
				1,389	1,032	$0.0436	$1.79M	$44,617	$1.21M	984,624	1,441,610
						$0.0960	$2.16M	$166,829	$0.00	1,737,802	0

Figure 55: HOMER Best Configuration

As it can be seen from the results in figure 55 that HOMER selects the best option of 1389kW of and a converter value of 1032kW.

Electricity generation from PV

Quantity	Value	Units
Rated Capacity	1,389	kW
Mean Output	267	kW
Mean Output	6,404	kWh/d
Capacity Factor	19.2	%
Total Production	2,337,600	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,384	kW
PV Penetration	135	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0439	£/kWh

Figure 56: Generic Flat Plate PV Electrical Data

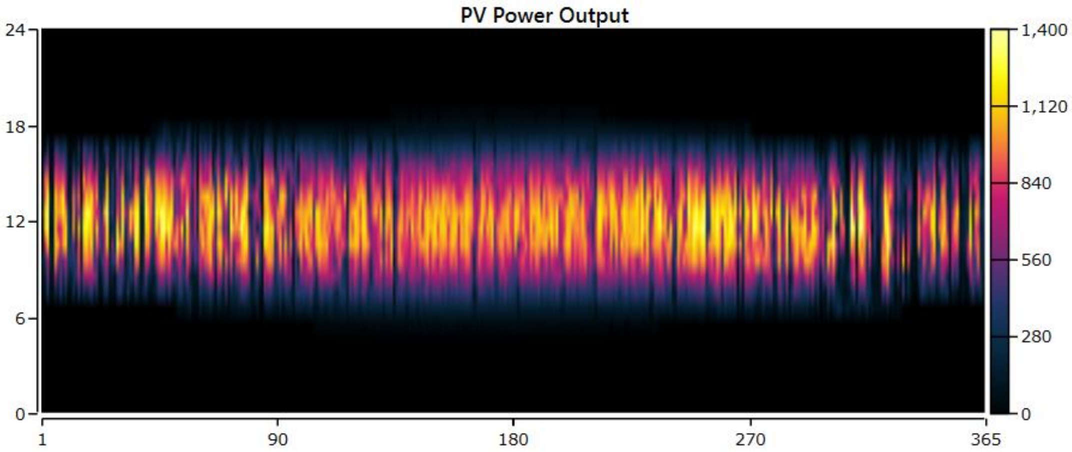
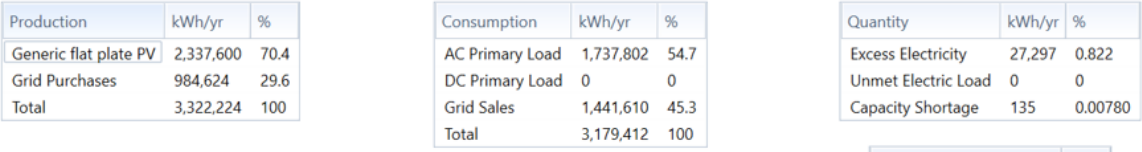


Figure 57: Illustration of PV Power Output (1389kW)

The rated power of PV is 1389kW and operates between 6am to 6pm in summer and 7am to 5pm in winter totalling about 4387 hours/year. The PV has a total output of 2,337,600 kWh/year with a mean output of 267kW and a PV penetration of 135%.

Electrical Generation



Production	kWh/yr	%
Generic flat plate PV	2,337,600	70.4
Grid Purchases	984,624	29.6
Total	3,322,224	100

Consumption	kWh/yr	%
AC Primary Load	1,737,802	54.7
DC Primary Load	0	0
Grid Sales	1,441,610	45.3
Total	3,179,412	100

Quantity	kWh/yr	%
Excess Electricity	27,297	0.822
Unmet Electric Load	0	0
Capacity Shortage	135	0.00780

Figure 58: Electrical Data

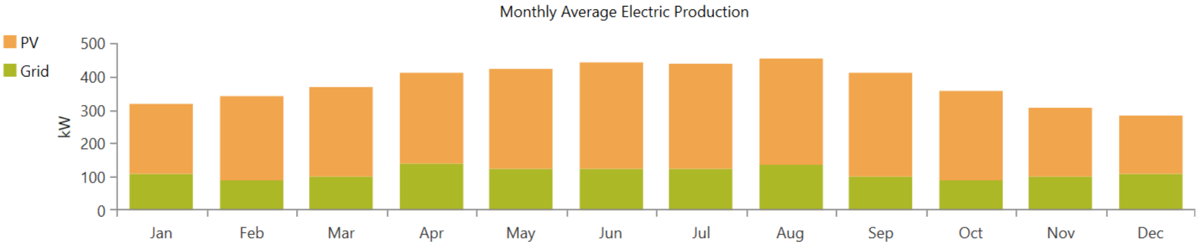


Figure 59: Individual Components Average Production

It can be seen from above figure 58 that the total production of PV is 2,337,600kWh/year which accounts for 70.4% of total electricity generation. The primary load is 1,737,802. Since PV production occurs during the day time typically between 6am to 6pm it is able to meet the demand during that time but not in evening. Therefore, resulting in grid sales of 1,441,610kWh/year because during the midday when the production exceeds demand a huge amount of useful energy is exported to the grid. Total of 984,624kWh/year of electricity is imported from the grid during the evenings or when the demand exceeds the PV production, this accounts for 29.6% of the total generation. Resulting in 3,322,224kWh/year of total production.

Total RE Electricity Generation and Electric Load

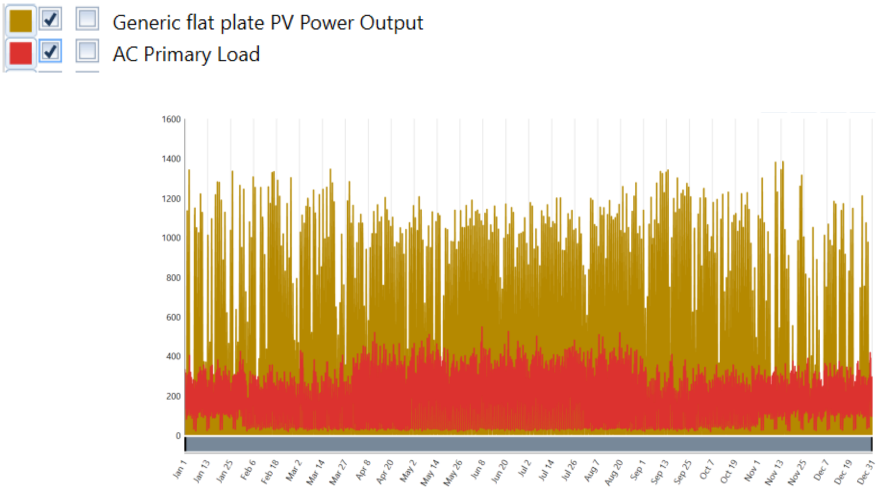


Figure 60: Annual Primary Load and PV Output

As it is observed from the results of “Electrical Generation” and figure 60, the PV generation has the potential to satisfy the demand for the whole year. PV output is 1.45 times higher than the load, there is still sufficient grid import required. About 984,624kWh/year to meet the demand. This import occurs during the evening when there is no solar energy for the PV to generate electricity. Also, PV generates electricity during the day time when the demand is less compared to the generation, this results in energy surplus that is exported to the grid. During evening when the demand increases there is no generation from the PV resulting in energy deficit and electricity is imported from the grid, it is important to match the supply and demand.

A closer look of winter week (8th Jan to 14th Jan) and summer week (10th July to 16th July) is considered.

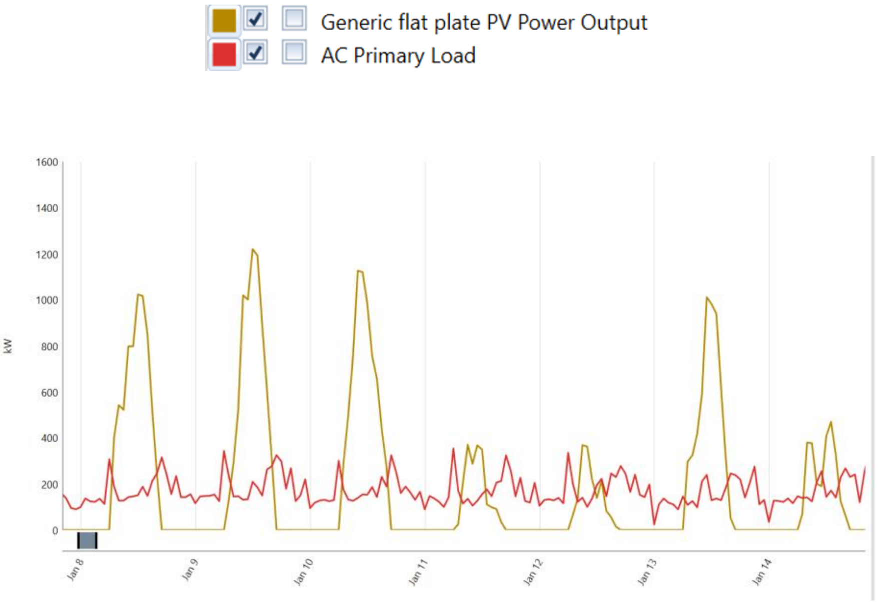


Figure 61: Winter Week Primary Load and PV Output

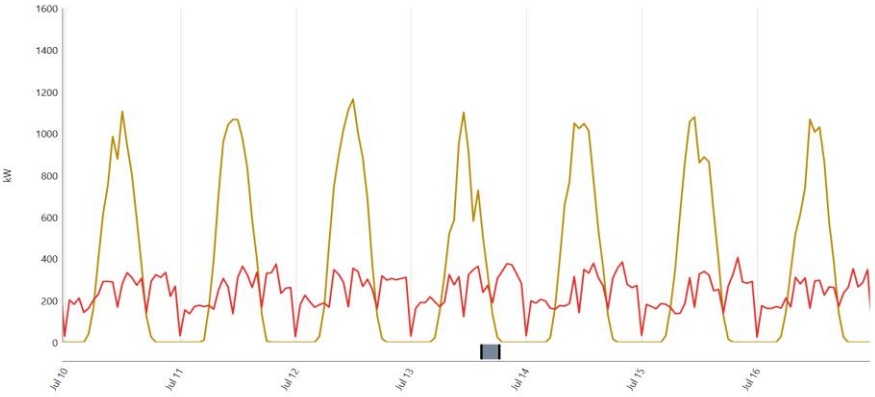


Figure 62: Summer Week Primary Load and PV Output

From figure 60 it can be seen that the annual RE generation (Solar PV output) is higher than the annual load. However, the renewable output varies over days and hours resulting in the mismatch of generation and demand. Also from figure 61 and 62 the PV output is not always synchronised with the load. Peak load can occur even when the renewable output is low or not generating at all. As it can be seen from the above figure 61 and 62 that RE output is always higher than the load during daytime. Detail figures are shown below that represents a winter day on 10th Jan and a summer day on 12th July.

10th Jan

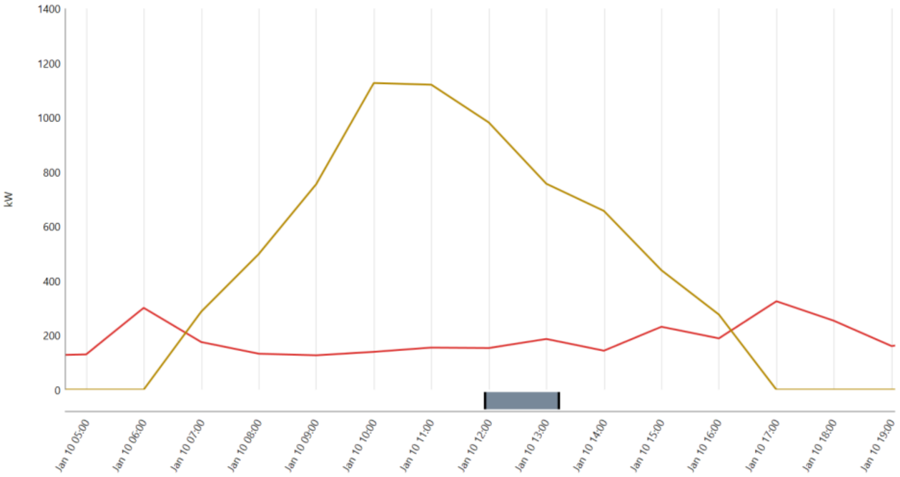


Figure 63: Typical Winter Day Load and PV Output

12th July

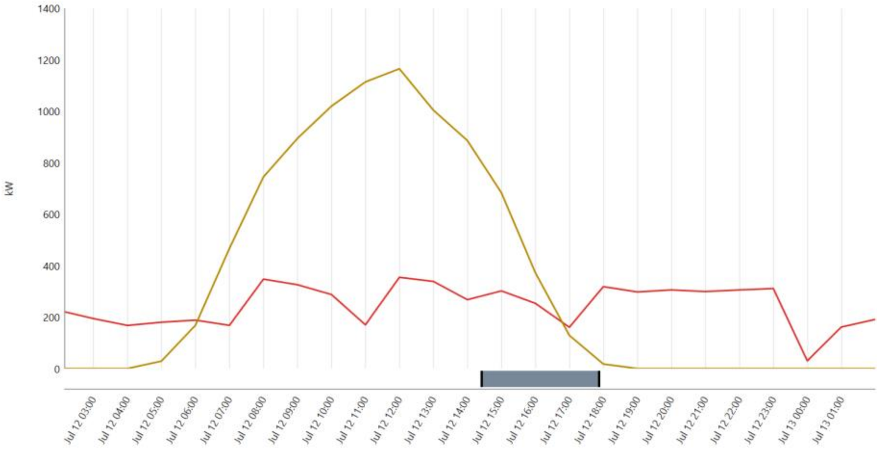


Figure 64: Typical Summer Day Load and PV Output

From figure 63 and 64 it can be seen that, the instant electricity generation can be 13 times higher than the instant load during winter and 4 times higher during summer. Also, PV only operates between 5am to 6pm during summer and 6am to 5pm during winter, there is mostly surplus of electricity during that time this results in energy being exported and during evenings electricity is imported to meet the load. This results in electricity surplus and electricity deficit as shown in figure 65, 66 and 67 below for whole year, winter day (10th Jan) and summer day (12 July) respectively.

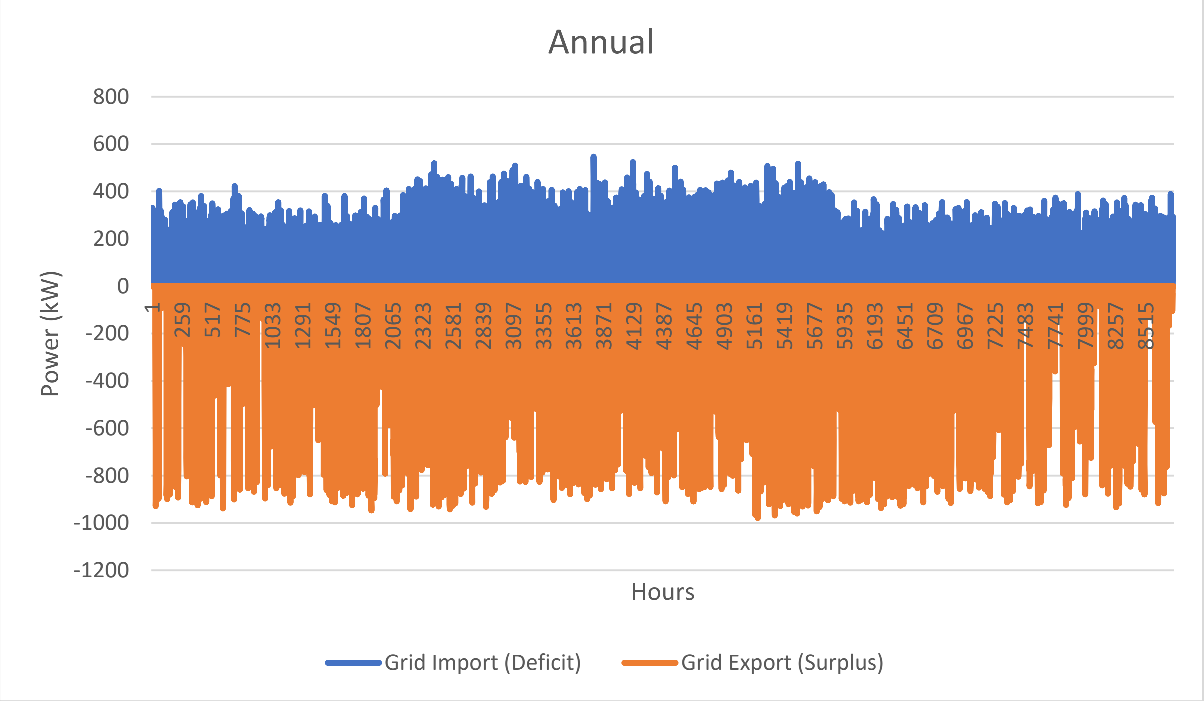


Figure 65: Annual Surplus and Deficit

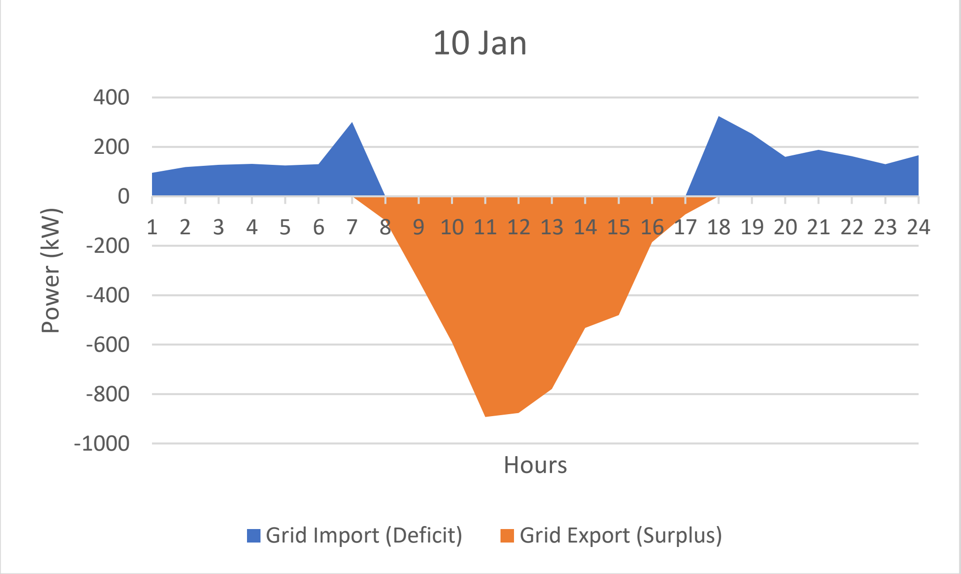


Figure 66: Surplus and Deficit on 10th Jan

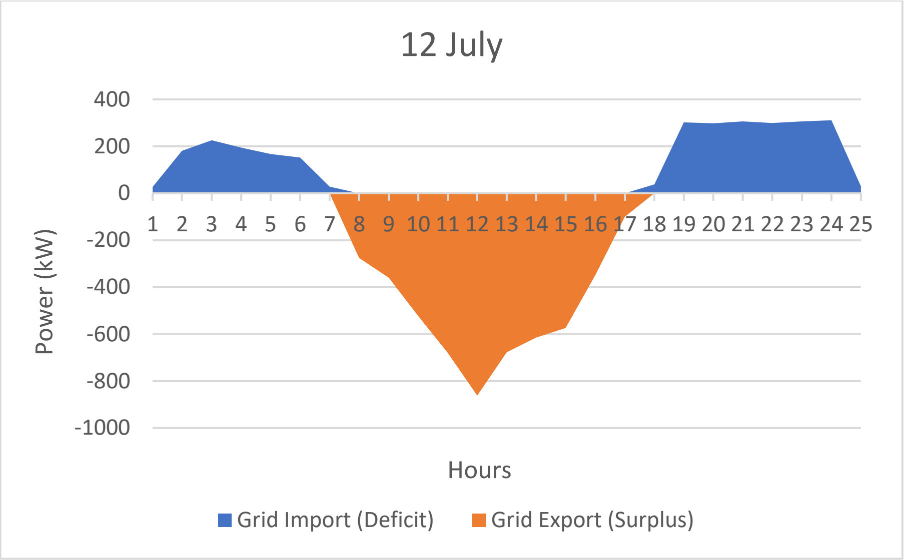


Figure 67: Surplus and Deficit on 12th July

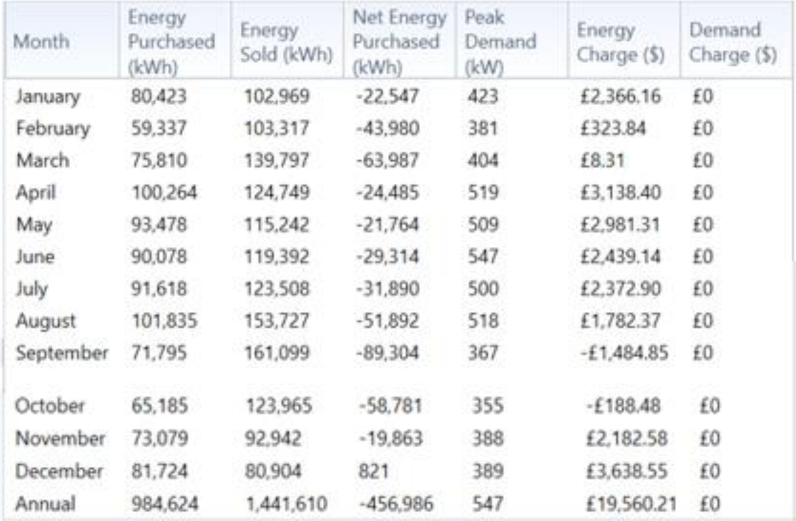
It can also be seen from figure 60 that the PV system is over sized and exceeds the primary load this results in surplus of energy being generated and exported to the grid. Although, it benefits from FIT but reduces the onsite consumption, also a significant amount of grid import is required regardless of high RE output. There are communities where renewable generation is significantly higher than the primary load with various RES installed such as PV, wind, small-scale hydro, etc. However, it's of concern in this case as PV occupies a far larger area for the same capacity as wind turbine. PVs and battery storage are usually oversized in areas with unreliable grid or no access to grid especially in remote areas which have stand-alone PV system to attain system autonomy. This is not the case with community being investigated in Kuwait, as Kuwait has a 100% grid connection. Also, 1389kW of PV requires an area of 9723m^2 [lxxxvii]**.** Small DG that are installed in communities to meet the local demand should be sized according to the community requirements and area available. Although the community being investigated in this case has a large unoccupied area available but this is not the case for every community. Since PV only generates electricity during the day time when the load may be less, as it can be seen from figure, that the peak load occurs during evenings for the month of July. When the PV is not generating electricity, it is important to design a system which is able to meet local demand, have high renewable fraction, generate sufficient surplus to export to the grid and benefit from the extra income making the system economically feasible.

Further analyses include:

1) Reducing the PV capacity-
2) Adding energy storage to the system of 1389kW PV

These analyses are conducted to investigate the impact on the import, export, fraction of load met from renewable, green electricity used, COE and NPC and help in selecting the ideal system without oversizing the system. The objective of these two analyses is to study which option is better in terms of technical and economically feasibility. More details regarding these two analyses are provided in the section 4.

For the current system, monthly imports and exports of electricity are shown in the table 68 below:



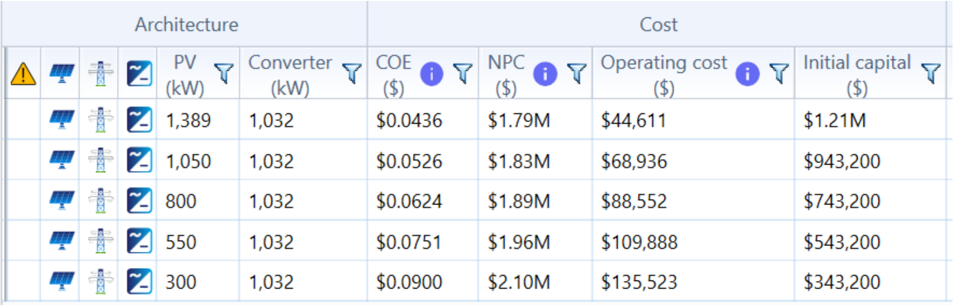
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
January	80,423	102,969	-22,547	423	£2,366.16	£0
February	59,337	103,317	-43,980	381	£323.84	£0
March	75,810	139,797	-63,987	404	£8.31	£0
April	100,264	124,749	-24,485	519	£3,138.40	£0
May	93,478	115,242	-21,764	509	£2,981.31	£0
June	90,078	119,392	-29,314	547	£2,439.14	£0
July	91,618	123,508	-31,890	500	£2,372.90	£0
August	101,835	153,727	-51,892	518	£1,782.37	£0
September	71,795	161,099	-89,304	367	-£1,484.85	£0
October	65,185	123,965	-58,781	355	-£188.48	£0
November	73,079	92,942	-19,863	388	£2,182.58	£0
December	81,724	80,904	821	389	£3,638.55	£0
Annual	984,624	1,441,610	-456,986	547	£19,560.21	£0

Figure 68: Grid Electricity Exchange

3.3.2 Reducing the PV Capacity

The converter size was fixed at 1032kW and the PV capacity was reduced to 1050kW, 800kW, 550kW and 300kW.

3.3.2.1 Simulation Results



Architecture		Cost			
PV (kW)	Converter (kW)	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
1,389	1,032	$0.0436	$1.79M	$44,611	$1.21M
1,050	1,032	$0.0526	$1.83M	$68,936	$943,200
800	1,032	$0.0624	$1.89M	$88,552	$743,200
550	1,032	$0.0751	$1.96M	$109,888	$543,200
300	1,032	$0.0900	$2.10M	$135,523	$343,200

Figure 69: HOMER Best Configuration

PV Size (kW)	PV Generation (kWh/year)	Green Electricity Used (%)	Green Electricity Used (kwh/year)	Fraction Of Load Met By Green Electricity (%)	Import (kWh/year)	Export (kWh/year)
1389	2,337,740	32	753184	43	984618	1441769
1050	1,767,190	40	717839	41	1019963	960991.8
800	1,346,430	50	676246	39	1061556	602863.6
550	925,671	64	595564	34	1142238	283824
300	504,911	82	417167	24	1320635	62499.13

Table 28: Impact of Increased PV Capacity on the System

It can be seen from the above table 28 that as the PV size reduces from 1389kW to 300kW the import increases by 34% times but the export significantly reduces by 96%. Moreover, green electricity consumed locally increase from 32% to 82% and fraction of load met by green electricity decreases from 43% to 24%. Having a larger PV capacity has little effect on the grid import than export. Although PV generation varies over days and hours but generates electricity only during the daytime and meets the demand during that period. As mentioned earlier and also in the section 1.4 (Aim & Objective) that it is important to install a PV system that has high renewable fraction, aligns with the aim of the community, reduces the reliance on grid, lowers CO_2 emissions and is economically feasible without having to oversize. The only advantage of bigger PV is that the system benefits from FIT but may not necessarily increase the fraction of load met from the PV.

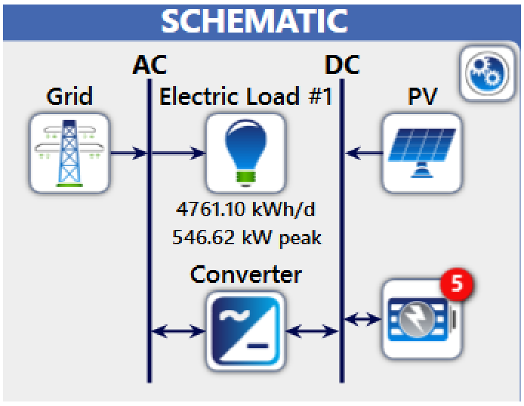
For the PV capacity of 1389kW and 1050kW, the fraction of load met by the green electricity only increases by 2% but the green electricity consumed decreases by 8%. Also, the grid import reduces slightly, about 3.5%. However, the area required increase by about 33%. The increase in area required isn't practical for such a difference in fraction of load met or import reduced, considering the COE of both the system is still lower than the grid purchase price. Proving both systems has financial benefits.

HOMER selects the best option of 1389kW PV because of low NPC and low COE. In the next analysis, we add storage system to PV of 1389kW capacity to further reduce the grid export/import, increase the renewable energy fraction and study the feasibility of implementing a PV system with storage.

3.3.3 Storage

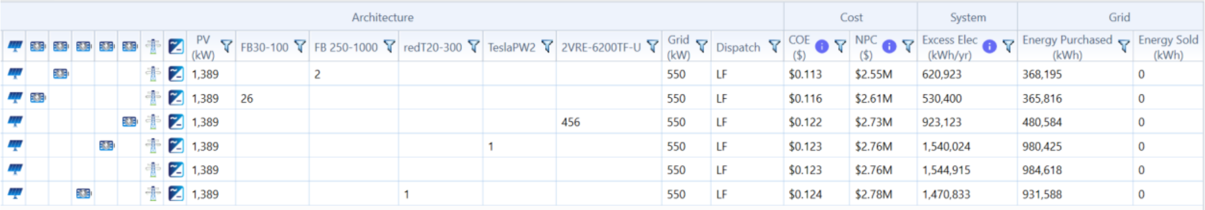
The grid was set at 550kW, converter size of 1032kW was selected and grid export set to 0kW to make full use of the energy storage and restrict from selling to the grid. The HOMER simulation takes into account capital, replacement and O&M cost set for batteries and selects the best option based on lowest NPC. It determines if its profitable to sell the surplus electricity to the grid or store it in batteries to keep the NPC as low as possible.

In this simulation, we direct the surplus energy to be stored in the batteries by restricting the grid export to increase the onsite consumption of the RES. Also, for this analysis LF strategy was selected as explained in section 2.12.4.



System Configuration with Storage

3.3.3.1 Simulation Results



Architecture								Cost		System	Grid	
PV (kW)	FB30-100	FB 250-1000	redT20-300	TeslaPW2	2VRE-6200TF-U	Grid (kW)	Dispatch	COE ($)	NPC ($)	Excess Elec (kWh/yr)	Energy Purchased (kWh)	Energy Sold (kWh)
1,389		2				550	LF	$0.113	$2.55M	620,923	368,195	0
1,389	26					550	LF	$0.116	$2.61M	530,400	365,816	0
1,389					456	550	LF	$0.122	$2.73M	923,123	480,584	0
1,389				1		550	LF	$0.123	$2.76M	1,540,024	980,425	0
1,389						550	LF	$0.123	$2.76M	1,544,915	984,618	0
1,389			1			550	LF	$0.124	$2.78M	1,470,833	931,588	0

Figure 70: HOMER Best Configuration

It can be seen that HOMER selects the best option of two FB 250-1000 batteries. This results in reduction of grid import by 63% compared to system with no storage and increase the fraction of load met by renewable energy as shown in the table 29 below. Since the grid sale is restricted excess energy that cannot be stored in batteries is curtailed and as the battery size increases less energy is curtailed. It can be seen from figure 70 above that as the battery capacity increases more energy is stored and utilised later during the day than battery of small capacity.

Battery	Number Of Batteries	Green Electricity Used (%)	Green Electricity Used (kWh/year)	Fraction Of Load Met By Renewable Energy (%)
FB 250-1000	2	58.59	1369607.2	78.8
FB 30-100	26	58.68	1371985.5	78.9
2VRE-6200TF-U	456	53.778	1257217.6	72.3
TeslaPW2	1	32.40	757377.4	43.6
redT 20-300	1	34.49	806214.2	46.4
No Battery	No Battery	32.22	753184	43.3

Table 29: Impact of Batteries on the System

Using two FB 250-1000 batteries increases the green electricity used in the system compared to system with no storage from 32% to 59%. Fraction of load met by green electricity increases from 43% to 78.8%. Import is also reduced by 63%. It can also be seen that having 26 FB 30-100 batteries have a slight increase of 0.09% of green electricity used and 0.1% increase in fraction of load met compared to 2 FB250-1000 battery, but has a higher NPC and COE. Also, 456 batteries of 2VRE-6200TF-U provide a high fraction of green electricity used and load met by green electricity of 53.78% and 72.3% respectively. However, it requires a large number of batteries to achieve high percentage of green electricity used and fraction of load met by green electricity. The values are still lower than both the vanadium flow batteries, FB250-1000 and FB30-100. There is not much difference in green electricity and fraction of load met by renewables between a system with 1 TeslaPW2, 1 RedT20-300 and a system with no battery. These results were produced by HOMER based on NPC value.

Months	Import Reduction (%)	PV Output	AC Primary Load
Jan	56	156542.2456	123088.8493
Feb	73	169668.2644	113348.8762
March	73	198473.134	121879.0335
April	54	195065.268	160295.9792
May	59	219904.2361	186382.4375
June	62	226709.0752	185233.7153
July	66	233209.6971	188767.1516
Aug	59	235846.9502	169605.0469
Sept	77	223776.7302	118393.3676
Oct	81	199818.5854	129186.1224
Nov	55	148498.6465	117867.2166
Dec	47	130086.838	123753.7091

Table 30: Monthly Grid Import Reduction due to FB 250-1000

It can be seen from table 30 that the FB 250-1000 battery has significant impact on the imports in the months of September and October with an import reduction of 77% and 81% respectively. This is because the PV output is significantly higher than the AC load during these months allowing large amount of surplus energy to be stored and used later in the day reducing grid import. Import reduction is lowest during the month of December, this is because the PV output is low during this month due to hours of sun being less compared to summer months and has a lower clearness index of 0.46 and solar radiation of 2.650kW/m2/day. Compared to average clearness index and solar radiation of 0.6 and 6kW/m2/day respectively during the summer as shown in table 1. The clearness index is significant to the performance of PV since a value over 0.5 indicates clear skies which is important for PV for generating electricity[xxxi].

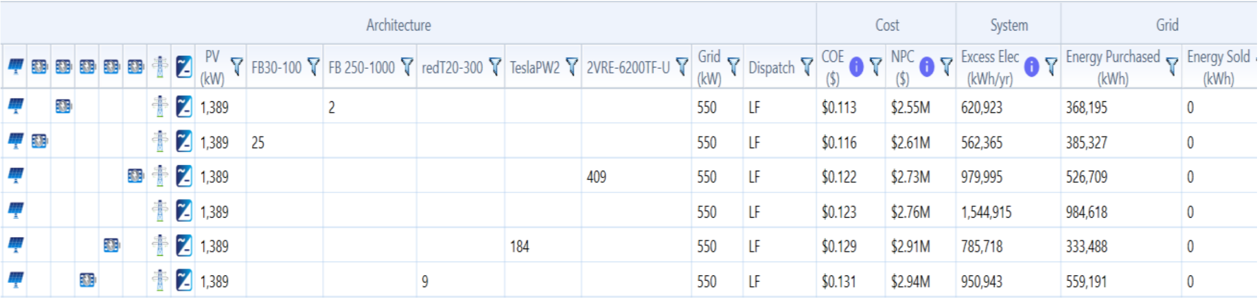
Since the storage option selected for PV of capacity 1389kW and converter of 1032kW was 2 FB-1000 battery with a total nominal capacity of 2480kWh, further analysis was carried out for the rest of the batteries by scaling their nominal capacity to 2480kWh to study the performance of battery with a higher nominal capacity.

Number of batteries for each battery type to achieve a nominal capacity of 2480kWh are given in the table 31 below.

Battery Type	**FB250-1000**	**redT20-300**	**2VRE-6200TF-U**	**TeslaPW2**	**FB 20-300**
Number of Batteries	2	25	409	184	9

Table 31: Number of Batteries Required to Achieve a Nominal Capacity of 2480kWh

Results



Architecture									Cost		System	Grid	
PV (kW)	FB30-100	FB 250-1000	redT20-300	TeslaPW2	2VRE-6200TF-U	Grid (kW)	Dispatch		COE ($)	NPC ($)	Excess Elec (kWh/yr)	Energy Purchased (kWh)	Energy Sold (kWh)
1,389		2				550	LF		$0.113	$2.55M	620,923	368,195	0
1,389	25					550	LF		$0.116	$2.61M	562,365	385,327	0
1,389					409	550	LF		$0.122	$2.73M	979,995	526,709	0
1,389						550	LF		$0.123	$2.76M	1,544,915	984,618	0
1,389				184		550	LF		$0.129	$2.91M	785,718	333,488	0
1,389			9			550	LF		$0.131	$2.94M	950,943	559,191	0

Figure 71:Best HOMER Configuration

Battery Type	Number Of Batteries	Import Reduction (%)	Green Electricity Used (kWh/Year)	Green Electricity Used (%)	Increase In Green Electricity Used (%)	Fraction Of Load Met By Green Electricity (%)
No Battery	/	/	753,184	32	/	43
FB 250-1000	2	63	1,369,607	59	82	79
redT 30-100	25	61	1,352,475	58	80	78
2VRE-6200TF-U	409	46	1,211,093	52	61	70
TeslaPW 2	184	66	1,404,314	60	86	81
FB 20-300	9	43	1,178,611	50	56	68

Table 32: Impact of Batteries on the System

It can be seen from the above table 32 that tesla battery has the highest green electricity consumption of 60% and highest fraction of load met by green electricity of 81%. for the same capacity. This is because for the same capacity tesla battery have a faster charge and discharge rate. Tesla battery also reduces the import from grid by 66%. The next best solution in terms of green energy and fraction of load met by green electricity is FB250-1000. Although tesla battery is better in terms of performance but they have a higher COE, NPC and large amounts of batteries are required to achieve the results. From figure 71, another thing to be highlighted is that for the same capacity FB 30-100 has the least excess electricity.

It can be seen from table 29 and 32 that higher the useable nominal capacity, higher is the renewable fraction and lead to more efficient use of locally generated electricity as more energy can be stored, and discharged when required. However, due to small capacities of lead acid and Li-ion batteries a significant number of batteries are required to achieve the results. As the number of batteries for lead acid and Li-ion increases to achieve a high capacity, the COE and NPC also increases.

Further analysis is conducted only for academic purpose. For the system with no storage the PV has an annual output which exceed the primary load but there is a significant grid export of 1,441,769 kWh/year. For better management and consumption of locally generated electricity the battery is oversized based on the grid export. The impact of a larger battery capacity on the renewable electricity fraction and reduction in grid imports is studied.

Average exported energy per day:

$$Average\ Export\ per\ Day = \frac{Annual\ Export, kWh}{Number\ of\ days} = \frac{1{,}441{,}769kWh}{365}$$

$$Average\ Export\ per\ Day = 3950kWh/day$$

Number of batteries required for each battery type:

$$Number\ of\ Batteries\ Required = \frac{Average\ Export\ per\ Day, kWh}{Nominal\ Capacity, kWh}$$

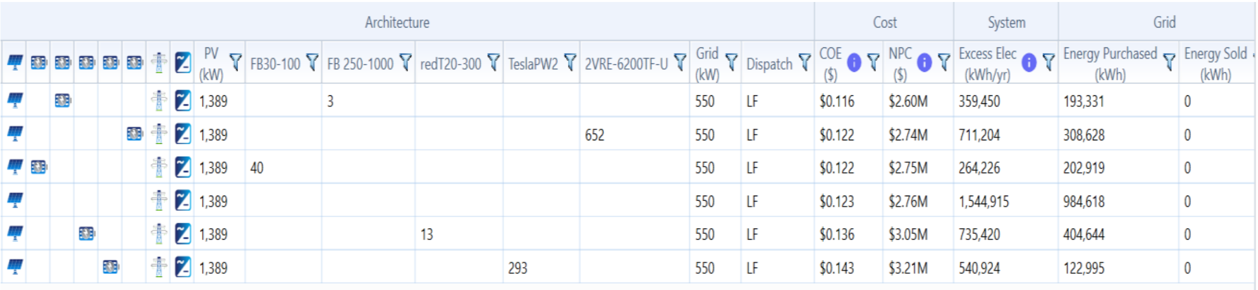
The table 33 below shows the number of batteries required for each storage type.

Battery Type	**FB250-1000**	**FB30-100**	**redT 20-300**	**TeslaPW2**	**2VRE-6200TF-U**
Number of Batteries Required	3	40	13	293	652

Table 33: Number of Batteries Required to Sturge Average Daily Export

Results

Optimisation was carried out by HOMER based on lowest NPC and results are presented below.



Architecture									Cost		System	Grid	
PV (kW)	FB30-100	FB 250-1000	redT20-300	TeslaPW2	2VRE-6200TF-U	Grid (kW)	Dispatch		COE ($)	NPC ($)	Excess Elec (kWh/yr)	Energy Purchased (kWh)	Energy Sold (kWh)
1,389		3				550	LF		$0.116	$2.60M	359,450	193,331	0
1,389					652	550	LF		$0.122	$2.74M	711,204	308,628	0
1,389	40					550	LF		$0.122	$2.75M	264,226	202,919	0
1,389						550	LF		$0.123	$2.76M	1,544,915	984,618	0
1,389			13			550	LF		$0.136	$3.05M	735,420	404,644	0
1,389				293		550	LF		$0.143	$3.21M	540,924	122,995	0

Figure 72: Best HOMER Configuration

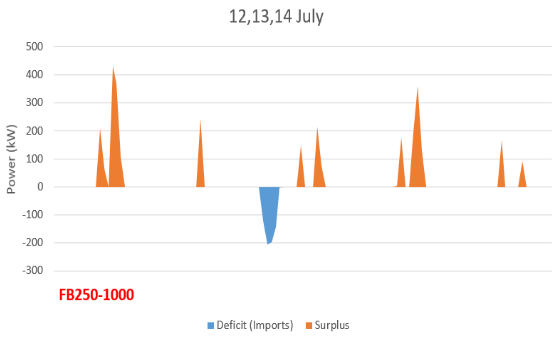
Battery Type	Number Of Batteries	Import Reduction (%)	Excess Electricity Reduction (%)	Green Electricity Used (kWh/Year)	Green Electricity Used (%)	Increase In Green Electricity Used (%)	Fraction Of Load Met By Green Electricity (%)
No Battery	/	/	/	753,184	32	/	43
FB 250-1000	3	80	77	1,544,471	66	105	89
2VRE-6200TF-U	652	69	54	1,429,174	61	88	82
redT 30-100	40	79	83	1,534,883	66	104	88
FB 20-300	13	59	52	1,333,158	57	77	77
Tesla PW2	293	87	65	1,614,807	69	114	93

Table 34: Impact of Batteries on the System

It can be seen from the table 34 above that Tesla batteries have the highest import reduction of 87% and green electricity used of 69%. It also increases the green electricity consumption from 32% to 114%. This is because Li-ion batteries have faster charge discharge rate. However excess electricity reduction is only 65% which is lower that FB250-1000 and FB30-100 vanadium batteries this is because vanadium batteries have higher usable nominal capacity than lithium ion battery and a 100% depth of discharge. Therefore, they are able to store more energy compared to Li-ion battery. This is being illustrated with the help of figures 72-80 below. The figures are based on results from table 34.

Although Li-ion batteries have higher performance than vanadium batteries, the COE and NPC are higher than vanadium batteries. Also, from the above storage simulations in table 32 and 34 it was observed that Li-ion batteries have a better energy performance than vanadium redox flow batteries when the capacity exceeds 2MWh. However, requires large number of batteries are required to achieve the results. On the other hand, large scale storage technologies such as vanadium batteries require fewer batteries and have higher storage capacity therefore are better storage option because of overall energy performance, cost and practical feasibility of installation.

Summer Week (12-14 July)



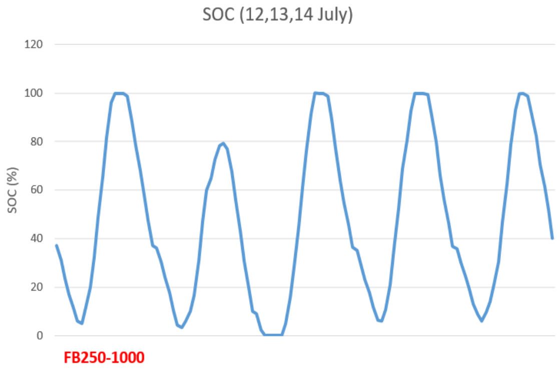
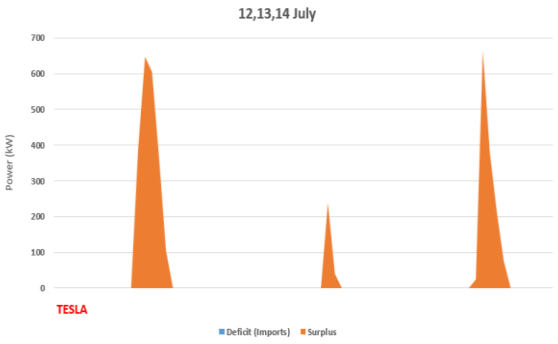


Figure 73:FB 20-1000 Surplus & Deficit for a Summer week

Figure 74: SOC for FB 250-1000 in Summer week



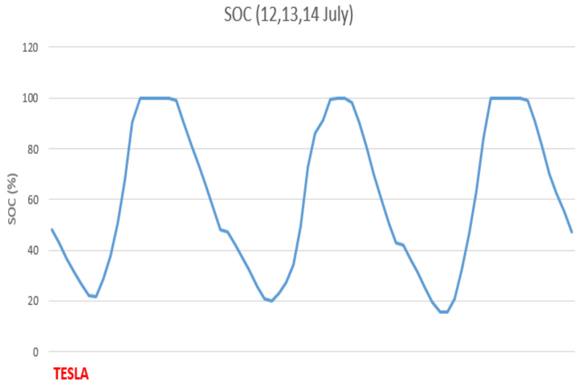
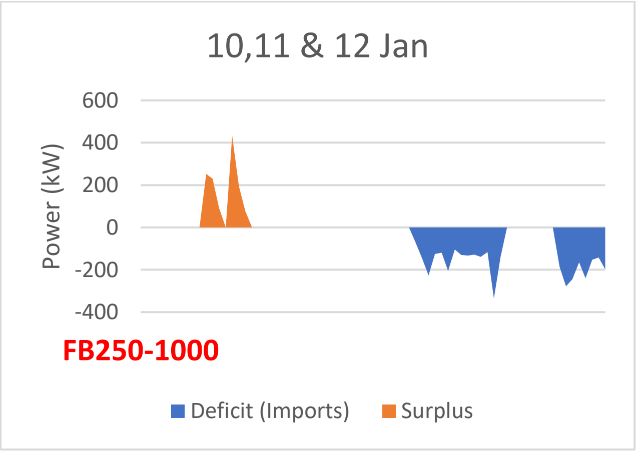


Figure 75: TESLA Surplus & Deficit for a summer week

Figure 76: SOC for a TESLA Battery in a Summer Week

Winter Week (10-12 Jan)



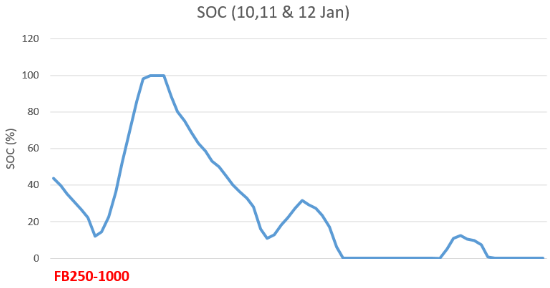


Figure 77: FB 20-1000 Surplus & Deficit for a Winter Week

Figure 78: SOC for a FB250-1000 Battery in a Winter Week

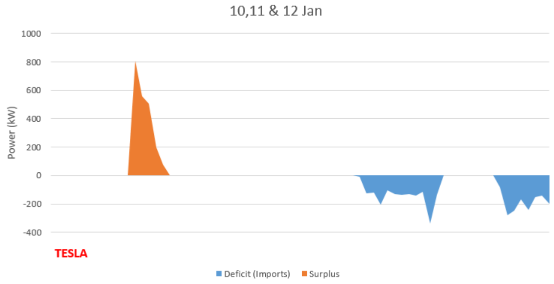


Figure 79: TESLA Surplus & Deficit for a summer week

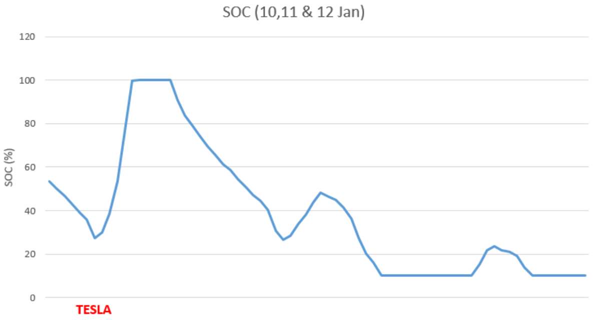


Figure 80: SOC for a TESLA Battery in a Winter Week

Two batteries were considered, FB 250-1000 and Tesla, in figures 72-80. As already mentioned earlier and also from the figures it can be seen that for the same days in summer and winter, vanadium battery has less excess (surplus) energy being curtailed than tesla battery due to higher usable nominal capacity and a 100% DOD, vanadium batteries are able to store more energy compared to Li-ion battery.

3.4 Changing Grid Prices and FIT Rates for Scenario 2

3.4.1 Sensitivity Analysis

Since HOMER selects the PV capacity based on the lowest NPC value, which is dependent on the prices set for grid purchase price, grid sellback price, and PV. In this section, we vary the prices of grid purchase and grid sellback to see the effect it has on the PV capacity selected. The prices of PV and converter we not changed.

1) ***<u>Without Storage and Grid Export Permitted</u>***

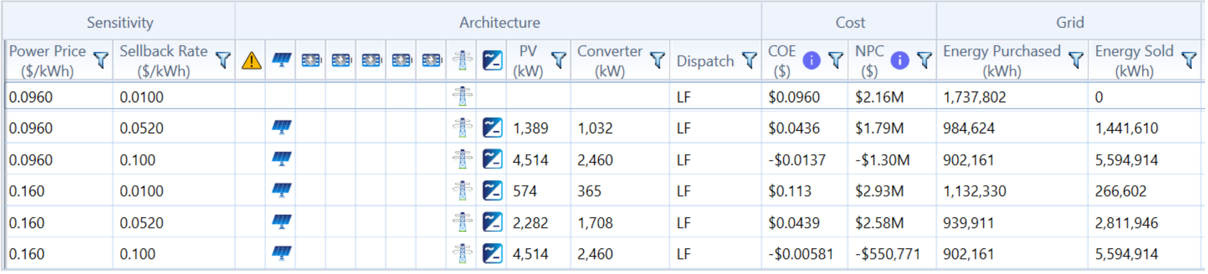
Effect of sellback price and grid purchase price was studied on the system. Current assumption made for Kuwait is for year 2025, where the cost of electricity was assumed to be \$0.16/kWh (section 3.3), and it was further assumed that the subsidies would drop to 40%, compared to current 60%.

For this section, two different grid purchase prices were considered:

1) with 40% subsidy, i.e. \$0.096/kWh

2) No subsidy, i.e. \$0.16/kWh

Sellback prices were also changed: $0.01/kWh, $0.052/kWh and $0.1/kWh.



Sensitivity		Architecture			Cost		Grid	
Power Price ($/kWh)	Sellback Rate ($/kWh)	PV (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Energy Purchased (kWh)	Energy Sold (kWh)
0.0960	0.0100			LF	$0.0960	$2.16M	1,737,802	0
0.0960	0.0520	1,389	1,032	LF	$0.0436	$1.79M	984,624	1,441,610
0.0960	0.100	4,514	2,460	LF	-$0.0137	-$1.30M	902,161	5,594,914
0.160	0.0100	574	365	LF	$0.113	$2.93M	1,132,330	266,602
0.160	0.0520	2,282	1,708	LF	$0.0439	$2.58M	939,911	2,811,946
0.160	0.100	4,514	2,460	LF	-$0.00581	-$550,771	902,161	5,594,914

Figure 81: HOMER Best Configuration

It was observed that as the grid purchase price increase along with sellback price, higher PV capacity is selected by HOMER. HOMER selects higher PV capacity as the best option with the lowers NPC. This analysis highlights the impact of different incentives, purchase price and regulations on the renewable capacity selected.

2) *With Storage and Grid Export Restricted*

The PV capacity is set to 1389kW and converter size of 1032kW. Gird export is restricted and gird purchase is set to 550kW for this scenario as explained in section 3.3.3. Since in this case the grid is restricted changing the sellback price will not make a difference to the battery size or type selected, we only change the grid purchase price and analyse the impact on the battery size and the type selected by HOMER.

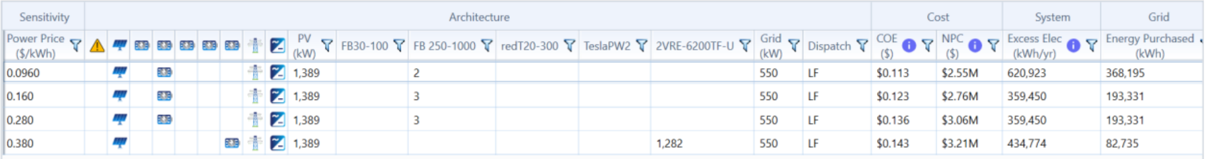
Hence sellback price was ignored in this and grid purchase price was changed to:

1) $0.096/kWh, i.e. 40% subsidy

2) $0.16/kWh, i.e. No subsidy

3) $0.28/kWh, since the cost of electricity increased by $0.14/kWh between 2004 to 2017 in Kuwait in the past 13 years, a grid price was selected as $0.28/kWh in the next 13 years (i.e. 2030) from current price of $0.14/kWh (2017).

4) $0.38/kWh, further increase in grid purchase price was considered.



Sensitivity	Architecture								Cost		System	Grid
Power Price ($/kWh)	PV (kW)	FB30-100	FB 250-1000	redT20-300	TeslaPW2	2VRE-6200TF-U	Grid (kW)	Dispatch	COE ($)	NPC ($)	Excess Elec (kWh/yr)	Energy Purchased (kWh)
0.0960	1,389		2				550	LF	$0.113	$2.55M	620,923	368,195
0.160	1,389		3				550	LF	$0.123	$2.76M	359,450	193,331
0.280	1,389		3				550	LF	$0.136	$3.06M	359,450	193,331
0.380	1,389					1,282	550	LF	$0.143	$3.21M	434,774	82,735

Figure 82: HOMER Best Configuration

It can be seen from the above table that HOMER selects different number and type of batteries based on the different grid purchase prices set. HOMER selects FB250-1000 for when the grid price is \$0.096/kWh, \$0.16/kWh and \$0.28/kWh, but the number of batteries increases from 2 for the grid price of \$0.096/kWh to 3 for the grid purchase price \$0.16/kWh and \$0.28/kWh. However, 2VRE-6200TF-U (lead acid battery) is selected when the grid price significantly increases to \$0.38/kWh. Regardless of the type of battery, as the grid price increases the capacity of battery selected increases. This is because HOMER runs on the principle that is based on reducing NPC, and it is more profitable to draw more electricity from the battery as grid price increase to meet the load rather than importing it from the grid. Since the grid export is restricted the electricity than cannot be stored is curtailed, but because the capacity of storage selected increases with the increase in grid price, less energy is curtailed and imported to meet the load as it can be seen from the figure 82, which leads to more consumption of locally generated green electricity compared to scenario with no storage.

3.5 Validation of HOMER Results

Average annual solar insolation for Kuwait = 2080 kWh/m^2/year

Module efficiency = 13%

Area of 1kW is estimated = 7m^2

Area required for 1389 kW = 9513m^2

Daily average insolation = 5.2 kWh/m^2/day

Therefore, annual average insolation = 1898 kWh/ m^2/year

$$\begin{aligned} &Annual\ Output\ Power\ (AOP) \\ &\qquad = Average\ insolation\ /m2/year\ x\ module\ efficiency\ x\ module\ area \end{aligned}$$

$$AOP\ =\ 1898\ kWh/m2/year\ x\ 0.13\ x\ 9513\ m2$$

$$AOP\ =\ 2{,}347{,}237.62\ kWh/year$$

HOMER gives a value of 2,337,740 kWh/year as can be seen from figure 85 given below in section 5. The value of AOP calculated and the value provided by HOMER are similar with only a difference of 0.41%.

4 Discussions

The aim of the project was to design and access the feasibility of a PV and storage system to meet the demand of residential community in Kuwait. Objective of the project further included having a high renewable fraction, reducing the CO_2 emissions and grid import. The overall system had to be both technically and financially feasible.

Two scenarios were considered. Scenario 1 was based on the current situation (2017) and was further divided in to grid export restricted and grid export allowed. Scenario 2 was based on the future situation, 2025. The assumption made and approach for scenario 1 & 2 are given in the section 3.1, 3.2 and 3.3.

4.1 Scenario 1

A comparison is made between the system that allowed grid export and restricted grid export in terms of imports, green electricity used, NPC, COE, and fraction of load met by green electricity and the difference between the two systems is shown below.

PV (kW)	Decrease In Imports (%)	Increase In Green Electricity Used (%)	Increase In Fraction Of Load Met (%)	Decrease In CO_2 (%)	COE Decrease (%)	NPC Increase (%)
150	0.52	3.45	1	0.78	0	0
300	1.22	4.07	1	5.89	0.31	3.43
450	0	0	0.16	13.65	8.57	0
600	0.82	1.56	1	30.48	13.51	3.66
750	1.36	2.27	0.59	50.48	17.17	8.41
900	1.69	2.56	1	71.58	24.47	7.98
1050	0.25	0.36	0.3	91.19	30.88	6.04
1200	0.78	1.08	0.12	107.38	34.73	7.27
2000	1.44	1.80	0.48	248.02	52.76	11.76

Table 35: Difference in Impact of PV on system for Both Scenarios

As the size of the PV capacity increases from 150kW to 2000kW in each case, there is a significant reduction in CO_2 emissions, grid import and increase in fraction of load met by green electricity as can be seen in tables 18 to 24.

However, it can be seen from the above table 35 that restricting the grid has little effect on the load met by green electricity. This is because the PV generates electricity during the daytime when the load may not he high and having the option to export only means that the excess useable energy can be exported to the grid, rather than being curtailed. This has financial benefits but due to unavailability of FIT, as in our case, it doesn't apply to us.

Although with the grid export permitted, as the PV capacity increases from 150kW to 2000kW the COE decreases to about 53% but is still significantly higher than the current grid purchase price which is \$0.05/kWh. Also, the NPC increases by 12%. Despite the potential of meeting a significant amount of load with the increase in PV capacity the project under current situations is not economically feasible.

Since the PV capacity selected for 1st scenario is 150kW, there is no effect on COE and NPC if the grid export restriction is applied. However, it increases the green electricity use and fraction of load met by green electricity use by 3.45% and 1% respectively with grid export allowed as seen from the table 35. Also, there is a negligible decrease in grid import and CO_2 emissions of 0.52% and 0.78% respectively. The COE is still higher than the grid purchase price by \$0.007.

Even though the government is encouraging public through various campaigns to install PV units to meet part of their demand though RE, this system is only possible without the investment from the government. Also, the current prices of Renewable Energy Technologies (RET) are high.

4.2 Scenario 2

For the PV system alone considering the input data, the best option given by HOMER based on the lowest NPC was 1389kW of PV, with a COE of \$0.0436/kWh and \$1.79M.

However, despite the large renewable energy output the fraction of load met by the PV was only 43% and green electricity used was 32%. This highlights the limitation of solar energy. It was decided to further investigate how the renewable fraction could be increased in the system by adding storage & analysing the feasibility of such a system. Since 1389kW of PV occupied a large area and only met less than 50% of the load, despite the PV's annual output exceeding the annual load. It was important to make the most of the locally generated electricity, further reducing the dependency on grid.

Another approach adopted was the of reduction of PV capacity and the ability of PV to meet only the load during daytime. This was done because some of the PV projects undertaken by the Kuwait government installed PV capacity of a reasonable size so they would meet the peak load during day time in summer.

These two-analyses helped in concluding if PV and storage was a feasible option or not. The model selected based on these two approaches is given in section 5.

Reducing PV Capacity

The PV size was decreased from 1389kW to 1050kW, 800kW, 550kW and 300kW. It can be seen from the table 28 as the PV capacity decreased from 1389kW to 300kW, as expected, the fraction of load met by the PV also decreased from 43% to 24% and imports increased by 34%. The export significantly decreased by 96% and green electricity consumed significantly increased from 32% to 82%. Also, the COE and NPC increased from \$0.0436/kWh and \$1.79M to \$0.090/kWh to \$2.10M, respectively. Although there is a slight difference between the COE of 300kW PV and grid purchase price, it is still lower than the grid purchase price, meaning that the system is still economically viable. Also as the PV capacity decreases from 1389kW to 300kW the area required also decrease from 9723m^2 to 2100m^2, that is a 78% decrease.

It was also found that after a certain PV capacity increasing the PV capacity further doesn’t guarantee a high renewable fraction. This is explained in table 28 between PV capacity of 1389kW and 1050kW. As the PV capacity increase from 1050kW to 1389kW (339kW increase) there is only a 2% increase in the fraction of load met by the green electricity and 8% reduction in the green electricity consumed. The imports were further reduced only by 3.5%. The drawback of this slight difference in electricity consumption by the community is that the areas required increases by 33%, from 7350m^2 to 9723m^2. The increase in area required is impractical for such a slight difference of renewable energy on the overall system.

Storage

With PV of large capacity such as 1389kW selected by HOMER it would be beneficial to add a storage system to make better use of the locally generated electricity. This section discusses the effect of batteries on the system.

HOMER selected the 2 FB 250-1000 vanadium battery as the best financial option. It increases the green electricity consumed from 32% to 59%. Also, the fraction of load met by the green electricity increased from 43% to 79%. It was also found that the best use of storage was in the months of September and October reducing the imports by 77% and 81% respectively. To achieve the same results as FB 250-1000 battery 26 FB 30-100 batteries were required. This however increase the COE and NPC of the system.

Further analyses were carried out by increasing the nominal capacity of all the batteries above 2MWh. It was found that the Li-ion battery had a better energy performance than vanadium and lead acid battery when the nominal capacity exceeded 2MWh. Due to the minimum state of charge of each battery type, the useable nominal capacity was affected. For example, for a nominal capacity of 2MWh the useable nominal capacity for vanadium, Li-ion and lead acid battery are 2MWh (min SOC=0%), 1.8MWh (min SOC=10%) and 1.6MWh (min SOC=20%) respectively.

Li-ion batteries had a better energy performance than the vanadium and lead acid batteries due to faster charge-discharge rates and higher round trip efficiency. The round-trip efficiency of Tesla battery was 90% compared to 85% of lead acid and between 64% to 75% for the three vanadium batteries selected. Round trip efficiency is important when considering a battery for storage purpose. In general terms round trip efficiency is the ratio of energy in to energy out of the storage expressed in percentage (%). Higher the round-trip efficiency the more efficient is the system. Since it results in less energy lost due to storage. Ideally the grid system engineers prefer a storage with a round trip efficiency of 80% if possible **Error! Bookmark not defined.**.

However, the vanadium batteries have a higher storage capacity and are able to reduce the excess energy more than other battery types. This is due to their nominal capacity equalling to useable nominal capacity since the DOD is 100%. Whereas, the state of charge of Li-ion and lead acid batteries were 10% and 20% respectively.

Considering the financials and energy performances for large scale energy storage, vanadium batteries would be the best choice than Li-ion and lead acid. This is mainly due to large storage capacity and lower number of batteries required.

5 Model Selection, HOMER Limitations and Future Work

For scenario 1 it wasn't economically feasible to install the PV panels under current grid tariffs and high price of RET without the investment from the government.

For scenario 2 the PV capacity selected by HOMER was 1389kW as the best option and the system was able to meet 43% of the load from green electricity. The PV system alone was feasible to install and the COE was significantly lower. Also, HOMER allowed for a more realistic technical and financial analysis for this case considering there was a two-way flow of electricity. However, battery modelling in HOMER was based on a one-way flow of electricity since the grid export had to be restricted to make full use of the battery and the battery energy performance was then analysed. This resulted in significant amount of useful energy being curtailed which could have been potentially sold to the grid resulting in a lower NPC and COE. This was not possible due to the limitation of HOMER for modelling batteries and a special control setup was set which required grid exports to be restricted.

It was found that the HOMER software is a better for modelling an off-grid system rather than a grid tied system when storage system is added. Although a realistic financial case was not possible in this setup it did allow to study the battery performance and provided with in depth analysis and impact of PV and battery systems for the community.

The financial analysis could have been improved by using other softwares that allowed for modelling a system with two-way flow of electricity when batteries were added. This would allow for the energy that is curtailed during HOMER battery modelling due to restriction of grid to be sold and generate extra income. Further reducing the COE and NPC and giving a more realistic output and analyses of the financials.

However, HOMER is treated as a pre-planning tool that allows to access the feasibility of different system designs. Also, providing with multiple simulation options, such as economic comparison, chronological simulations, sensitivity analysis and optimisation to access the impact of different renewable energy systems on the community and the grid.

The system cost provided by HOMER in models with storage system doesn't necessarily mean that the system is not viable, this is just a worst-case financial scenario presented by HOMER.

This shouldn't discourage from selecting a model provided reasonable and realistic assumptions are made.

However, the main scenario considered was with a gird purchase price of \$0.096/kWh this was after a subsidy assumed of 40%. The original COE however was assumed as \$0.16/kWh at the start of the simulations. The system selected by HOMER of 1389kW PV and 2 FB 250-1000 vanadium battery had a COE of \$0.113/kWh in the worst case financial scenario. This shows that such a system is a viable option even in the worst case financial scenario. Furthermore, from section 3.4 it was found that as the grid purchase price increased to \$0.16/kWh, \$0.28/kWh, and \$0.38/kWh the PV-storage model selected by HOMER was a more economically viable option even in the worst case financial scenario when the grid export was restricted. This shows that the grid tariffs play a major role in designing a system.

Other limitations of the software are: HOMER presents the best system option based on Net Present Cost (NPC) and selects the system with the lowest NPC. NPC is also referred as lifecycle cost. The software does not take into account multiple criteria and focusses solely on NPC. Also, Battery modelling is challenging and the grid exports have to be adjusted to direct the surplus energy to charge the batteries rather than exporting to the grid.

It can be concluded based on the simulations done that PV and storage can be an option for meeting the electrical demand of Kuwait's residential sector with high renewable fraction. Ultimately the decision of installing a renewable system with storage depends on the requirements of the community: such as percentage of electricity met by the renewable, percentage reduction in grid imports or percentage reduction in CO_2 and other government aims and tariffs offered. Considering all the above results and HOMER limitations it was decided for this project PV capacity of 1389kW and two Fb 250-1000 would be selected. This has a potential of meeting the load during the day and part of the demand during the evenings as shown in the figures 83 and 84 below.

With Storage

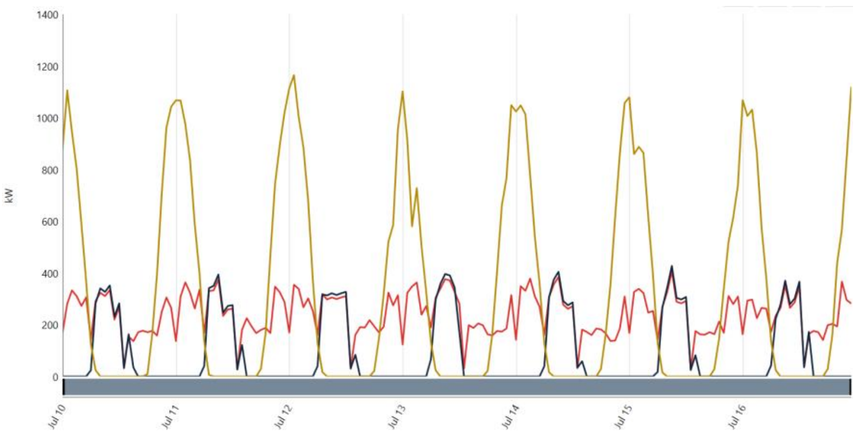


Figure 83: Load Met by PV and Battery During a Week in Summer

Without Storage

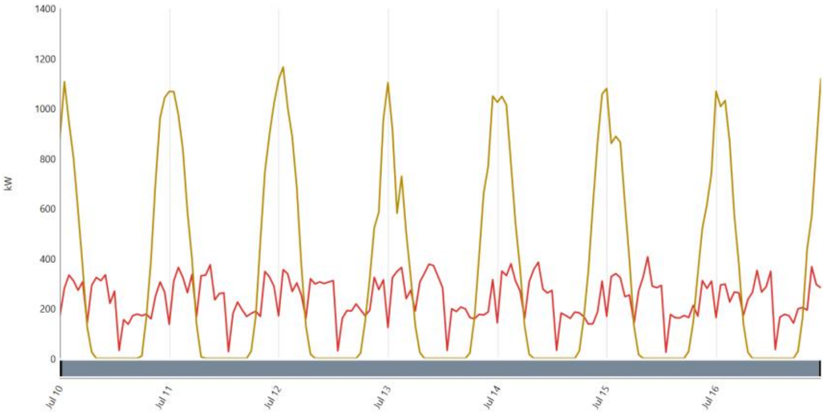
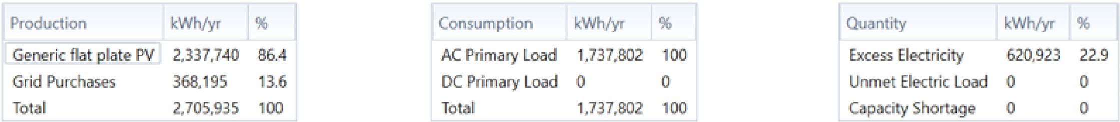


Figure 84: Load Met by PV During a Week in Summer

It can be seen in figure 83 and 84 that with the addition of storage system during a week in July which the peak month, most of the demand during the evenings are met by the renewable energy, further reducing the reliance on grid.

Electricity Generation



Production	kWh/yr	%
Generic flat plate PV	2,337,740	86.4
Grid Purchases	368,195	13.6
Total	2,705,935	100

Consumption	kWh/yr	%
AC Primary Load	1,737,802	100
DC Primary Load	0	0
Total	1,737,802	100

Quantity	kWh/yr	%
Excess Electricity	620,923	22.9
Unmet Electric Load	0	0
Capacity Shortage	0	0

Figure 85: Electrical Data

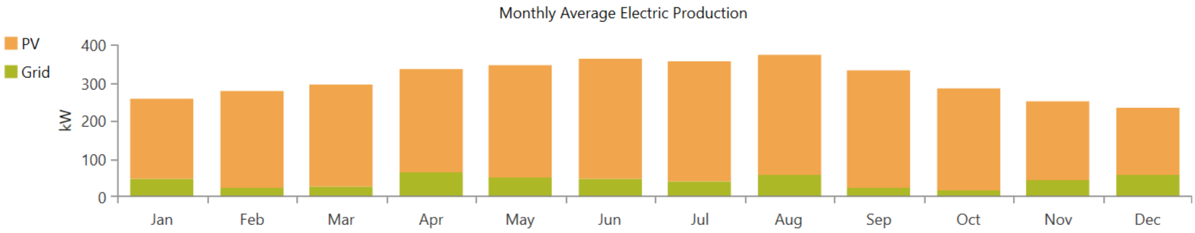
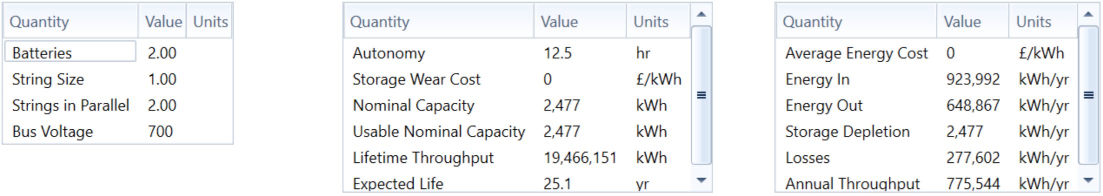


Figure 86: Individual Components Average Production

It can be seen from above that the total production of PV is 2,337,740kWh/year which accounts for 86.4% of total electricity generation and the gird imports accounts for 13.6% of the total electricity generation, i.e. 368,196kWh/year. Compared to a model with no storage, model with 2 FB 250-1000 batteries reduces the grid imports from 984,624kWh/year to 368,196kWh/year. Since the PV electricity production occurs roughly between 6am to 6pm, it generates more electricity than the demand resulting in excess energy being stored in the batteries and used later in the day. Hence significantly reducing the grid imports and resulting in higher use of green electricity on site. The PV production increase from 70.4% to 86.4% and grid imports reduces from 29.6% to 13.6% with the addition of batteries.

Gildemeister 250kW-4hr CELLCUBE® FB 250-1000



Quantity	Value	Units
Batteries	2.00	
String Size	1.00	
Strings in Parallel	2.00	
Bus Voltage	700	

Quantity	Value	Units
Autonomy	12.5	hr
Storage Wear Cost	0	£/kWh
Nominal Capacity	2,477	kWh
Usable Nominal Capacity	2,477	kWh
Lifetime Throughput	19,466,151	kWh
Expected Life	25.1	yr

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	923,992	kWh/yr
Energy Out	648,867	kWh/yr
Storage Depletion	2,477	kWh/yr
Losses	277,602	kWh/yr
Annual Throughput	775,544	kWh/yr

Figure 87: Gildemeister 250kW-4hr CELLCUBE® FB 250-1000

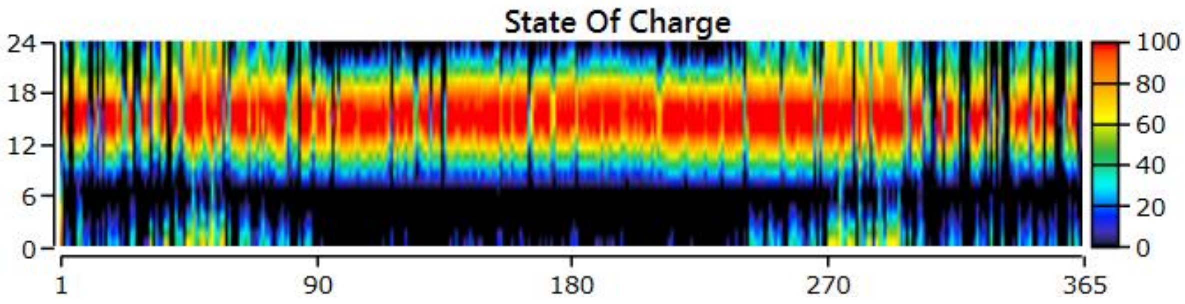


Figure 88: SOC for Gildemeister 250kW-4hr CELLCUBE® FB 250-1000

It can be seen from the above figure that the battery operates for 12.5 hours, has a nominal capacity and usable nominal capacity of 2,477kWh. This is because the DOD for FB 250-1000 is 100%. The battery starts charging after 7am and are fully charged between 12pm to 6pm and completely emptied out by morning.

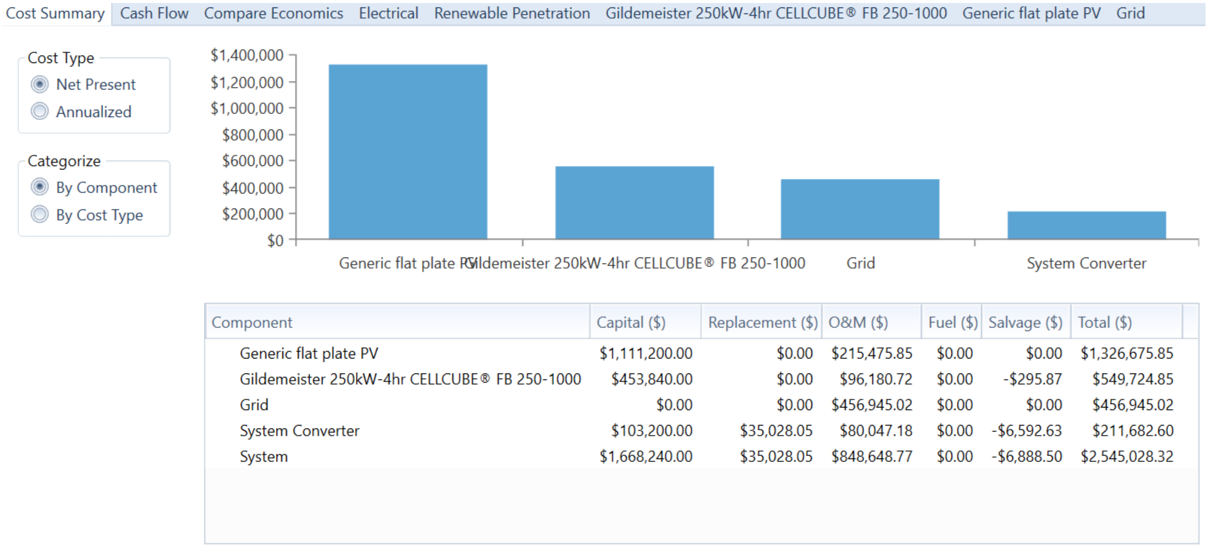
They have a life time throughput of 19,466,151kWh with annual throughput of 775,544kWh. Storage depletion occurs at the rate of 2,477kWh/year and losses at 277,602kWh/year

Future Work

As part of the future work, feasibility of wind turbine could be assessed in meeting the local demand. This would provide the much-needed energy mix and would also be able to meet part of the demand during the evenings since Kuwait has a reasonable amount of wind speed. Wind turbine was not included in this due to the short period of project and also there are no current or future provisions for installing wind turbines at residential level. Kuwait should consider providing incentives for installing wind turbines to meet the demand of a community. This would assist in a more efficient and reliable system. It was suggested in the report "Development of Renewable Energy Potential in Kuwait" that hybrid solar-wind can be a more reliable and environmentally friendly alternative for Kuwait .

Although HOMER does takes into account the cost of equipment's and tariffs but the major plus point of the software is the analysis of technical aspects. It is a great tool for pre-planning, designing and studying the feasibility of a hybrid system but doesn't account for the cost of land, labour, unexpected changes in the O&M cost of the equipment over the years, cost of transportation of the equipment's or Demand Side Management (DSM). To build a more realistic model these things should be taken into account.

6 Economics



Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	$1,111,200.00	$0.00	$215,475.85	$0.00	$0.00	$1,326,675.85
Gildemeister 250kW-4hr CELLCUBE® FB 250-1000	$453,840.00	$0.00	$96,180.72	$0.00	-$295.87	$549,724.85
Grid	$0.00	$0.00	$456,945.02	$0.00	$0.00	$456,945.02
System Converter	$103,200.00	$35,028.05	$80,047.18	$0.00	-$6,592.63	$211,682.60
System	$1,668,240.00	$35,028.05	$848,648.77	$0.00	-$6,888.50	$2,545,028.32

Figure 89: Cash Flow for a PV-Battery (Fb 250-1000) System

Based in the prices set for PV and Battery it was found that an initial capital of $1.69M is required this includes the capital cost for PV, FB 250-1000 battery, system converter and grid purchases. Further O&M cost for the whole system is around $848,649 over the lifetime of the project.

The lifetime of the project was set 25 and so was the life time of PV and the FB 250-1000 battery hence there were no replacement cost added for these two components. The only component replaced was the converter and cost $35,028 for the replacement. The NPC cost of the system was $2.55M.

The cost of electricity was reduced from $0.16/kWh to $0.113. The COE is lower even in the worst case financial situation. The main advantage of the system is that it guarantees a stable price of $0.113 for the PV-storage system. Unlike the COE for a fossil fuel based electricity generation which changes due to fluctuation in oil prices.

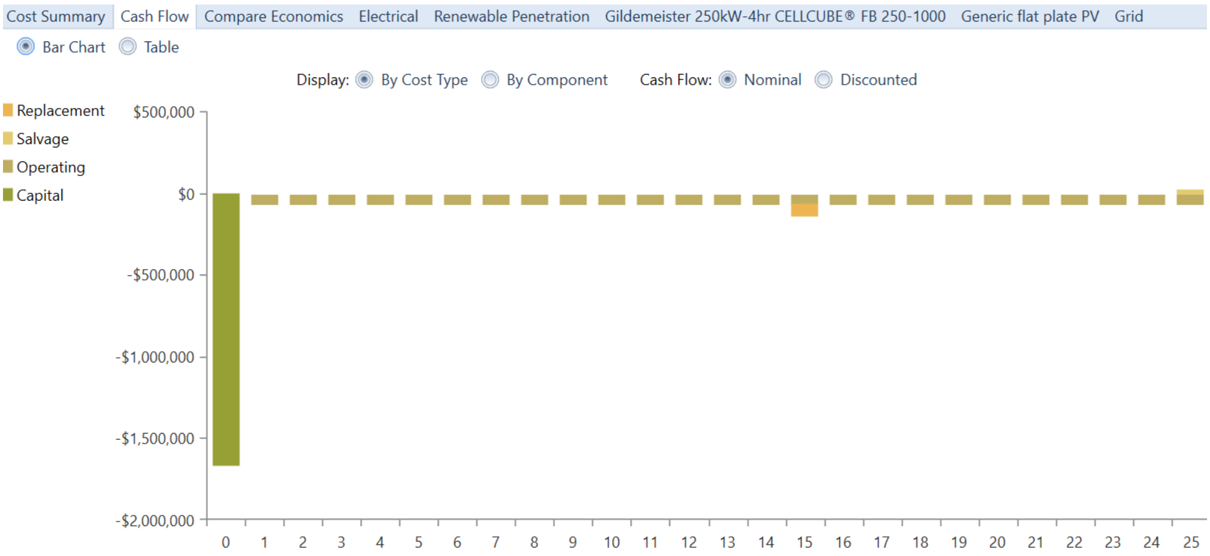


Figure 90: Cash Flow for a PV-Battery (FB 250-1000) System

7 Conclusion

The overall aim of the project was to access the feasibility of installing a PV-storage system in Kuwait to meet the electricity demand of a residential community. To achieve the aim and its objectives an intensive study of the Kuwait’s current generation system, policies and future aims were studied. It was concluded that in order for Kuwait to secure its power industry, diversification of the current power system is required not only to reduce its reliance of fossil fuels but also to maintain the cost of electricity production since prices of oil are unpredictable and likely to drastically increase in future.

The first step was to access the solar potential of the country followed by selecting a suitable location to carry out the study. The electrical demand data was not readily available for the households so a demand survey was carried out for the household and the load profile for the whole year was created using LoadProGen and MATLAB and then added to HOMER to carry out the modelling. A generic PV was used but various storage system types were considered and compared to achieve the optimum configuration which was economically feasible with high renewable fraction.

Under the current situation it is not possible to install a financially feasible PV system for residential sector with large capacities due to high prices of RET as well as lack of proper government policies and targets. In future with the decrease of RET prices for PV, batteries etc and government incentives it is possible to have large renewable capacity installed in meeting large fraction of load from the RES. This would also help in achieving a more de-centralised and distributed energy system ensuring more reliable supply of electricity and a sustainable price. Furthermore, reducing the stress on the gird, the amount of CO_2 and helping Kuwait achieve a stable and reliable grid and a green and eco-friendly image.

It was found that storage was important to ensure high renewable fraction. For the modelling, an understating of HOMER was gained and it was found that the best results were obtained based on the NPC value. Also, there were several restrictions during the battery modelling. HOMER was a valuable tool in designing a PV and storage system with high renewable fraction, it also gave an insight into the technical and financial aspect of the system. However, due to limitations of the software such as restriction imposed during the modelling of battery, the financial results obtained were for a one-way flow which represented a worst-case financial scenario and it not applicable in reality. This showed that HOMER was better for modelling an off-grid hybrid system and also a great pre-planning tool.

Although, there are options for various inputs (tariffs, price of components, charge-discharge cycle, depletion rate etc) and options for sensitivity analysis, HOMER take into account all of these to present the most cost-effective results. The results obtained from HOMER are only as reliable as the data added. Ultimately, the user is responsible for ensuring reliable results are achieved.

It is also recommended that Kuwait should not only should focus on diversifying its energy mix but also encourage the DSM in long term. There are no strict laws in Kuwait regarding the standards of appliances that are imported in the country. Energy efficiency certificates must be issued to all appliances especially to large power consuming appliances such as air conditioning which account for bulk of the electricity demand. Most of the A/C units in the country are inefficient. Also, for a balanced and coherent energy policy, it is very important to forecast the electricity demand and optimal distribution of energy resources [xvi].

From the simulations, it can be concluded that the community has a potential of meeting 79% of its electricity demand from PV-storage system. The CO_2 emission were lowered to 232,699 kg/year. However, it depends on the incentives provided by the government and the price of RET. Also, a further study could have been conducted to achieve a more realistic financial result for the system with addition of battery. The model can be applied to other housing types as well and is not limited to the community investigated in this project.

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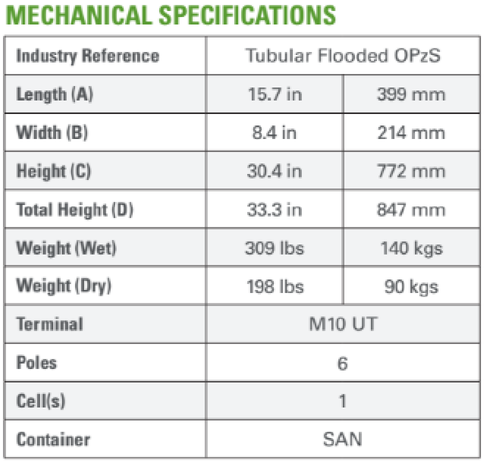
8 Appendix

Section A: PHS

Typical Capacity	Typical Power	Efficiency (%)	Storage Duration	$/kWh	$/kW	Lifespan	Cycling capacity	Comments
0.5 – 20 GWh	50MW – 3GW	75-85 [1,2]	Hours – days	14 – 28 [2]5 – 100 [3] 250 – 430 [4]	600-2000 [3]1500-4300 [4]	50 years	High	Requires favourable terrain. Mature technology

Table ***Error! Main Document Only.****: Summary of Characteristic of PHS* [xliv]

Section B: Discover 2VRE-6200TF-U

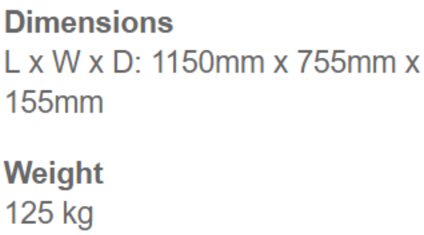


MECHANICAL SPECIFICATIONS

Industry Reference	Tubular Flooded OPzS	
Length (A)	15.7 in	399 mm
Width (B)	8.4 in	214 mm
Height (C)	30.4 in	772 mm
Total Height (D)	33.3 in	847 mm
Weight (Wet)	309 lbs	140 kgs
Weight (Dry)	198 lbs	90 kgs
Terminal	M10 UT	
Poles	6	
Cell(s)	1	
Container	SAN	

Table ***Error! Main Document Only.****: Mechanical Specification of Discover 2VRE-6200TF-U* [lxxiii]

Section C: Tesla 13.5kWh Powerwall 2.0

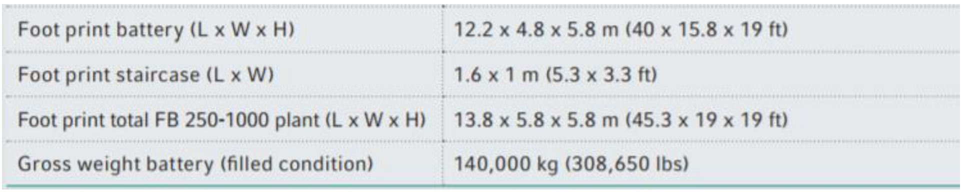


Dimensions
L x W x D: 1150mm x 755mm x 155mm

Weight
125 kg

*Table **Error! Main Document Only.**: Mechanical Specification of Tesla 13.5kWh Powerwall 2.0* [lxxix]

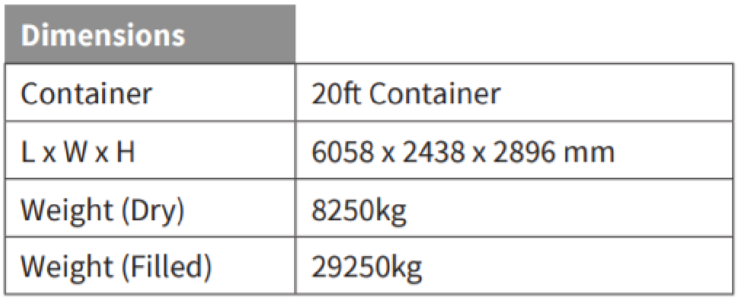
Section D: Gildemeister 250kW-4hr CELLCUBE® FB 250-1000



Foot print battery (L x W x H)	12.2 x 4.8 x 5.8 m (40 x 15.8 x 19 ft)
Foot print staircase (L x W)	1.6 x 1 m (5.3 x 3.3 ft)
Foot print total FB 250-1000 plant (L x W x H)	13.8 x 5.8 x 5.8 m (45.3 x 19 x 19 ft)
Gross weight battery (filled condition)	140,000 kg (308,650 lbs)

*Table **Error! Main Document Only.**: Mechanical Specification of Gildemeister 250kW-4hr CELLCUBE® FB 250-1000*[lxxxix]

Section E: redT 20kW-300kWh



Dimensions	
Container	20ft Container
L x W x H	6058 x 2438 x 2896 mm
Weight (Dry)	8250kg
Weight (Filled)	29250kg

*Table **Error! Main Document Only.**: Mechanical Specification of redT 20kW-300kWh Battery*[lxxxiii]