Technical and Economic Analysis of Solar Energy Application for a Hospital Building in Dammam, Saudi Arabia

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A thesis submitted to

Auckland University of Technology

in fulfilment of the requirements for the degree of

Master of Engineering (ME)

2018

School of Engineering, Computer and Mathematical Sciences

Acknowledgement

First and for most I thank Allah for providing me the ability to complete the research. Also, I cannot express my gratitude towards Dr. Ramon Zamora (my supervisor) and show how much he assisted and guided me to complete my degree. He has always been patient and encouraged me through my hardest times during the research in order to keep me on track despite any difficulties I may face. His knowledge of power generation developed me a lot and enriched my thesis. Sometimes words cannot be enough to express feelings especially when it is meant for Dr. Ramon for his continuous support and guidance through my research.

I would like to take this chance to thank my father (Hamed Saeed Alghamdi) who his continuous support is unlimited since I started to breathe, my mother (Nawal Abdullah Alghamdi) who never miss my name in her prayers for me asking Allah to guide me and support me through my studies, my brothers (Saeed and Abdulaziz Alghamdi) and my sister (Sharifa Alghamdi). My brothers and sister are always wishing me to achieve all my goals and trying to amuse when I am depressed. Even with this being said, I cannot thank all of my family enough and never will as even languages are limited for expressing feelings.

Lest I forget, there are friends that are sent to me to be brothers from other mothers who also did not give up on me and pushed me through my ups and downs in order to achieve my degree. I especially thank Adel Khwaji, Ayham Ghalayini, Azam Almalki, Faisal Alghamdi, Mansoer Abahussain, Naif Alqahtani, Saleh Al-Azmi and Yaser Alsahafi. I would love to list a longer list of them, but it would still not be enough to fit all those friends who were behind the scene of this success and once again words limit the real feelings.

List of Abbreviations and Symbols

PV	Photovoltaic
HOMER	Hybrid Optimization of Multiple Energy Resources
ML	MATLAB Link
CC	Cycle Charging
CO_2	Carbon dioxide
SO_2	Sulphur dioxide
NO_x	Nitrogen oxide
I	Output current for PV cell
FF	Fill factor
P_{PV}	Output power of PV cell
P_{max}	Maximum output power of PV cell
T_{cell}	PV cell temperature
S	Salvage value
NPC	Net Present Cost
NPV	Net Present Value
C_{NPC}	Cost of Net Present Cost
CRF	Capital recovery factor
COE	Cost of Energy
LCOE	Levelized Cost of Energy
$R_{discount\ rate}$	real discount rate
f_{cs}	The capacity shortage fraction
f_{ren}	Renewable fraction
O&M	Operation and Maintenance
$C_{om,\ other}$	Cost of another operation and maintenance costs
C_{cs}	Cost of the capacity shortage
$C_{emission}$	Cost of emissions
F	Fuel consumption rate
$C_{gen,\ fixed}$	Generator’s fixed cost of energy
$C_{gen,\ mar}$	Generator’s marginal cost of energy

M	Million
L	Litre

Abstract

An increase in energy demand is a consequence of the world's population growth. Hence, more energy supply is needed to meet the demand. Fossil based energy can run out as well as cause air pollution. Consequently, this thesis investigates the feasibility of involving PVs in a grid with diesel backup generator to reduce reliance on conventional energy as well as decreasing air pollutants (CO_2, SO_2 and NO_x) for a hospital building in Dammam. It also optimises the grid-connected PV system in terms of levelized cost of energy (LCOE), net present cost (NPC) and operating costs while verifying the effect of the grid power interruptions on the system costs. Moreover, energy sellback rates from the excess energy coming from PVs to the grid is included. HOMER Pro and MATLAB software were used to optimise both systems as HOMER Pro provided the ability to design, simulate and optimise power generation systems, and the ability to choose different type of control for any modelled systems. MATLAB was used to design a customised control strategy and linked to HOMER through MATLAB Link (ML) strategy for optimising both systems and compared it with built-in dispatch in HOMER Pro called Cycle Charging (CC). Using the project lifetime of 25 year in HOMER, the results reveal that ML strategy provides the optimum solution for the grid-connected PV system when the grid power outage occurs twice a year and with 5% sellback rate higher than the grid energy price as the LCOE is 0.05701 $/kWh, total NPC is $8,288,628.00 and annual operating costs are 156,658.00 $/year. The proposed system also results in huge reduction of all pollutants that ranges from 69.75% to 69.84%. To conclude, the results of the analysis of both systems show that the grid-connected PV system is a feasible regardless of the costly initial costs of PVs.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed Date 20/11/2018

1. Introduction

1.1. Background

Growth of the world's population has resulted in more energy usage and demand. Given that conventional energy sources (oil, coal, natural gas) are still the main energy sources used, especially in developing countries, this higher demand is likely to cause environmental problems including, but not limited to, greenhouse gases (GHG), especially CO_2 emissions. These energy sources are also affected by problems related to sustainability, price stability and environmental friendliness [1, 2]. Consequently, an alternative to meet this increase in usage is required; a reliable, efficient, sustainable, economic and environmentally-friendly energy source that either can be integrated with conventional energy sources (hybrid system) or used as a standalone system is needed.

Reliable, sustainable, economic and environmentally-friendly energy sources are called renewable energy sources. Renewable energy sources are increasingly attractive due to their high efficiency and reliability, even though they have the problem of intermittency. This is because some renewable energy sources are dependent on external factors including, among others, climatic conditions such as wind speed, ambient temperature and solar radiation [3]. The problem, however, can be overcome by using an energy storage system, for instance, batteries and fuel cells (FC). As a result, these renewable energy sources become more attractive, and receive more attention as a means to minimise the risks caused by conventional energy sources [2]. Among alternative energy sources, solar and wind energy sources are considered to be the most attractive ones [4, 5].

In 2015, according to the Electricity and Cogeneration Regulatory Authority's (ECRA) statistical booklet for Saudi Arabia, there had been an increase in the number of generation units since 2008, 682 units in 2008 compared with 884 units in 2015 [6]. Also, the total installed power capacity relatively increased from 47 GW in 2008 to 82 GW in 2015. In addition to this, the total annual consumption of fuel for electricity and seawater desalination industries also increased between 2008 and 2015, from 2,538 to 3,581 T BTU.

The main sources of energy used before 2015 were gas, crude, heavy fuel oil (HFO) and diesel. As the demand increased, these fuels were used in greater quantities to meet the increasing demand for energy. Continued high usage of these fuels multiplies the risk of GHG and CO_2 emissions, which is likely to impact on global warming as well as other environmental problems in the near future if no serious attention is given to finding solutions or replacements for these energy sources. Taking a proactive stand to prevent this from happening, Saudi Arabia has become part of a major joint international cooperation and invested in renewable energy research to reduce the harmful effects of using these fuels as energy [7].

The Saudi Vision 2030 states the increase in local energy consumption will triple by 2030 [8]. One of the main goals of this vision aims to meet an initial target of 9.5 GW generated by renewable energy not later than 2030. Nevertheless, some studies predict future production at more than 9.5 GW [9]. For example, King Abdullah City for Atomic and Renewable Energy's (KACARE) research suggests future production will have a capacity of 54 GW coming from renewable energy by 2032 [10]. This capacity will come from sources such as solar photovoltaic (PV) and wind. In addition, the legal and regulatory framework that allows buying and investing in the renewable energy sector by private companies is to be reviewed, and the industry is to be localised by encouraging public-private partnerships [8]. The competitiveness of renewable energy will be guaranteed through gradually liberalising the fuels market.

Saudi Arabia is moving towards the use of renewable energy to reduce dependency on oil, which will free this resource for export. Because Saudi Arabia is investing in renewable energy research, this thesis intends to focus on the possibility of using renewable energy in a large building, a building belonging to a hospital located in the east of the country. Furthermore, this thesis will discuss the technical and economic analysis of a grid-connected PV system in Dammam, Saudi Arabia.

1.2. Rationale and Significance of the Study

Electricity demand is rapidly increasing in Saudi Arabia due to the growth of population so that more energy production is required to meet that demand [11]. The annual growth rate was reported at 6.7% for electrical power. Saudi Arabia plans to reduce dependency on fossil fuels for electricity generation, and renewable energy has been proposed as the solution to accomplish this [8]. Solar and wind energy are deemed the most significant renewable energy sources for the country [12]. This is because the sun shines all year long and, with solar radiation variation around 4.0-7.5 $kWh/m^2/day$, it has five times the solar radiation of that in

Europe. Additionally, the annual average variations of wind speed in Saudi Arabia range from 3.0 to 4.5 m/s at a height of 10 m [13]. Hence, solar and wind energy are great resources, which need to be utilised to reduce the dependency on fossil fuels and protect the environment from harmful emissions such as CO_2.

Some projects for independent production are going through the Saudi Electricity Company (SEC); for example, SEC started development for renewable energy usage as an independent production [11]. Also, SEC announced two developmental projects for solar power generation in the cities of Al-Jawf and Rafha with a capacity of 100 MW.

Saudi Arabia is moving towards its vision 2030, which demands less dependency on oil and focuses more on non-oil production, a shift that will not only improve environmental cleanness but will also elevate the economy. Despite the potential high initial costs involved in providing an energy source that encompasses aspects of reliability, sustainability, efficiency and environmental friendliness, Saudi Arabia is focusing on the long-term benefits rather than current expenses. Also, the fuels market is going to be liberalised, so this means renewable energy will have a higher chance of becoming more competitive in the market [8].

This research thesis focuses on a hospital building as hospital buildings require a reliable energy system to ensure the continuous power supply especially for vital equipment and devices at any time. Also, it focuses on installing a rooftop PV system to supply this hospital building to examine whether or not it will increase the reliability of energy system as well as reducing the dependency on conventional energy sources which are existing in the hospital building. Furthermore, the time when the rooftop PV generates electricity is coincide with the time when air conditioners operate. Hence, the generated electricity from the rooftop PV system can be used directly to minimize losses due to the storing process.

1.3. Research Questions and Objectives

For this research thesis, a research question was formulated as follows:

How would a grid-connected PV system be a technically and economically favourable choice in comparison with a conventional grid + standby diesel engine system?

This question is broken down into sub-questions with the purpose of obtaining comprehensive details to provide a more accurate answer. The sub-questions are listed below:

1) How would a grid-connected PV system be a reasonable choice in terms of LCOE, NPC and operating costs?
2) How do the air pollutant emissions affect the system costs? By how much would the grid-connected PV system reduce these emissions and the system costs?
3) How could the customised control strategy using MATLAB provide an optimum solution compared to the cycle charging control strategy in HOMER?
4) How would the grid power interruptions impact the grid-connected PV system and the existing system? Would the grid-connected PV system still be a better solution?
5) How would an increase in sellback rates from PVs to the grid encourage the use of PV systems in the long run?

To meet the research question and sub-questions, objectives of this research are stated as follows:

1) To evaluate the possibilities of involving a renewable energy source, PV system in this case, to supply a large load, which will minimise dependency on conventional energy sources, such as a diesel generator.
2) To assess the economic and environmental effects of air pollutant emissions (CO_2, SO_2 and NO_x) on power generation selection or preferences.
3) To optimise the grid-connected PV system in regard to the levelized cost of energy (LCOE), net present cost (NPC) and operating costs with customised control strategy using ML in HOMER.
4) To examine the impact of the grid power interruptions on the system costs.
5) To assess the effect of increasing the sellback rate from excess energy production by the grid-connected PV system.

1.4. Thesis Structure

The rest of this thesis will be structured as follows:

- Chapter two provides a literature review for standalone and hybrid solar energy systems. Also, there is a brief discussion about renewable energy's potential, specifically in relation to solar energy for Saudi Arabia.

- Chapter three provides a brief history of solar energy, an overview of solar energy technology, description of solar cells and the factors impacting their efficiency.
- Chapter four discusses Saudi Arabia’s electricity capacity, and how it is developing to meet the growth of energy demand.
- Chapter five details the methodology of this thesis, including any computer software used. It discusses the usage of Hybrid Optimization of Multiple Energy Resources (HOMER) software and ML strategy. Also, it provides heuristic calculations and HOMER modelled system based on the heuristic calculations.
- Chapter six discusses and compares the results of the different system configurations with and without PVs to determine an optimal solution in terms of different factors.
- Chapter seven summarises the thesis findings and checks answers to the research questions, which in turn indicate whether the objectives have been met.

2. Literature Review

2.1. Overview

This chapter will start by covering the research that has been done in the field of solar energy. The technical and economic aspects of solar energy are reviewed from the conducted studies on standalone solar energy systems and hybrid renewable energy systems. Then, it will present the existing solar energy projects in Saudi Arabia. In addition, it will show the environmental and health issues that are related to the conventional energy followed by showing the economics of solar energy. Moreover, it will cover the recent research done on renewable energy potentials for Saudi Arabia. Lastly, there will be a summary for the chapter.

2.2. Review of Standalone Solar Energy Systems

A standalone solar energy system consists of PV modules, controller, inverter, a storage system and a load to be supplied. Fig. 2-1 illustrates a typical standalone PV system. Standalone PV systems has been growingly applied in developed and developing countries [14]. An optimisation analysis of PV system for health clinic in a rural area in Iraq was conducted using HOMER software [15]. This study considered different sizes of PV modules, diesel generator, batteries and inverter to be analysed and compared with the aim of achieving the least total net present cost (NPC) and cost of energy (COE). However, environmental and health factors were taken into account for choosing the optimal design system. In this study, the health clinic load was 31.6 kWh/day and it was met by five different system configurations with only two of them were not including PV modules. Nevertheless, the optimisation resulted in having two optimal systems consisting PV modules. The first optimal system that were chosen by HOMER consists of 6 kW PV, 80 batteries and 3 kW inverter with the initial cost, total NPC and COE of $50,700, $60,375 and 0.238 $/kWh, respectively. The second optimal system consists of 8 kW PV, 2 kW diesel generator, 80 batteries and 5 kW inverter with $69,500, $78,212 and 0.272 $/kWh for initial cost, total NPC and COE, respectively. In addition, the study showed that the electricity price of power production from diesel generator is greater than the electricity price from PV by four times. This clearly indicates the advantage of involving PV system for a rural area. Furthermore, this small PV system helped to prevent the emission of 14,927 kg/year, 329 kg/year, 278 kg/year, 36.9 kg/year, 30 kg/year and 4.08 kg/year for CO_2, NO_X, suspended particles, CO, SO_2 and HC orderly.

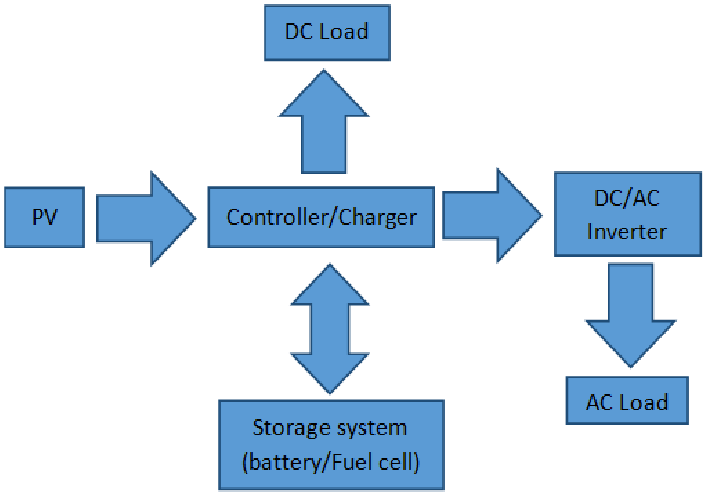


Fig. 2-1. Typical standalone PV system [14]

In a techno-economic analysis study that considered diverse system configurations which included PV modules, wind turbines, converter/inverter and battery banks, the aim was to investigate the feasibility of supplying a load of 50 rural households (24.4 MWh/year) with these renewable energy sources [16]. Additionally, the most cost-effective system out of these configurations was the aim in terms of total NPC and COE. Three options were simulated which are PV/battery, wind turbines/battery and PV/wind turbines/battery. The PV module slope in HOMER was varying from 5^{o} to 60^{o} with different power output ranging from 0-30 kW. To add, two hub heights were considered for wind turbines which are 20 m and 40 m with output generation ranging from 2-60 kW. Moreover, the inverter had rating ranges from 2-30 kW. This investigation revealed that PV/battery system was the best system when the PV at the slope of 5^{o}. Even though the hybrid system of PV/wind turbines/battery has lower initial cost and total NPC, HOMER chose that wind turbines (at hub height of 40 m) to provide the least amount of energy with only 4 kW, whereas PV with 16 kW. Nevertheless, when the hub height of wind turbines set at 20 m, HOMER showed that PV/battery system is the optimal solution with most of the energy generation is coming from the PV modules with 19 kW. The total initial cost and NPC of the best hybrid system were $107,160 and $118,965, respectively. Whilst for the PV/battery system, the total initial cost and NPC were $110,740 and $120,738 in order. Therefore, this optimization study resulted in having PV/battery system as the optimal solution for the load tested.

2.3. Review of Hybrid Renewable Energy Systems

A hybrid renewable energy system (HRES) is a combination of different renewable energy sources with or without the existence of conventional energy sources, grid connection, controller, converter/inverter and a storage system. Fig. 2-2 shows the general HRES including PV module. A study considered alternative energy scenarios for Bozcaada island in Turkey; the potentials of solar and wind energy are good when connecting them to the grid in this island [17]. Therefore, in this study, a standalone and grid connected systems were considered. The main components of the system consist of PV array, wind turbines, hydrogen storage, electrolyser, FC and converter. From these components, six scenarios were simulated 1) grid, 2) gird/wind, 3) grid/wind/PV, 4) wind/FC, 5) wind/PV/FC and 6) grid/PV using HOMER software; HOMER tested the systems corresponding to their net present costs (NPC) and COE. The results of this analysis showed that the grid/wind is the most appropriate system when considering grid connected system as its COE is 0.103 $/kWh. In addition to this, the most suitable off-grid system was wind/PV/FC with COE of 0.836 $/kWh. To add, some factors were effective such as solar radiation and the wind speed. Furthermore, environmental perspective was considered; for instance, for CO_2 emissions, the highest emissions come from the system of using the grid only.

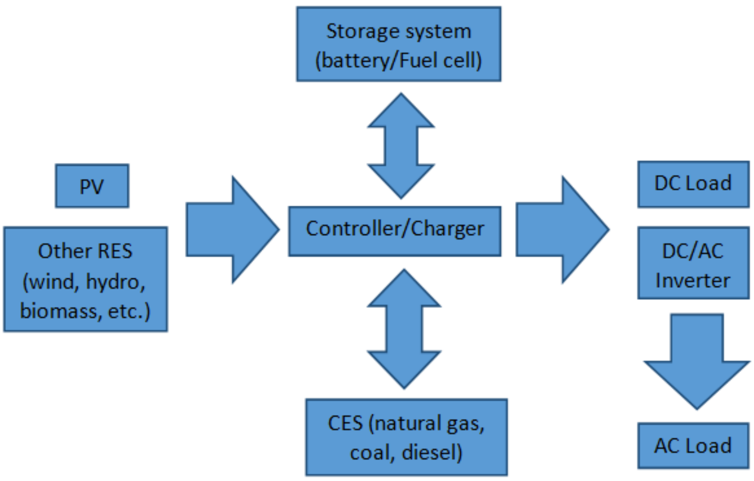


Fig. 2-2. The general HRES system including PV module [18]

In [19] global warming and energy crisis encouraged the integration of renewable energy in Central Queensland. Also, it was stated that energy demand is growing in the Capricornia region of Queensland, Australia. As a result, in order to reduce energy crisis and minimise global warming, a hybrid renewable energy integration (HREI) system was deployed. The study focused on proposing a HREI system that consists of a prediction model, a techno-economic model as well as a load management system to ease the integration of renewable energy into the distribution grid of Central Queensland. The study relied on solar (PV) and wind energy from renewable energy (RE) sources with grid-connected as the climate of Capricornia region is subtropical. The prediction model is to forecast in advance which RE sources that possibly generate energy, the techno-economic model is to investigate the beneficial aspects of RE systems economically and environmentally for the community and to ensure proper management of consumption of energy based on the generation of RE sources and load demand. This study used the prediction model, the load management as well as the economic analysis using HOMER software to gain the viability of the most cost-effective combination of RE system with grid connected. The results of the analysis showed that for small-scale, the hybrid system that consists of PV/battery/grid-connected is the most cost-effective (0.240 $/kWh), besides it reduces greenhouse gas emissions considerably. Notwithstanding, for large-scale, a wind/PV/grid-connected system is more cost-effectively viable (0.316 $/kWh), but high upfront costs will be required.

2.4. Solar Energy Projects in Saudi Arabia

Since 1960, solar energy applications have been growing in Saudi Arabia [20]. In 1977, King Abdulaziz City for Science and Technology (KACST) started the focus on development of solar energy technologies through research and development work. In 1980, the biggest project for producing solar energy was located 50 km northwest of Riyadh at a cost of $18 Million [21]. It supplied 1 to 1.5 MWh/day to three rural villages. In 1994, the Saudi Solar Radiation Atlas project was initiated as a collaborated research and development project between the KACST Energy Research Institute and the U.S. National Renewable Energy Laboratory (NREL) [22]. In addition, the Ministry of Higher Education established a centre of Research Excellence in Renewable Energy at the King Fahd University of Petroleum and Minerals in 2007; the goal is to aid scientific development in renewable energy with concentration on solar energy [20].

PV cells with capacity of 2 MW were installed at King Abdullah University for Science and Technology (KAUST), which is located in Thuwal [21]. The total cost of this PV grid-connected (PVGC) power plant was about 65 million Saudi Riyals (SR) which is almost equivalent to $17,329,650.00 US dollar. Operations started in May 2010, and it has 9300 PV modules, each with 215 W_p, in an area of 11,600 m^2. It is expected to produce 3300 MWh/year of clean energy as well as saving 1700 tons of carbon emissions per year. Another project, Farasan solar power plant with 500 kW_p capacity, was built on an area of 7700 m^2 in Saudi Arabia. This plant is an off-grid PV system, which was intended to supply Farasan Island and has been operating since June 2011. Additionally, according to [20], the world's largest solar parking project has a solar carport system with 10 MW capacity located at the headquarters of Saudi Aramco in Dhahran, Saudi Arabia.

2.5. Environmental and Health Issues

As conventional energy sources are still the primary energy sources providing electricity in most developing countries, this is liable to cause environmental issues, such as GHG and especially CO_2 emissions, resulting in air pollution. Low quality fuels, for instance, crude oil that is used for power generation in Saudi Arabia with insignificant emission controls, produce a range of pollutants known to cause health problems in the general public [23]. Saudi Arabia is the highest contributor towards CO_2 emissions within the Gulf Cooperation Council (GCC), producing 56% [24]. In Fig. 2-3, the relationship between electricity consumption and its contribution towards CO_2 emissions is shown [25]. It is clear that electricity consumption is directly proportional to the CO_2 emissions. This suggests the increasing demand for electricity and a dependence on fossil fuels as primary energy sources will produce a greater increase in CO_2 emissions. The usage of renewable energy sources, such as PV, however, will play an important role in reducing the level of CO_2 emissions.

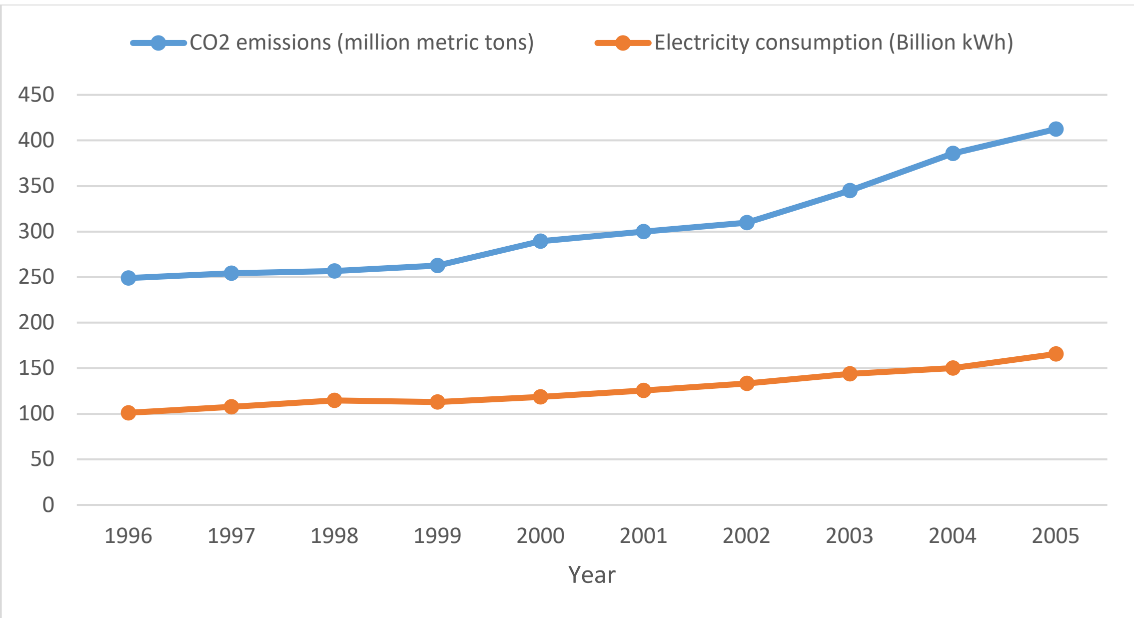


Fig. 2-3. CO2 emissions from electricity generation consumption [25]

According to Presidency of Meteorology and Environment in Saudi Arabia, the concentration of particulate matter (PM) in the annual average should not surpass 80 μg/m^3 at any location [26]. Nevertheless, in Saudi Arabia, the average annual concentration of PM is 113 μg/m^3 [27]. In addition, the average annual concentration of SO_2 and NO_x ought not to exceed 80 and 100 μg/m^3, respectively [26]. However, in Saudi Arabia, the amounts of SO_2 released into the air surpasses the reported amounts for Sweden, Portugal, Netherlands and Finland [28]. The energy produced from conventional sources can be linked to the emission rates of each pollutant [20]. The rates of CO_2, SO_2, and NO_x emissions related to the power generation used in Saudi Arabia are 180, 3.16 and 2.13 g/kWh, respectively [29]. In [30], the impact on health costs from gas power plants in Germany is 0.0034 €/kWh. Whereas, in Saudi Arabia health impact costs are expected to equal 0.0178 SR/kWh [31]. This is equivalent to 0.0047 $/kWh.

2.6. Economics of Solar Energy

The costs of solar energy dropped from 90 ¢/kWh in 1980 to about 20 ¢/kWh, according to [32]. The US has a target to make the cost of electricity generation from PV competitive with conventional energy sources by 2020 [33]. The PV cost is currently about 2.5 $/W$_p$, with a goal to reduce it to around 1 $/W$_p$ [34].

World oil prices are estimated to rise from 70 to 95 $/barrel by 2015 and 108 $/barrel by 2020 [35]. Therefore, as the price of oil increases, the energy costs coming out of it will also increase. The energy costs of renewable resources compared to the energy cost of conventional resources would be more favourable if environmental and health costs were taken into account [24].

The economics of solar energy are better served in regions that possess high solar radiation [20]. Ignoring the indirect costs relating to environmental and health impacts from conventional energy resources when comparing those sources with solar energy is unfair. Table 2-1 summarises the costs from conventional generation [31]. These values in Table 2-1 are in US dollar equivalent to 0.0096 $/kWh for CO_2, 0.0072 $/kWh for SO_2, 0.0230 $/kWh for NO_x and 0.0047 $/kWh for health. To add, the external costs of CO_2, SO_2, and NO_x on average are 0.0001, 0.0086 and 0.0412 SR/g correspondingly [23]. That is in US dollar is 0.0027 ¢/g for CO_2, 0.23 ¢/g for SO_2 and 1.1 ¢/g for NO_x. According to [31], the total cost resulting indirectly from conventional generation approximates 0.1688 SR/kWh. This is also 0.045 $/kWh.

Table 2-1. Indirect costs from conventional generation [31]

External damage	Damage cost (SR/kWh)	Damage cost ($/kWh)
CO_2	0.036	0.0096
SO_2	0.027	0.0072
NO_x	0.088	0.0230
Health	0.0178	0.0047
Total indirect costs	0.1688	0.0450

2.7. Renewable Energy Potentials for Saudi Arabia

A review on research work on wind farms and solar parks in different locations was discussed in [36]. Moreover, it analysed wind speed and solar radiation data for Dhahran, Saudi Arabia, to evaluate technical and economic potentials of hybrid wind/PV/diesel power systems in order to cover the load demand of normal commercial buildings. The study showed that the RE fraction is 36% (24% wind and 12% PV) for the hybrid system consisting of 100 kW capacity of wind farm, 40 kW capacity of PV both with 175 kW capacity of diesel system (two diesel generators) with no annual shortage of capacity. The COE of this hybrid system found to be 0.154 US$/kWh with the assumption of diesel fuel price of 0.1$/L and the total Net Present Cost found to be US$ 1,483,767. To add, this hybrid system resulted in having no unmet load. Fuel savings as a consequence of this system was found to be 27% relative to diesel-only; consequently, the carbon emissions reduced by the same percentage of fuel savings. Additionally, the study showed that as the wind farm and solar PV capacities increases, the operating hours of diesel generators decrease. The use of this hybrid system possibly avoided approximately 44 tons annually of carbon emissions.

The feasibility of utilising power of the wind and the sun to minimise fossil fuel usage for power generation in order to meet the energy demand of Rowdat Ben Habbas (small village) located in north eastern part of Saudi Arabia was addressed in [37]. This study found that the hybrid system of wind/PV/diesel power generations was the most cost-effective power generation with COE of 0.212 US$/kWh with 35% of RE fraction (26% wind and 9% solar). The system was consisting of 3 wind turbines (600 kW each), 1000 kW PV panels and four diesel generating sets 1120 kW rated power each. The study showed that this system was able to satisfy the energy demand of the village with energy surplus of 4.1%. The sensitivity analysis showed that for every increase of wind speed by 0.5 m/s, it contributed in 5% rise in wind energy in the hybrid system, the COE linearly decreased and the RE fraction linearly increased.

Moreover, this proposed hybrid system consequently aided to avoid 4976.8 tons of greenhouse gas (GHG) in the local atmosphere of this village and annually saving 10,824 barrels of fossil fuel.

In coastal locations of Saudi Arabia, economic possibility of development of wind plants was reviewed in [13]. In this study, a development of 75 MW wind farms was studied by analysing wind speed data for long-term. The locations that the study concentrated on are Al-Wajh, Jeddah, Yanbu and Jizan, these are located in the west coast. The simulated wind farms comprised diverse combinations of 600 kW wind machines with 50 m hub-height. For the techno-economic analysis, HOMER software was used. The study showed that the wind speed less than 3 m/s for 41%, 45%, 52% and 53% of the time through the year in Yanbu, Al-Wajh, Jizan and Jeddah, respectively; hence, this indicated that wind system will not generate power for about 41-53% of the time yearly. The annual production of energy by the 75 MW wind farms was found to be 135,822 MWh in Yanbu, 107,196 MWh in Al-Wajh, 81,648 MWh in Jeddah and 80,896 MWh in Jizan. The cost of this wind farms found to be 0.0423 US$/kWh in Yanbu, 0.0536 US$/kWh in Al-Wajh, 0.0704 US$/kWh in Jeddah and 0.0711 US$/kWh in Jizan. Furthermore, the study determined the capacity factor of wind power plants and found 21% for Yanbu which indicated that Yanbu was better place for wind power generation when compared with the other coastal locations.

The possibility of employing renewable energy systems to provide electricity in Saudi Arabia is discussed in [12]. This study stated that the 46,000 MW available power generation in Saudi Arabia will have problem to supply demand due to the annual demand growth of 3000 MW. Also, a high percentage (53%) of power consumed was by households in Saudi Arabia. This study analysed the COE of different combinations of solar and wind energy with a storage system as well as grid-connected. The study was conducted using HOMER software to simulate the three types of combinations which are a) PV alone with grid-connected, b) hybrid system of PV-wind with grid-connected and c) hybrid system of PV-wind-FC to calculate the COE. The results of the study showed that the lowest COE was 0.362 $/kWh which is the system of PV alone with grid-connected. Nevertheless, it showed that the highest COE was the system of PV-wind-FC with amount of 7.35 $/kWh.

A techno-economic energy analysis was performed that included hybrid wind and solar energy system in the west coast of Saudi Arabia in [38]. The study concentrated on the COE and energy produced from both PV and wind turbine in the hybrid system, and shortage and excess electricity were taken into account. In this study, the considered wind speed and solar irradiation on annual average were 3.53 m/s and 5.95 kWh/m^2/day, respectively. MATLAB and HOMER software were used to technically and economically analyse the hybrid system proposed. According to the results, the west coast of Saudi Arabia has adequate potential energy from solar and wind to supply electricity; nevertheless, PV array produced more energy than wind turbine when both have the same size as well as at the same site. Additionally, battery and wind turbine are important at night time to meet load requirements irrespective of the additional cost of wind turbine and battery that will contribute in the largest cost for the hybrid system. This is because the COE for wind turbine alone is 0.149 $/kWh which is more expensive than the COE for solar energy alone which is 0.0637 $/kWh.

The possibilities of power generation and hydrogen production using solar and wind energy resources at diverse locations in Saudi Arabia were conducted in [2]. These locations include Dhahran, Riyadh, Yanbu, Abha and Jeddah. These locations were chosen due to their climate variety that results in different solar radiation and wind speed. Different renewable Off-grid power generation systems were used to cover a load demand of a normal house combining PV array, wind turbines, batteries, electrolyser, converter, hydrogen tank and FC. From the PV array, wind turbines, batteries and FC, six systems considered in the simulations hourly base, which are a) PV/battery bank, b) PV/wind/battery bank, c) PV/FC, d) PV/wind/FC, e) wind/battery bank and f) wind/FC. HOMER simulations were used to analyse and investigate the most economic hybrid renewable energy integration system and in which location. In each location, each system of these six systems was simulated. The results of the study revealed that the system of PV/wind/battery bank has the lowest COE of 0.609 $/kWh at Yanbu area. On the other hand, the outcomes showed that the system of PV/wind/FC gives the most cost-effective of 1.208 $/kWh at Abha when battery bank replaced with FC, hydrogen tank and electrolyser in each system.

2.8. Summary

In summation, the reviewed studies focusing on standalone solar energy systems and hybrid renewable energy systems show that solar energy source play an important role in reducing the COE regardless of the high initial capital cost. To add, Saudi Arabia is focusing on the usage of renewable energy resources, especially solar energy, and this is shown by the projects that

Saudi Arabia has already done by using solar energy. In addition, the environmental and health issues of conventional energy sources have been discussed. What's more, the economics of solar energy is provided, and some studies suggest that the price of this energy will decrease in the future. Lastly, with reviewing the last conducted studies about the renewable energy potentials for Saudi Arabia, it is clear that Saudi Arabia has high potential to utilise renewable energy resources, especially solar and wind energy, to reduce dependency on conventional energy sources, depending on the location in Saudi Arabia.

3. Solar Energy

3.1. Overview

This chapter will provide the solar energy background and brief history of how this technology discovered. Then, there will be a brief description of the photovoltaic (PV) technologies and followed by description of the solar cells and their ways of connections. Next, the chapter will show the factors that will have an impact on the efficiency of the PV modules. Finally, a summary will be provided for the chapter.

3.2. Solar Energy Background

One of the fastest growing industries globally is photovoltaic solar energy (PV) [39-41]. Hence, development has been increasing in a range of related fields including, but not limited to, material use, amount of energy consumption for manufacturing materials and the efficiency of the cells.

In 1839, Becquerel was the first person to observe solar radiation conversion into electricity because of the photovoltaic effect [40-48]. Photovoltaic effect happens in semiconductor materials using two energy bands. One of them (valence band) allows the presence of electrons, while the second (conduction band) is completely empty, has an absence of electrons [49]. Fig. 3-1 depicts the different types of materials known as conductors, semiconductors and insulators. The common semiconductor material used is silicon. For silicon, 1.12 eV (electro volts) is needed for electrons to pass the gap [50]. The semiconductors have to be able to absorb the solar spectrum in a large amount [45].

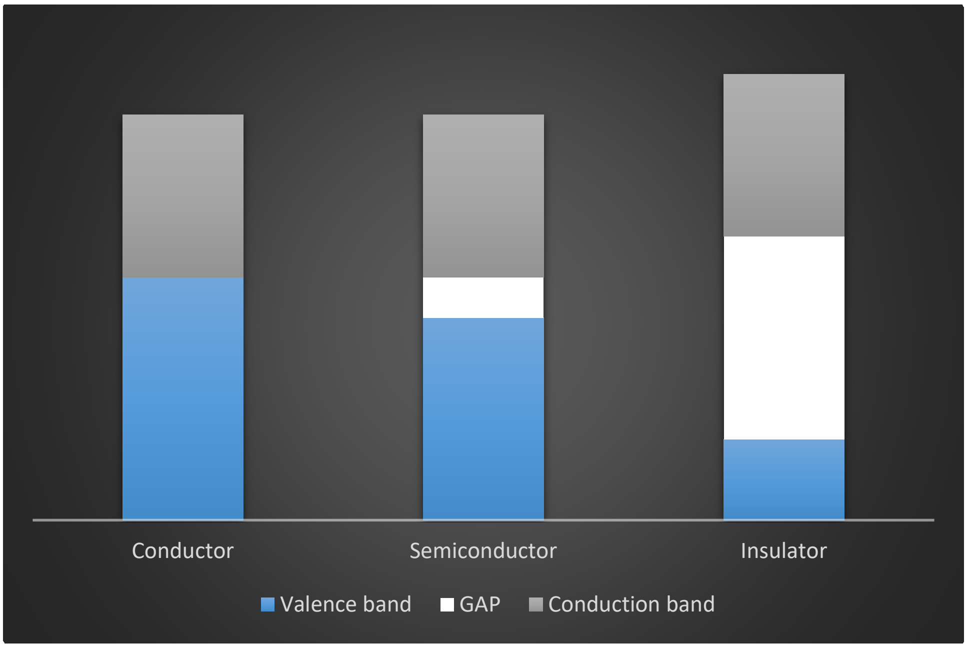


Fig. 3-1. Conductor, semiconductor and insulator materials [49]

3.3. Photovoltaics (PV) Technologies

All devices or materials with the ability of converting sunlight energy into electrical voltage fall under the photovoltaic (PV) term [51]. Using this technology to produce energy has numerous benefits. Firstly, it has the ability to generate electricity cleanly, without producing harmful waste [52]. Secondly, the low cost of operation and maintenance for PV was one of the main advantages in [43, 47, 53, 54]. Thirdly, PV systems are reliable [53, 55].

Conversely, there are some drawbacks to PV, which might have an impact on the use of this technology. The high initial cost of PV systems is one of the main disadvantages [44, 47, 53, 54]. Furthermore, geographical conditions are critical, according to [54], as is the need for a large area for installation [53].

Solar cells play an important role in the conversion of sunlight energy into electrical energy [56]. Nowadays, there is diversification of PV cell technologies in the market that uses different types of materials [57, 58].

3.4. Solar Cells

Solar cells are the types of semiconductor devices that can generate electricity when they are exposed to sunlight [59]. Also, they are called photovoltaic cells (PV). PV devices are commonly created from pure crystalline silicon, but their key technology is related to that which produces transistors, diodes and the other semiconductor devices generally used, these days, all over the world [51]. Fig. 3-2 shows the silicon atom, which has 14 negatively-charged electrons orbiting around a nucleus that is positively charged. Additionally, 10 of the 14 electrons are travelling tightly around the nucleus, while the other four have a weaker bond with the nucleus. These are the ones that play a key role in PV systems because this bond is likely to be broken when adequately jolted by an external source of heat or light [51].

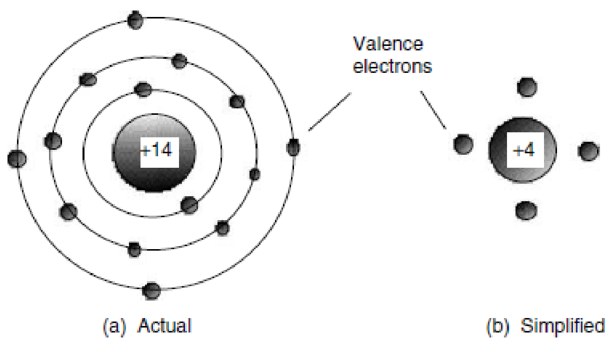


Fig. 3-2. Silicon atom [51]

However, a single pure silicon will not be able to produce electricity even if exposed directly to strong sunlight. Therefore, a connection to a mechanism driving electrons in opposite directions in the crystal lattice is required. This mechanism is provided by the semiconductor p-n junction [51]. In order to create the cell, which has two layers of silicon, its layers are doped with impure atoms. Phosphorus is usually added because it makes a large number of free atoms when it dopes the silicon. When the silicon is doped with boron, other holes are created from broken bonds in the crystal. This situation is reversed with respect to phosphorus, and the holes become the majority carriers whereas the electrons become the minority carriers. This conductor is referred to as an n-type or p-type conductor [60].

When forming a p-n junction with the doped material, free electrons in the n-type material diffuse into the p-type side, and the hole in p-type diffuses into the n-type side. As this happens, they make two layers, one positively and one negatively charged. The diffusion continuously occurs until the electrons and holes reach a balanced condition. In this state, charge carriers are located far from the junction and have formed a “depletion region” as can be seen in Fig. 3-3 [51].

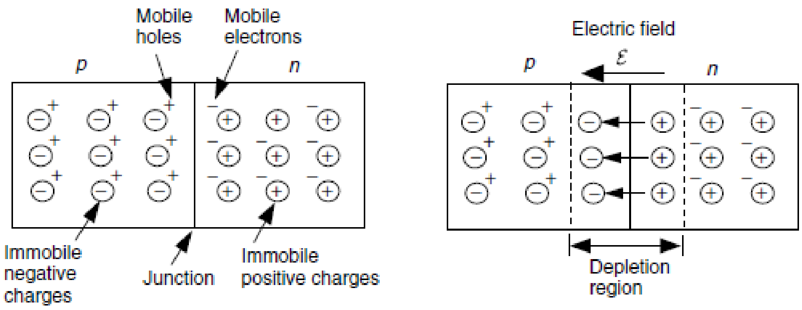


Fig. 3-3. Depletion region [51]

The current flows through the depletion region in one direction because the depletion region works like a diode. When the solar cell is exposed to the sun, sunlight energy helps to free the electrons from their nucleus in the form of packets of energy called photons. These photons are sufficiently strong enough to make hole-electron pairs, and the resulting voltage will drive the current to any attached load [51]. Fig. 3-4 displays how sunlight creates the resulting voltage that drives the current to the load [61]. To obtain the highest efficiency for crystalline silicon, it needs to be exposed to a strong source of sunlight [60].

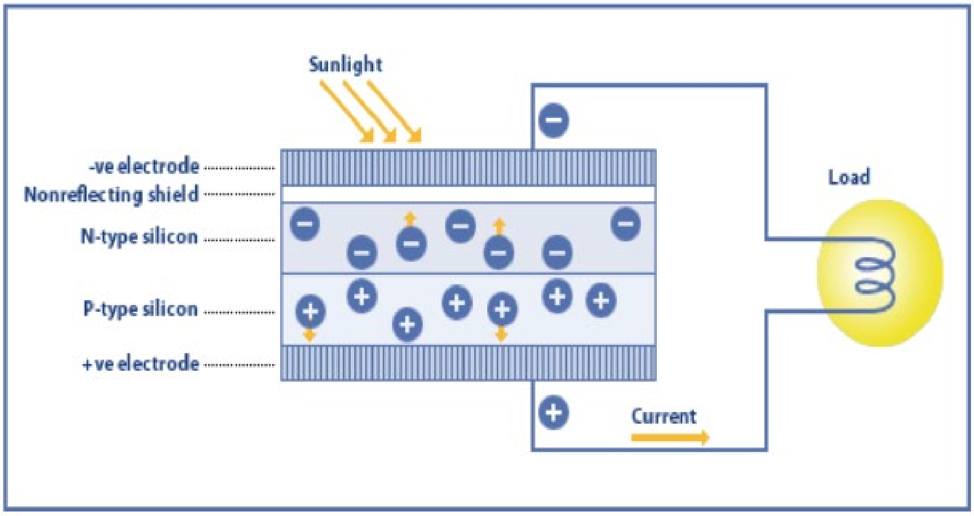


Fig. 3-4. Solar cell [61]

The PV cell in ideal conditions is represented by a current source with a diode in parallel as can be seen in Fig. 3-5 [62]. The output current is represented by equation (3.1):

$$I = I_L - I_O[e^{\left(\frac{qV}{nkT}\right)} - 1] \tag{3.1}$$

where:

I_L is the current from the light,

I_O is the inverse saturation current of the diode, q is the absolute value of the electron charge [C],

V is the measured cell voltage that is either produced or applied across the diode,

n is the ideality factor,

k is the Boltzmann constant [1.380 x 10^{-23} J/K],

T is the absolute temperature [K].

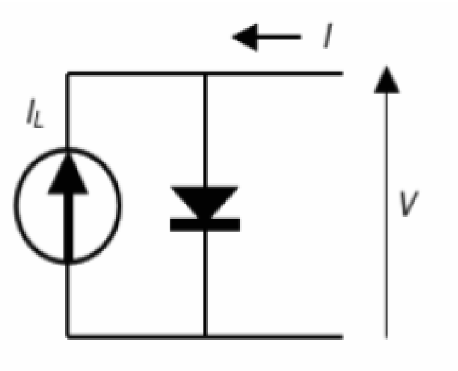


Fig. 3-5. Ideal model of PV Cell [62]

The characteristic curve for a solar cell is represented by an I-V and P-V curve as shown in Fig. 3-6 [63]. The limit values for solar cells are the short circuit current (I_{SC}) and the open circuit voltage (V_{OC}) as can be seen in Fig. 3-6. The output power of the solar cell is equal to the result of any multiplication of I by the V and, as illustrated, the maximum power point (MPP) occurs close to the knee of the I-V curve [64].

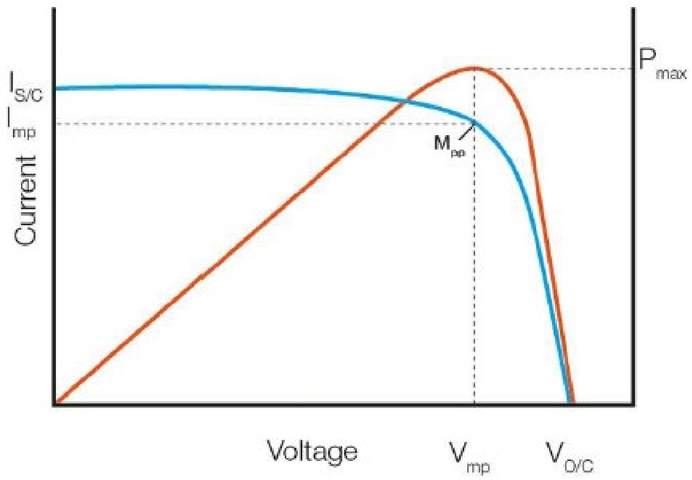


Fig. 3-6. Typical I-V and P-V curve, where I_{SC} and V_{OC} are short circuit current and open circuit voltage respectively, and maximum power points at (I_{mp}, V_{mp}) [63]

The fill factor (FF) is a measure typically used to present the performance of the PV module. FF is the ratio between the product of I_{mp} and V_{mp}, as well as the product of I_{SC} and V_{OC} as in equation (3.2):

$$FF = \frac{I_{mp}V_{mp}}{I_{SC}V_{OC}} \tag{3.2}$$

or it can be rewritten to make P_{max} the subject by substituting ($P_{max} = I_{mp}\, V_{mp}$) as shown via equation (3.3):

$$P_{max} = I_{SC}V_{OC}FF \tag{3.3}$$

To produce electrical energy by solar panels, solar panels are formed in modules employing a number of solar cells that are connected in series and parallel [65]. These solar modules, in series and parallel, are distributed in a particular way to produce a desired voltage and current to meet the operating conditions required.

When the solar modules are connected in series, the link is made by connecting the positive terminal of one module to the negative terminal of the next one. Consequently, the output voltage of this connection becomes equal to the sum of the output voltage of all connected modules. Conversely, the current stays equal to the output current of one module.

In parallel connection, the positive terminal of a solar module is connected to the other positive terminals of the other modules and vice versa. This results in the current remaining equal to the sum of output current in all connected modules, whereas the output voltage stays the same as for one module. A representation of the output differences due to the connection of the modules is shown in Fig. 3-7 [66].

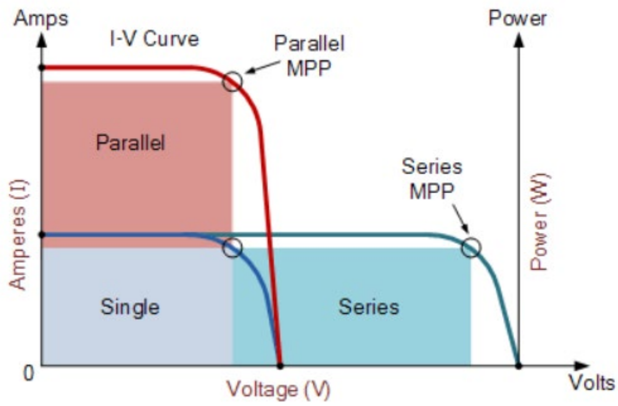


Fig. 3-7. Parallel and Series modules connection curve representation [66]

3.5. Factors affecting the efficiency of PV Modules

The efficiency of PV modules is affected by ambient conditions such as temperature and solar irradiance when they are operating. These conditions have an impact on the output voltage and current of the modules [65]. The output voltage of PV modules is directly affected by the temperature, and the output current is affected by the solar irradiance intensity. As a result, the efficiency of the PV modules are dependent on the temperature and the solar irradiance intensity. Manufacturers use standardised values for irradiance and temperature to plot characteristic curves for I-V and P-V of their modules. These values are 1 kW/m^2 for irradiance and 25^{o}C for the temperature.

3.5.1. Temperature effects

Factors such as ambient air temperature, the material of PV module characteristics and solar irradiance determine the operating temperature for the solar cells [65]. As stated previously, the effect of the temperature on PV cells will decrease the output voltage, which directly will affect the output power of the cells. This operating temperature for the solar cells is determined through equation (3.4):

$$T_{cell} = T_{amb} + [(NOCT - 20^o)/0.8]S \tag{3.4}$$

where:

T_{cell} is the cell temperature [^{o}C],

T_{amb} is the ambient temperature [^{o}C],

NOCT is the nominal operating cell temperature given by manufacturers,

S is the solar insolation [kW/m^2].

The NOCT is the cell temperature in the module when ambient, solar irradiation and wind-speed is 20ºC, 0.8 kW/m^2 and 1 m/s, respectively [51]. Fig. 3-8 displays how the operating temperature of solar cells affect the I-V curve and the output voltage of solar cells [67].

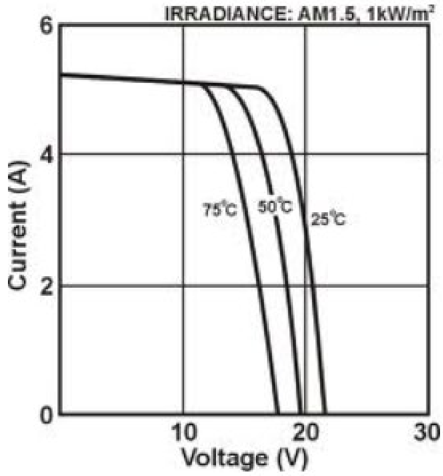


Fig. 3-8. I-V curve and output voltage affected at diverse operating temperatures [67]

3.5.2. Solar irradiation effects

Solar cells must receive as much solar irradiation as possible from a sun whose position in the sky depends on the time of day and the time of year. For solar cells to track the movement of the sun, PV cells have to hold equipment trackers that allow them to receive as much solar irradiation as possible [51]. However, these trackers are expensive and need regular maintenance, hence, most PV cells are installed in a specific position. Usually, the PV modules are installed at a fixed angle determined by the local latitude and characteristics of the demand. This prescribed installation assists in optimising the received amount of solar irradiations. Fig. 3-9 shows the effect of different solar irradiance values on the output voltage and current [67].

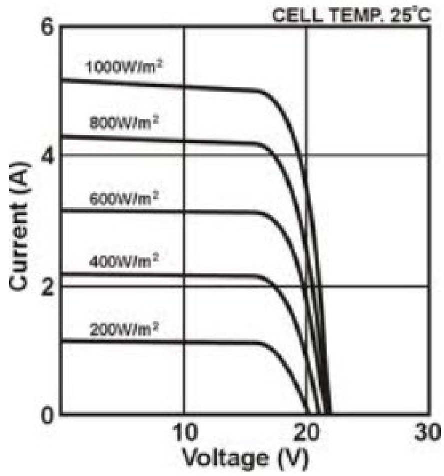


Fig. 3-9. I-V curve and output voltage and current affected at diverse solar irradiances [67]

3.6. Summary

To conclude, a brief history of the discovery of solar energy as well as the PV technologies is discussed. Next, solar cells are covered and the different ways of connection that the solar cells can be organised in parallel and series are detailed with showing the effects of these connections on the output voltages and currents of solar cells depending on which connection method is used. As parallel connection is used when higher output currents needed and series method for higher voltages. Furthermore, the factors that have an impact on the efficiency of PV modules are provided with displaying their effects on the output voltages and currents, thus the output power. These factors are the cell temperature and solar irradiation.

4. Saudi Arabia Electricity Background

4.1. Overview

In the beginning of this chapter, Saudi Arabia generation capacities, including the detail of the companies providing the electricity in Saudi Arabia, are discussed. Next, the growth of electricity industry and energy demand in Saudi Arabia will be presented. As well, statistical information about power interruptions and the frequency of these interruptions in Saudi Arabia will be provided. Then, the Saudi Arabia electricity tariff will be shown. Eventually, the chapter will be summed up.

4.2. Saudi Arabia Electricity Generation Capacity

Different companies contribute to electricity production in Saudi Arabia. Table 4-1 shows the number of plants each company has and the amount of installed capacity in MW. Saudi Electricity Company (SEC) has the largest number of plants and installed capacity, 47 plants and over 57 MW, respectively [6]. This capacity amounts to 70% of all available installed capacities provided by all licensees; Table 4-1 summarises all the existing power plants. The total number of plants and installed capacity are 81 plants and 81,603 MW, respectively.

Table 4-1. Electricity Generation Capacity for All Licensees - as per the licences [6]

Producer	No. of Plants	Installed Capacity (MW)	Percentage (%)
SEC	47	57,138	70
Saline Water Conversion Corporation (SWCC)	7	6,222	8
Hajr for Electricity Production Company	1	4,098	5
Jubail Water & Power Company	1	2,875	4
Saudi Aramco	7	1,563	2
Durmah Electric Company	1	1,756	2
Marafiq	1	1,589	2
Rabigh Electric Company	1	1,320	2
Shuaibah Water & Electricity Company	1	1,191	1
Tihama Power Generation Company	4	1,643	2
Shaqaiq Water & Electricity Company	1	1,020	1
Rabigh Arabian Water and Electricity	1	600	1
Jubail Energy Company	1	250	
Saudi Cement Company	2	227	
Tuwairqi Energy Company	1	74	1
Alaman Company	3	22	
Obeikan Paper Industries Company	1	16	
Total[1]	81	81,603	100

These capacities are produced by different types of generators: steam turbines, gas turbines, diesel generators and combined cycle units. Fig. 4-1 below shows that most of these capacities are produced by gas turbine, 47% of the total production; diesel generators produce the least capacity, 1% of the total.

[1] The available capacity was 69,155 MW

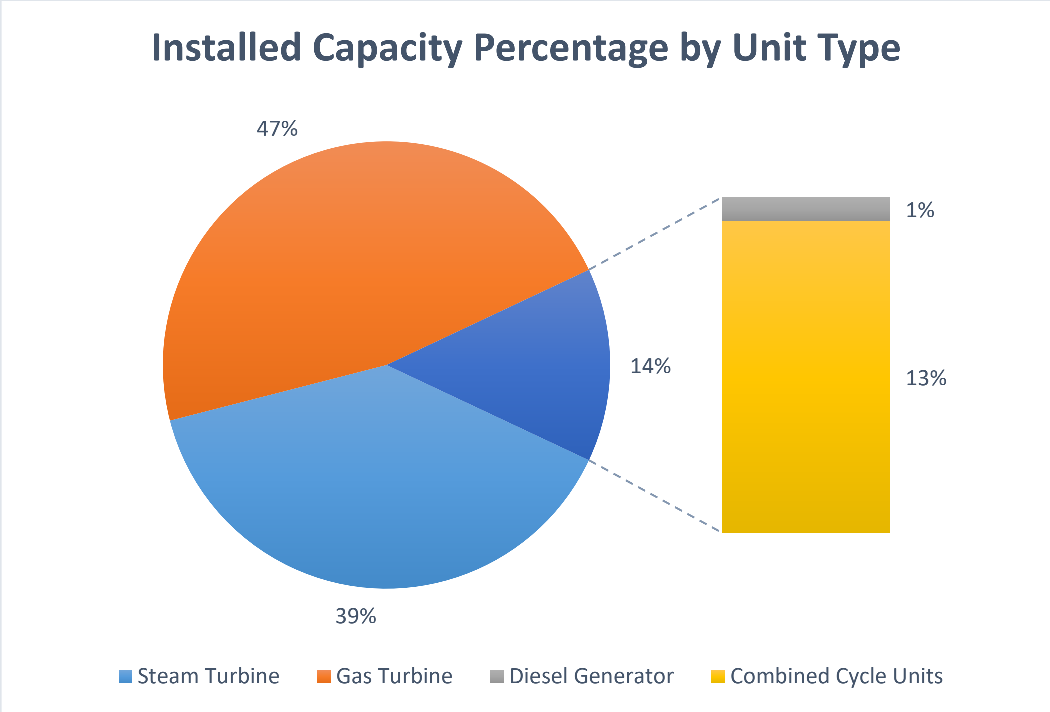


Fig. 4-1. Installed Capacity Percentage by Unit Type [6]

4.3. Growth of the Electricity Industry and Energy Demand

The electricity industry in Saudi Arabia has grown so fast between 2008 and now due to an increase in population, and this has resulted in a greater energy demand. Fig. 4-2 shows the increase in capacity of generation units over the period 2008 to 2015 [6]. In addition, it confirms the main generation units used were steam turbine and gas turbine, and that their capacities increased from 18 to 32 GW and 25 to 38 GW, respectively. Moreover, combined cycle units increased from 3 to 10 GW over the eight years presented in this figure.

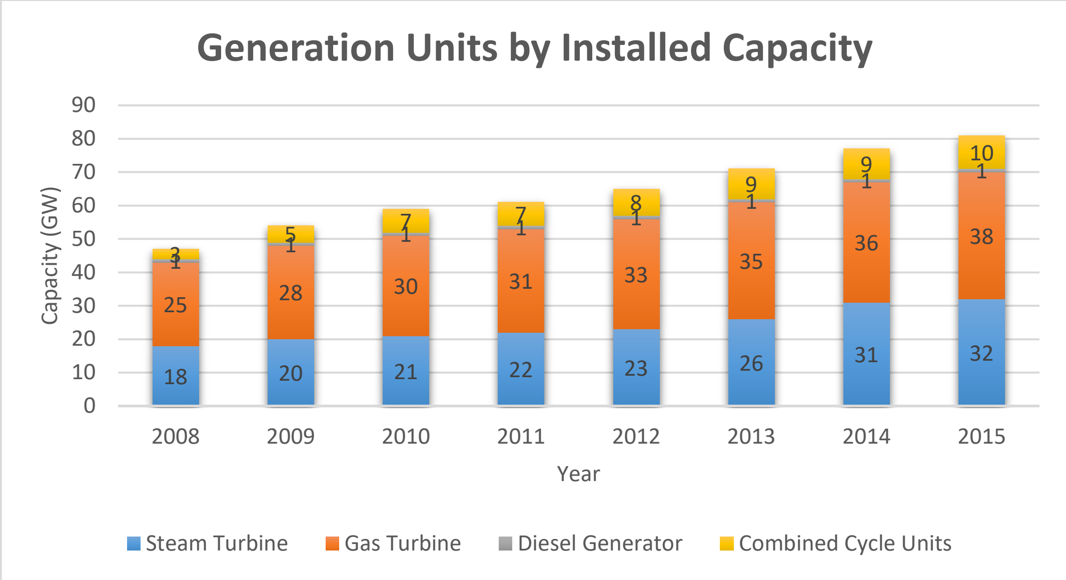


Fig. 4-2. Generation Units by Installed Capacity [6]

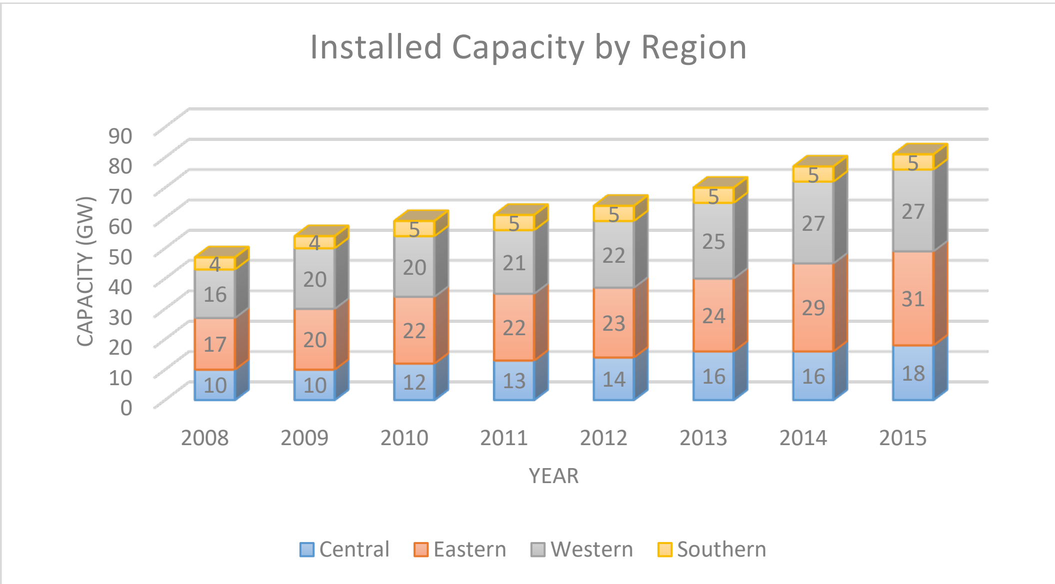


Fig. 4-3. Installed Capacity by Region [6]

As detailed in Fig. 4-3, as the capacity of generation increases, the demand for these capacities differs from region to region. The regions showing the highest capacity in 2015 are the Eastern and Western with 31 and 27 GW. Even in 2008, these same regions had the highest capacity with 17 for the Eastern and 16 for the Western.

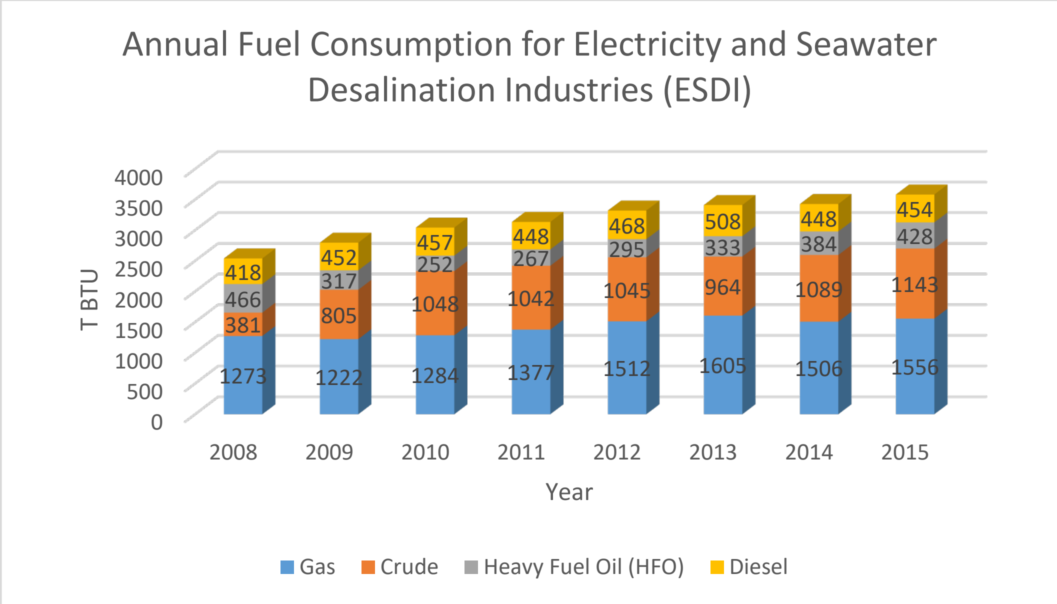


Fig. 4-4. Annual Fuel Consumption for ESDI by all licensees [6]

Fig. 4-4 clearly displays the increase in annual fuel consumption from 2538 T BTU in 2008 up to 3581 T BTU in 2015. Gas and crude form the bulk of these fuel consumptions, producing 1556 and 1143 T BTU, respectively, in 2015.

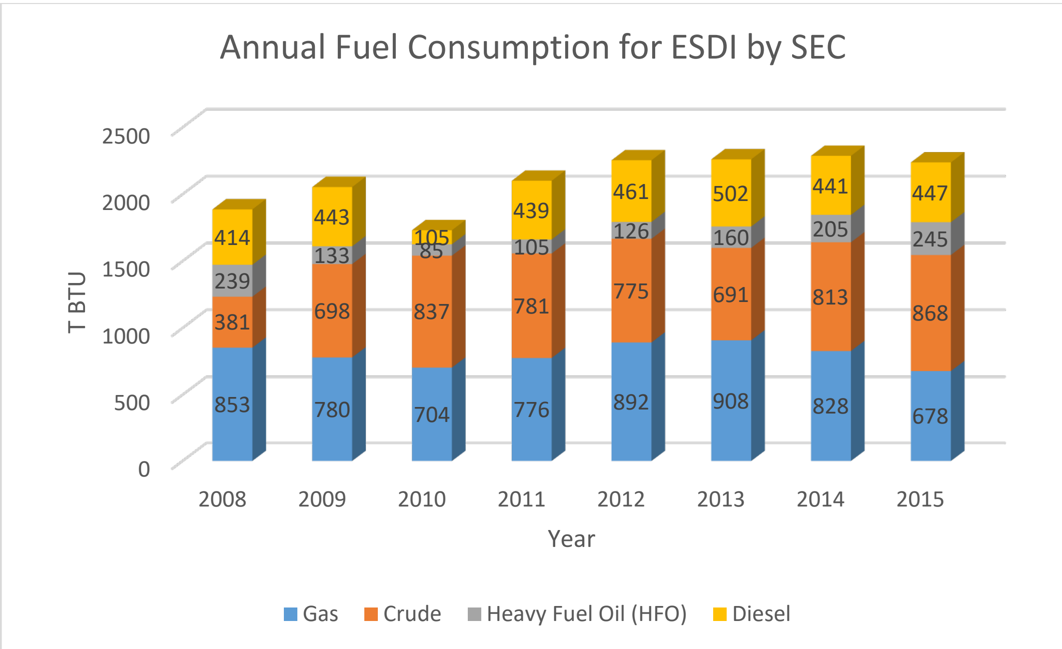


Fig. 4-5. Annual Fuel Consumption for ESDI by SEC [6]

Fig. 4-5 shows how SEC contributed toward annual fuel consumption over the period covering 2008 until 2015. As SEC has the highest installed capacity, it also records the highest annual fuel consumption. The minimum fuel consumption occurred in 2010 with 1731 T BTU, and the maximum was logged in 2014 with 2287 T BTU. However, it can be seen that over this time SEC lowered the usage of gas as a fuel and instead increased its use of diesel, crude and HFO.

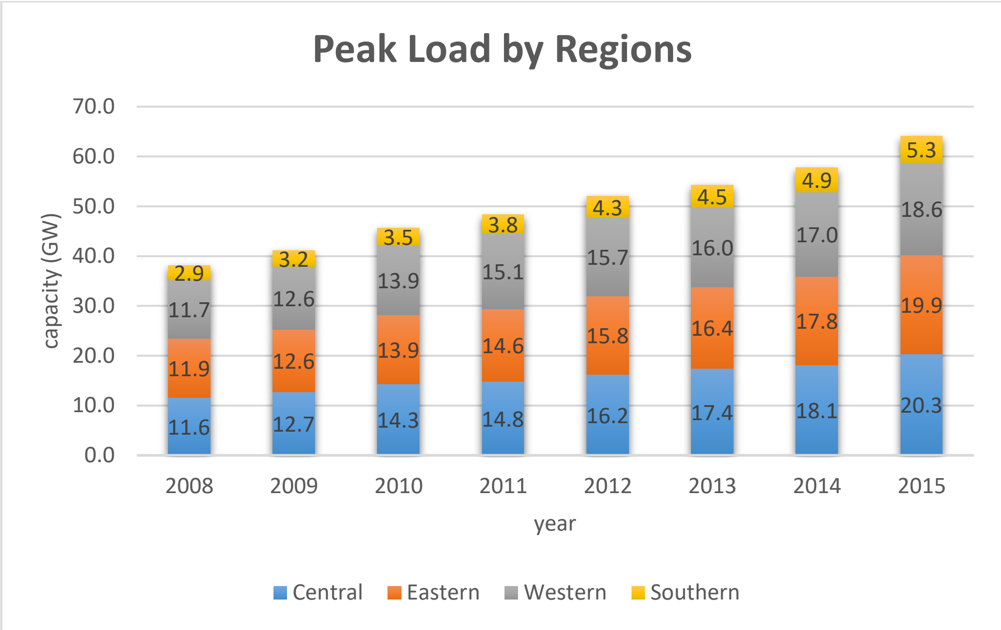


Fig. 4-6. Peak Load by Regions [6]

Taken from the annual statistical booklet for ESDI, peak load by regions was compared for the duration 2008 to 2015. Fig. 4-6 shows the increase in peak load in all regions from 38.1 GW in 2008 to 61.4 GW in 2015 [6]. Fig. 4-7 shows the available capacity is also increasing rapidly to cover the peak load. In 2008, the difference between the available capacity and peak load was 1 GW only, whereas in 2015 this difference had risen to 7 GW.

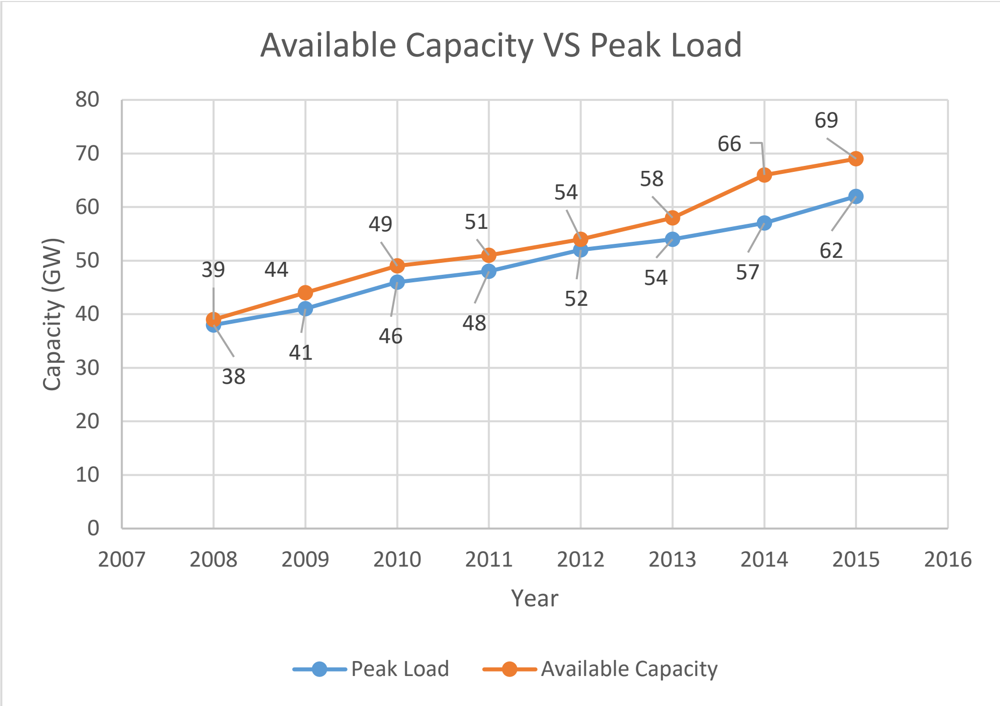
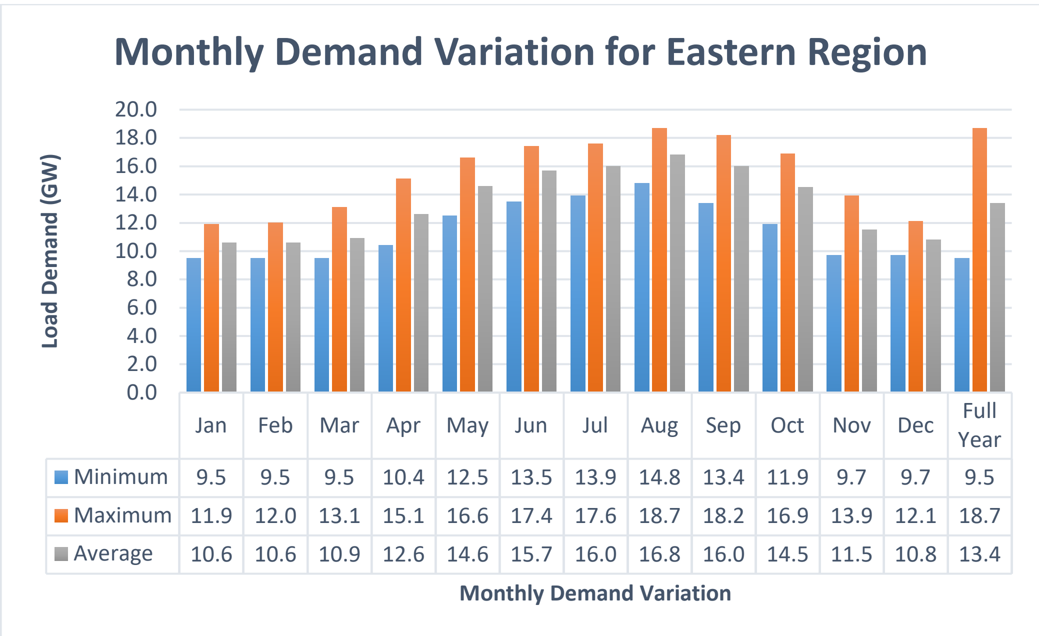


Fig. 4-7. Available Capacity versus Peak Load [6]

Fig. 4-8 displays the monthly demand variation for Eastern Region in Saudi Arabia. This figure indicates that load demands increase during the months of May until October, when maximum demand varies from 16.6 GW in May to 18.7 GW in August. Also, it shows the average annual load demand for the region is 13.4 GW.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Full Year
Minimum	9.5	9.5	9.5	10.4	12.5	13.5	13.9	14.8	13.4	11.9	9.7	9.7	9.5
Maximum	11.9	12.0	13.1	15.1	16.6	17.4	17.6	18.7	18.2	16.9	13.9	12.1	18.7
Average	10.6	10.6	10.9	12.6	14.6	15.7	16.0	16.8	16.0	14.5	11.5	10.8	13.4

Fig. 4-8. Monthly Demand Variation for Eastern Region – National Grid Saudi Arabia [6]

4.4. Power Interruptions and its Frequency

According to ECRA's statistical booklet, there had been a number of customers' complaints for different reasons [6]. Fig. 4-9 presents the number and types of the complaints for the four regions in Saudi Arabia.

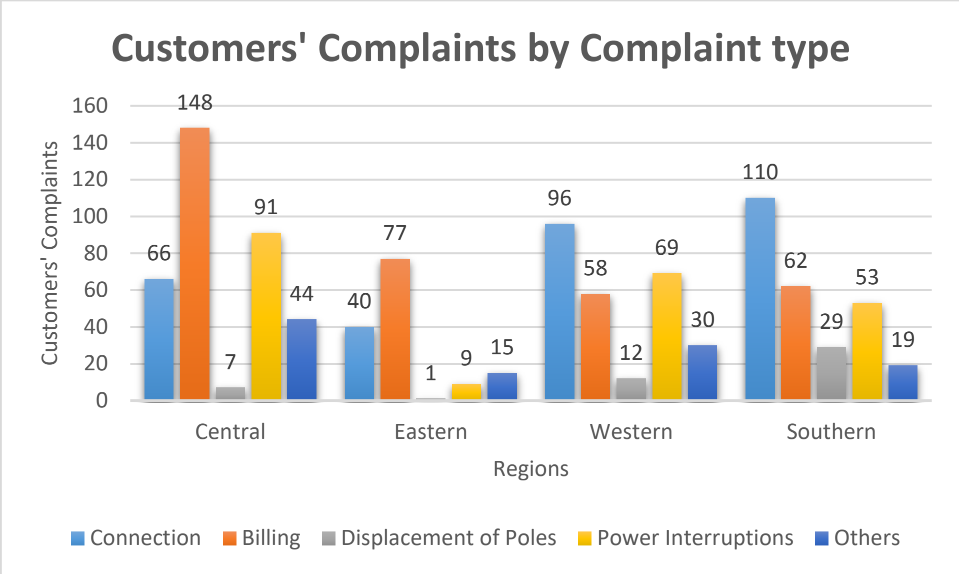


Fig. 4-9. Customers' Complaints by Complaint type [6]

This figure indicates that the top three complaints types are:

1- Billing with 345 complaints, most of them from central region.
2- Connection with 314 complaints, most of them from southern and western regions.
3- Power interruptions with 228 complaints, most of them from central region.

Also, ECRA's statistical booklet provides the average power interruptions duration for most of the regions and cities in Saudi Arabia [6]. It shows the interruptions of the main electricity supplier (SEC) in Saudi Arabia for all the regions and the interruptions of the same company for each region and city. In the period of 2011, Jazan had the longest time of power interruption with 1009 min/customer, whereas in 2014 Assir had the longest time with 698 min/customer. Fig. 4-10 displays the system average interruption duration since 2011 up to 2014 for SEC, Riyadh city, Jeddah, Assir and Dammam.

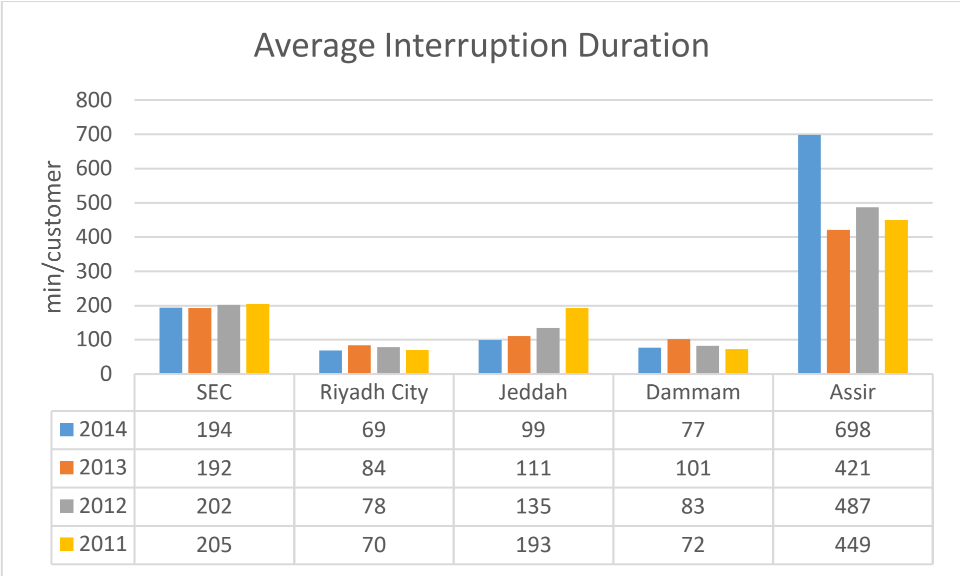


Fig. 4-10. Average Interruption Duration [6]

ECRA's statistical booklet includes the average frequency of these interruptions for the same regions and cities [6]. In 2011, Jazan had the highest number of average interruption frequency by 20.9, while Assir had the highest frequency of 24.5 in 2014. Fig. 4-11 depicts the average interruption frequency for the period of 2011 until 2014 for SEC, Riyadh city, Jeddah, Assir and Dammam.

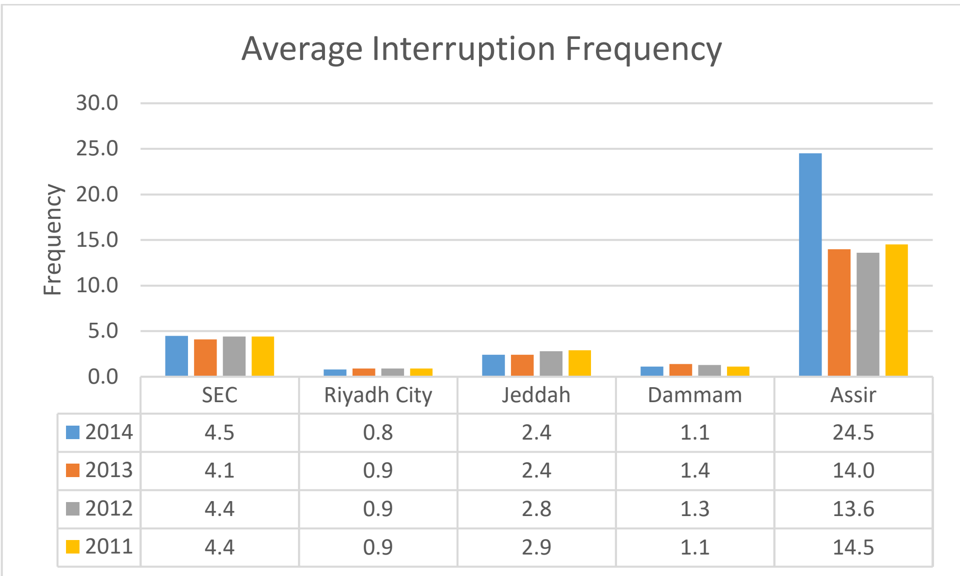


Fig. 4-11. Average Interruption Frequency [6]

4.5. Saudi Arabia Electricity Tariff

The consumption tariff has been changed since 1/1/2018 according to [68]. The new rates for the consumption tariff changed for all categories of service that SEC supply electricity, which are residential, commercial, agricultural and charities, governmental, industrial and private educational facilities and private medical facilities (PEF & PMF) as shown in Table 4-2. The prices of the electricity expressed in Halalah per kWh (H/kWh).

Table 4-2. Consumption tariff rates for all categories supplied by SEC [68]

Consumption Categories (kWh)	Residential (H/kWh)	Commercial (H/kWh)	Agricultural & Charities (H/kWh)	Government (H/kWh)	Industrial (H/kWh)	PEF & PMF (H/kWh)
1-6000	18	20	16	32	18	18
More than 6000	30	30	20			

This table shows the prices of electricity in Halalah which is the subdivided of Saudi Riyal (SR). The SR is subdivided into 100 Halalas. The prices in the above table transformed to US dollar in Table 4-3.

Table 4-3. Consumption tariff rates for all categories supplied by SEC in US dollar [68]

Consumption Categories (kWh)	Residential ($/kWh)	Commercial ($/kWh)	Agricultural & Charities ($/kWh)	Government ($/kWh)	Industrial ($/kWh)	PEF & PMF ($/kWh)
1-6000	0.048	0.053	0.043	0.085	0.048	0.048
More than 6000	0.080	0.080	0.053			

4.6. Summary

To sum up, this chapter shows that the main electricity supplier company in Saudi Arabia is SEC with the installed capacity of 57,138 MW. To add, the electricity generation in Saudi Arabia grows due to the increase in demand, as shown between 2008 and 2015. Moreover, there has been an increase in the peak load and the capacity available to cover this growth. The average monthly demand in Eastern region of Saudi Arabia is presented, and it displays that the high average load demand, with annual demand of 13.4 GW, occurs between May and October.

Several complaints from customers using the electricity in Saudi Arabia is provided. Among these complaints, the third top complaint type is power interruptions with 228 complaints from the four main regions (Eastern, Western, Southern and Central). In addition, the average system interruption duration between 2011 and 2014 for SEC, Riyadh city, Dammam, Assir and Jeddah is shown. For the same regions, company and between the same periods, the average system interruption frequency is presented. At the end of this chapter, Saudi Arabia Electricity tariff from SEC is also provided.

5. Study Methods and System Design

5.1. Overview

Firstly, this chapter will briefly discuss how HOMER software helps in designing and optimising power generation systems that involve renewable energy sources. Secondly, the load profile of the system studied in this thesis will be presented. Thirdly, solar resource data and air temperature, for the location that will be considered for this study, will be detailed. Fourthly, a heuristic design calculation for the PV and inverter sizing to have a better estimation of how many wattages at least needed from both to be designed later on in HOMER will be addressed. Fifthly, HOMER will be utilised to design the system including the sizing for the PV and the inverter taken into account the heuristic design calculations for their sizes. Sixthly, the grid design in HOMER will be detailed and the scenarios that will be considered in this study for the grid will be included in this part of this chapter. Lastly, a summary of the methodology and system design will be included.

5.2. HOMER software

HOMER, which stands for Hybrid Optimization of Multiple Energy Resources, is a computer software that the U.S. NREL developed in order to aid in designing micro-power systems and to provide easier way of comparison between different power generations [69]. HOMER allows modelling a power system's physical behaviour and its life-cycle cost, total cost of installation and operating the system over its lifetime. Additionally, it provides the ability of technically and economically comparing diverse system designs and understanding the effect of any uncertainty or changes in the inputs of the models.

Micro-power system is a system that produces electricity to serve a load that is nearby. Any combination of power generation and storage technologies may be employed in micro-power systems. Also, they might be grid-connected or off-grid. HOMER has the power of modelling off-grid and grid-connected systems to serve an electrical load and thermal loads. The systems include any mix of PV modules, wind turbines, small hydro, biomass power, generators, micro-turbines, fuel cells, batteries and hydrogen storage.

With the large number of design options that HOMER can provide and the uncertainty in parameters like load size and fuel price, these can make analysing and designing of the micro-power system difficult. Involving renewable energy sources in the design adds complexity to the analysis as some renewables may have an intermittent power output and dependent on season. Moreover, the availability of renewable resources could be indeterminate.

HOMER has three tasks to perform when running a micro-power system analysis. These tasks are simulation, optimisation and sensitivity analysis. In the first task (simulation), HOMER testifies the performance of any designed micro-power system configuration to determine its technical and economic (life-cycle cost) possibility. The second task, which is optimisation task, HOMER models various system combinations to search for the optimal system that meets the technical constraints provided by the modeller at the lowest cost of life-cycle. In the sensitivity analysis task, the third task, HOMER reproduces several optimisations with a different range of assumed inputs to aid in understanding the effects of any uncertain changes in the model inputs. Fig. 5-1 demonstrates the relationship between these three tasks.

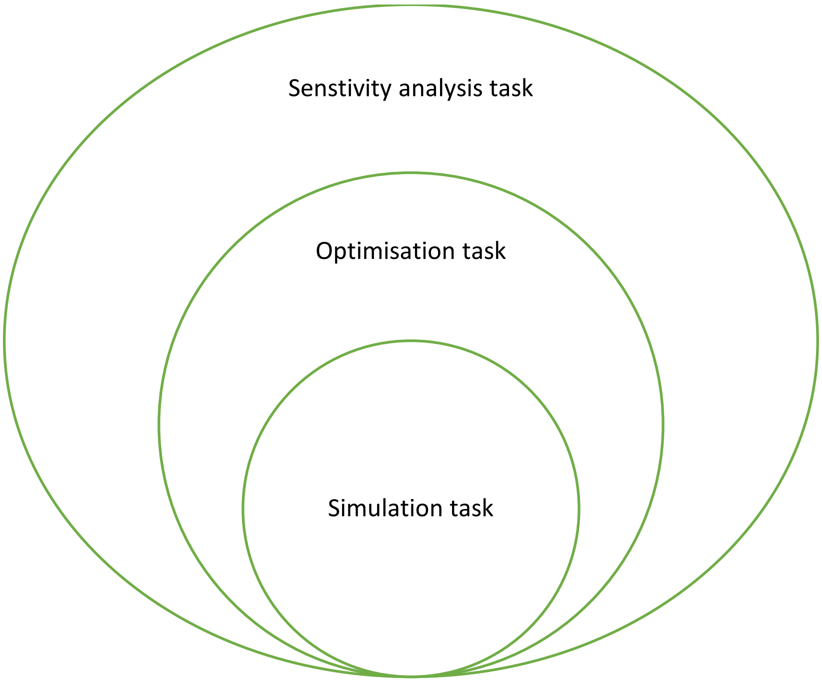


Fig. 5-1. The relationship between simulation, optimization and sensitivity analysis tasks [69]

5.2.1. HOMER Controller strategies

HOMER has the controller component that controls how HOMER system operates while doing the simulation task [70]. All controllers have a different control algorithm (dispatch strategy). HOMER enables using several controllers for the simulations and the optimisations of the system and shows the results to compare the system's performance according to each dispatch strategy chosen. In addition, for each controller, HOMER Pro provides the ability of specifying the capital cost and lifetime or if the capital cost set to zero then lifetime does not matter. The best dispatch strategy is relied on several factors such as, but not limited to, the sizes of the generators, the fuel price and the amount of renewable energy resources.

HOMER previously had only two dispatch controllers which are load following (LF) and cycle charging (CC) dispatch. However, the new HOMER Pro includes two more dispatches which are generator order (GO) and Pro MATLAB Link (ML). In LF strategy, if a generator is required to operate, it generates just adequate power to meet a specific load, and it tends to be optimal where the systems have lots of renewable resources. In CC strategy, if a generator required to operate, the generator provides full capacity power and the excessive power goes to charge a battery if it exists in the system. The CC strategy is the opposite of the LF in the tendency to be optimal if little renewables or no renewable energy sources are involved. In GO strategy, it provides the ability of organising the generator combinations in a particular order and makes HOMER obeys this defined order list that satisfies the operating capacity. This strategy only supports systems that includes generators, PVs, wind turbines, a converter and storage components. Nevertheless, when the modelled systems include thermal or Combined Heat and Power (CHP) components, hydrogen components and the grid, the GO does not support these systems. In ML strategy, HOMER Pro MATLAB Link enables writing or creating dispatch algorithm for HOMER Pro using MATLAB software. HOMER Pro will interface with the MATLAB software to follow the ML strategy while the simulation is running. In this study, two controller strategies are used and their results are compared which are the CC and ML strategies.

5.2.2. Economic Modelling

One of the main usages of HOMER is to provide an economic system while meeting the system constraints. Economics play a vital role in HOMER’s simulation and optimisation processes [69]. As in the simulation process, it runs the system combinations in order to minimise total net present cost (NPC). Whereas, it searches for the system combination that results in the lowest NPC in the optimisation process.

The cost characteristics of renewable and conventional energy sources generally have an opposite relationship in terms of initial capital and operating costs. Renewables typically have high initial capital costs, but low operating costs; while, non-renewables have the inverse that is low initial capital costs and high operating costs. In the optimisation process, HOMER has to compare the economics of system combinations involving changing amounts of renewables and non-renewables. These comparisons have to take into consideration both capital and operating costs to be justifiable. Therefore, NPC, life-cycle cost, analysis accounts for that by involving all costs that happen during the lifetime of the system.

HOMER uses total NPC to denote the life-cycle cost of the system. All the costs of initial construction, replacement costs, maintenance, fuel, and the electricity cost of purchasing from the grid and various costs like penalties from pollutant emissions are included in the calculations for the total NPC. Revenues consist of selling electricity back to the grid as well as any salvage value that presents at the end of the system lifetime. The NPC is opposite of the net present value (NPV) as in the NPC costs is considered a positive value, while a negative value is for the revenues. Consequently, the NPC and the NPV only differ in sign.

HOMER uses equation (5.1) to calculate the salvage value from each component in the system at the end of the project lifetime:

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{5.1}$$

where:
S is the salvage value,
C_{rep} is the replacement cost of the component,
R_{rem} is the remaining life of the component,
R_{comp} is the life span of the component.

An annualised cost calculated for each component by HOMER includes the capital, replacement, maintenance and fuels as well as the salvage value and any other costs or revenues. HOMER adds the annualised costs for each component besides any various costs caused by penalties for pollutant emissions in order to determine the total annualised cost of the system. This value is a significant value as HOMER includes it in the calculations for the two key economic records of merits for the system which are the NPC and the LCOE. HOMER calculates the total NPC by equation (5.2):

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{5.2}$$

where:

$C_{ann,tot}$ is the total annualised cost,

CRF is the capital recovery factor,

i is the annual real interest rate (the discount rate),

R_{proj} is the project lifetime.

The capital recovery factor is calculated through equation (5.3):

$$CRF\ (i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5.3}$$

where:

i is the annual real interest rate,

N is the number of years.

HOMER follows equation (5.4) to determine the value of the LCOE:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{5.4}$$

where:

$C_{ann,tot}$ is the total annualised cost,

E_{prim} is the total amount of primary loads served yearly by the system,

E_{def} is the total amount of deferrable loads served yearly by the system,

$E_{grid,sales}$ is the amount of energy sold to the grid yearly.

5.2.3. Economics, constraints and emissions inputs

For economic inputs in this project, the nominal discount rate, expected inflation rate and project lifetime are chosen to be 5.00%, 2.94% and 25 years as shown in Fig. 5-2. These rates inputs and lifetime of the project are used for both system configurations for this thesis. In addition, the currency selected for this project is US dollar ($). The nominal discount and expected inflation rates are assumed with those numbers in order to achieve the real discount rate at 2.00%. These two rates (nominal discount and expected inflation) are used by HOMER to calculate the real discount rate [70]. This is because the real discount rate will be used to calculate discount factors and annualised costs from NPC. HOMER uses equation (5.5) to calculate the real discount rate:

$$R_{discount\ rate} = \frac{N_{discount\ rate} - Inflation}{1 - \frac{Inflation}{100\%}} \tag{5.5}$$

where:

$R_{\text{discount rate}}$ is the real discount rate [%],

$N_{\text{discount rate}}$ is the nominal discount rate (the rate of borrowing money) [%],

Inflation is the expected inflation rate [%].

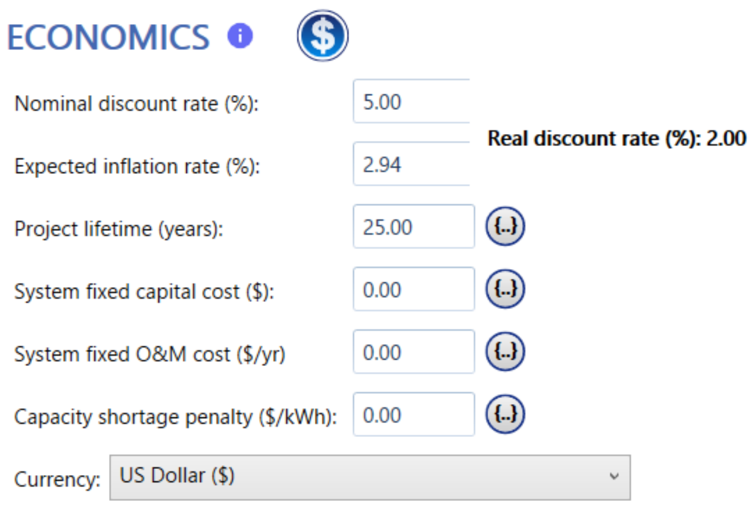


Fig. 5-2. Economics input

The considered constraints for the project are maximum annual capacity shortage (%), minimum renewable fraction (%) and operating reserve. In the operating reserve, there are two different considerations which are a) percentage of load and b) percentage renewable output. Under the first one, there are two factors that are a) load in current time step (%) and b) annual peak load (%). Under the second one, there are solar power output (%) and wind power output (%). These constraints are assumed depending on the system configurations. For the grid and diesel backup system, these constraints are assumed to be as shown in Fig. 5-3. While for the grid-connected PV with diesel backup system, the constraints are given in Fig. 5-4.

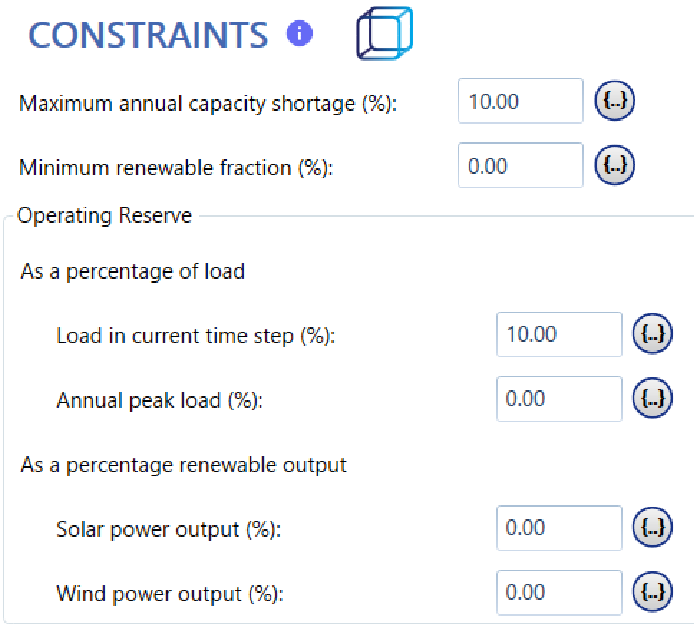


Fig. 5-3. The constraints for the Grid and Diesel Backup system

As shown in Fig. 5-3, the annual capacity shortage chosen to be 10% at maximum, and as there is no renewable source, then the minimum renewable fraction set to be zero. To add, in the operating reserve, the operating reserve as a percentage of load in current time step assumed to be 10% of the required load in case of a sudden increase of the load.

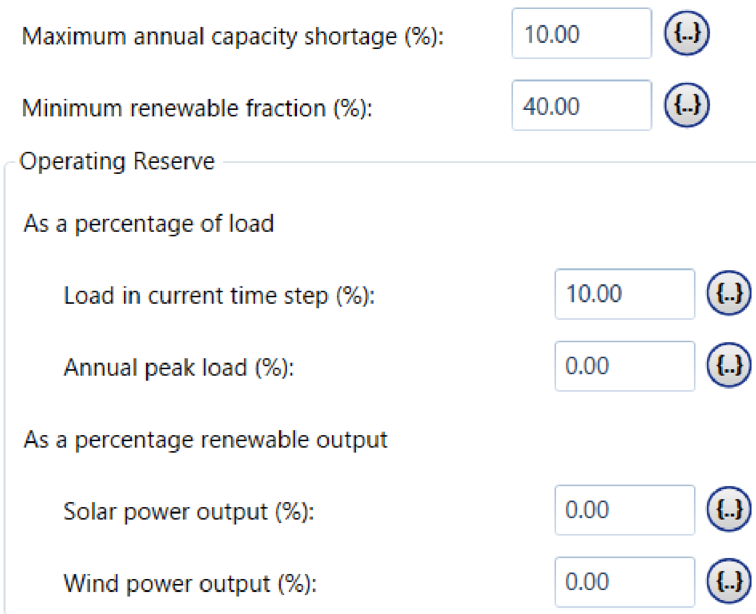


Fig. 5-4. The constraints for the PV/Grid/Diesel system

In Fig. 5-4, the only difference from the previous assumptions made is that the minimum renewable fraction is selected to be 40% to ensure supplying the requested load with at least 40% or more by the PVs. HOMER decides whether or not the system is viable depending on the capacity shortage fraction that should be equal to or less than the maximum annual capacity shortage [70]. This capacity shortage fraction is calculated by equation (5.6):

$$f_{cs} = \frac{E_{cs}}{E_{demand}} \tag{5.6}$$

where:

E_{cs} is the total capacity shortage [kWh/yr],

E_{demand} is the electrical demand (primary and deferrable load) [kWh/yr].

Also, renewable fraction is calculated via equation (5.7):

$$f_{ren} = 1 - \frac{E_{nonren}+H_{nonren}}{E_{served}+H_{served}} \tag{5.7}$$

where:

E_{nonren} is the non-renewable electrical production [kWh/yr],

$E_{grid,sales}$ is the energy sold to the grid [kWh/yr], included in E_{served},

H_{nonren} is the non-renewable thermal production [kWh/yr],

E_{served} is the total electrical load served [kWh/yr],

H_{served} is the total thermal load served [kWh/yr].

However, as both system configurations that are considered in the study have no thermal load and production, the thermal terms will be zero which will give the following equation (5.8):

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}} \tag{5.8}$$

The required operating reserve is calculated for AC loads via equation (5.9) [70]:

$$L_{res,AC} = r_{load}\, L_{prim,AC} + r_{peak,load}\, \hat{L}_{prim,AC} + r_{wind}\, P_{wind,AC} \tag{5.9}$$

where:

$L_{res,AC}$ is the required operating reserve on the AC bus,

r_{load} is the input operating reserve as a percentage of load in the current time step,

$L_{prim,AC}$ is the average AC primary load in the current time step,

$r_{peakload}$ is the input operating reserve as a percentage of annual peak load,

$\hat{L}_{prim,AC}$ is the highest AC primary load experienced by the system during the year,
r_{wind} is the input operating reserve as a percentage of wind power output,
$P_{wind,AC}$ is the average AC wind power output in the current time step.

As there is no wind power and the annual peak load set to zero, therefore the equation become as equation (5.10):

$$L_{res,AC} = r_{load}\, L_{prim,AC} \tag{5.10}$$

The required operating reserve for the DC bus is given by equation (5.11) [70]:

$$L_{res,DC} = r_{load}\, L_{prim,DC} + r_{peak,load}\, \hat{L}_{prim,DC} + r_{wind}\, P_{wind,DC} + r_{solar} \tag{5.11}$$

where:
$L_{res,DC}$ is the required operating reserve on the DC bus,
$L_{prim,DC}$ is the average DC primary load in the current time step,
$\hat{L}_{prim,DC}$ is the highest DC primary load experienced by the system during the year,
$P_{wind,DC}$ is the average DC wind power output in the current time step,
r_{solar} is the input operating reserve as a percentage of solar power output,
P_{PV} is the average PV array output in the current time step.

Also, as there is no wind power considered and annual peak load set to zero, hence the equation shortened to equation (5.12):

$$L_{res,DC} = r_{load}\, L_{prim,DC} + r_{solar} P_{PV} \tag{5.12}$$

As all the system configurations considered in the HOMER analysis use conventional energy sources (grid and diesel generator), the cost of the released emissions are considered to provide more realistic results. Nevertheless, only costs of three of the pollutants are taken into account in this study which are CO_2, SO_2 and NO_x. The costs of these emissions shown in Fig. 5-5. The penalty cost is assumed to be one dollar per tonne (1 \$/t) for all three pollutants.

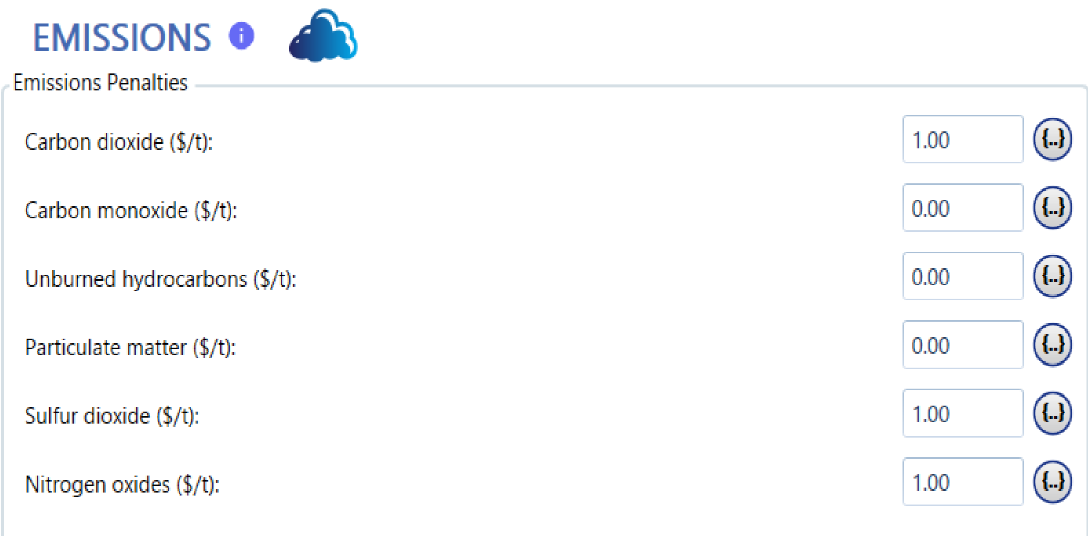


Fig. 5-5. Emission costs

These costs and penalty costs of capacity shortage will have an impact on the total NPC and COE of the analysed systems as they are included under a function called another O&M which includes the penalty costs of the emissions and the capacity shortage [70]. This another O&M costs are calculated by equation (5.13):

$$C_{om,other} = C_{om,fixed} + C_{cs} + C_{emissions} \tag{5.13}$$

where:

$C_{om,fixed}$ is the system fixed O&M cost [$/yr],

C_{cs} is the penalty for capacity shortage [$/yr],

$C_{emissions}$ is the penalty for emissions [$/yr].

But, as the system fixed O&M cost for the study selected to be zero, then it becomes as equation (5.14):

$$C_{om,other} = C_{cs} + C_{emissions} \tag{5.14}$$

The penalty costs of the capacity shortage is calculated via (5.15), and the penalty costs of the emissions is calculated by equation (5.16) [70]:

$$C_{cs} = c_{cs} + E_{cs} \tag{5.15}$$

$$C_{emissions} = \frac{c_{CO2}M_{CO2}+c_{CO}M_{CO}+c_{UHC}M_{UHC}+c_{OM}M_{PM}+c_{SO2}M_{SO2}+c_{NOx}M_{NOx}}{1000} \quad (5.16)$$

Nevertheless, as only CO_2, SO_2 and NO_x are considered in the study, equation (5.16) becomes as equation (5.17):

$$C_{emissions} = \frac{c_{CO2}M_{CO2}+c_{SO2}M_{SO2}+c_{NOx}M_{NOx}}{1000} \quad (5.17)$$

where:

E_{cs} is the total capacity shortage [kWh/yr],

c_{CO2} is the penalty for emissions of CO_2 [$/t],

M_{CO2} is the annual emissions of CO_2 [kg/yr],

c_{CO} is the penalty for emissions of CO [$/t],

M_{CO} is the annual emissions of CO [kg/yr],

c_{UHC} is the penalty for emissions of unburned hydrocarbons (UHC) [$/t],

M_{UHC} is the annual emissions of unburned hydrocarbons (UHC) [kg/yr],

c_{PM} is the penalty for emissions of particulate matter (PM) [$/t],

M_{PM} is the annual emissions of particulate matter (PM) [kg/yr],

c_{SO2} is the penalty for emissions of SO_2 [$/t],

M_{SO2} is the annual emissions of SO_2 [kg/yr],

c_{NOx} is the penalty for emissions of NO_x [$/t],

M_{NOx} is the annual emissions of NO_x [kg/yr].

5.3. System Load Profile

The considered location in this study is Dammam Medical Tower in Dammam, Saudi Arabia (26˚ 25.9' N, 50˚ 5.0' E). The load profile data used for this research in HOMER was based on the critical loads that are connected to two Diesel Generators, with capacity of 750kVA each, in case of grid outages at the Dammam Medical Tower [71]. In this study, it is assumed that the diesel generators provide an output power of 1350 kW in total. Therefore, the average daily demand from the critical loads are also assumed to be 15,826 kWh/day with peak load of 1350 kW. Fig. 5-6 depicts the load profile for the location to be analysed through different system configurations.

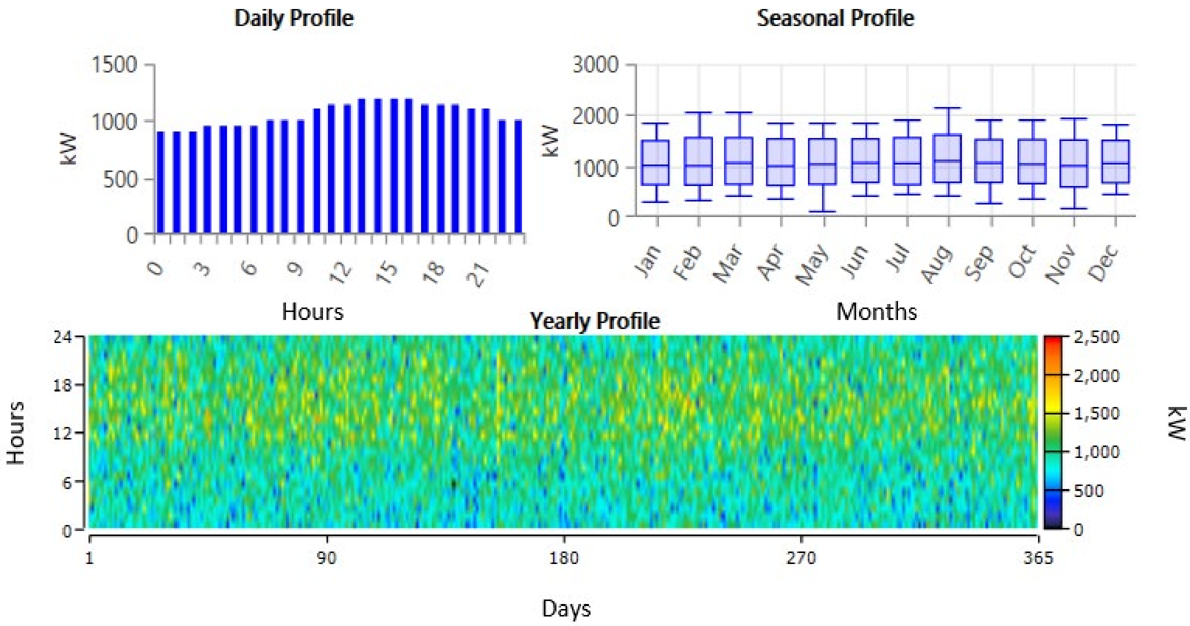


Fig. 5-6. The load profile for the system

The normal operating hours in this building is 24 hours daily. The high demand of energy is assumed to be from 12 pm until 5 pm with low load demand is from 12 am until 6 am. There is no monthly peak load assumed in this study for the load.

5.4. Solar Resource Data and Air Temperature

In order to model power generation involving renewable energy resources, data relating to the renewable sources must be provided to test for viability in the chosen location. This is because some renewable sources depend on climate, atmospheric circulation, latitude and geographic influences, such as solar and wind sources. As mentioned previously, solar source is one of the most important sources in Saudi Arabia because the sun shines all year long with a solar radiation variation of around 4.0-7.5 kWh/m^2/day [12].

This thesis examines the feasibility of using solar energy resource to supply the critical load at the location. The data for this solar energy was obtained from National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy (SSE) Database.

5.4.1. Solar Resource Data

Solar resource data shows the amount of global solar radiation that comes to the surface of Earth in a typical year [69]. HOMER presents this data in one of three forms, which include hourly average or monthly average global solar radiation in kW/m^2 and $kWh/m^2/day$. The third form is the clearness index that ranges from zero to one. This index compares the ratio of solar radiation on the surface of Earth to the solar radiation present at the top of the atmosphere and gives an indication of the clearness of the atmosphere. For monthly average solar radiation, HOMER creates synthetic hourly global solar radiation data based on an algorithm developed by Graham and Hollands [72].

NASA provides 22 years (1983-2005) of monthly solar resource data for the location [73]. The location has an annual average solar irradiation of 5.60 $kWh/m^2/day$. Fig. 5-7 shows the monthly average solar irradiation and the clearness index for the location. Data indicates that maximum solar irradiation occurs in June with a value of 7.730 $kWh/m^2/day$ and the minimum in December with 3.28 $kWh/m^2/day$. The months that have the highest solar irradiation throughout the year run from May until September. Moreover, the clearness index has an annual average of 0.62; the maximum clearness index occurs in June with a value of 0.685 and the minimum in December with 0.536.

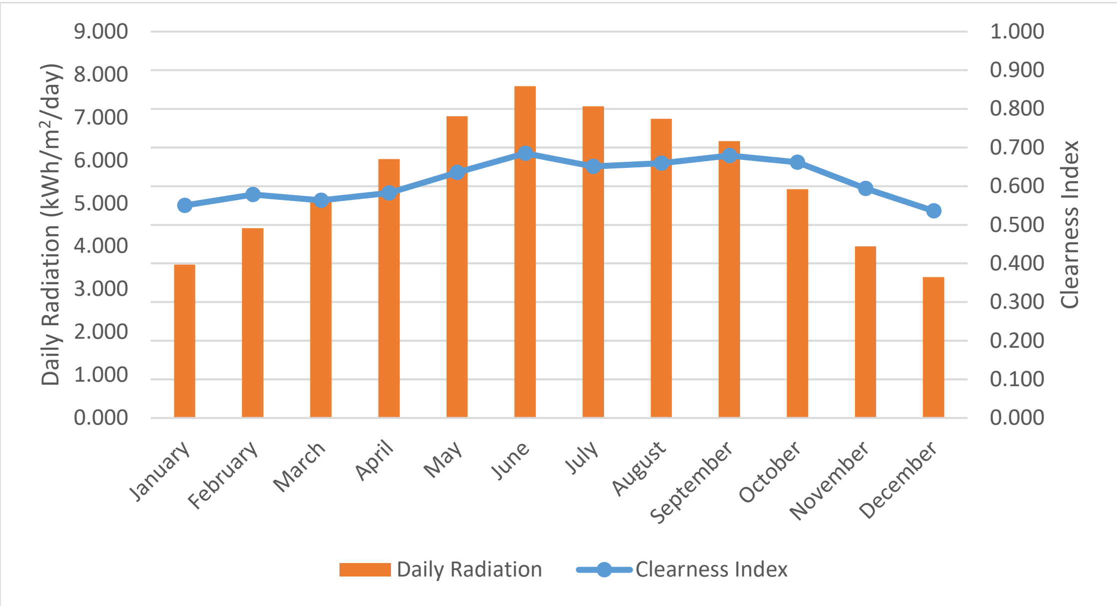


Fig. 5-7. 22 years of average monthly solar resource data for the location from 1983-2005 [73]

5.4.2. Air Temperature data

In addition, NASA provides monthly temperature data over the 22 years for the location. The location has an average air temperature of 27.44 ˚C. Also, as can be observed in Fig. 5-8, the maximum air temperature occurs during July and August with values of 35.12 ˚C and 35.2 ˚C respectively, and the minimum in January with 18.65 ˚C.

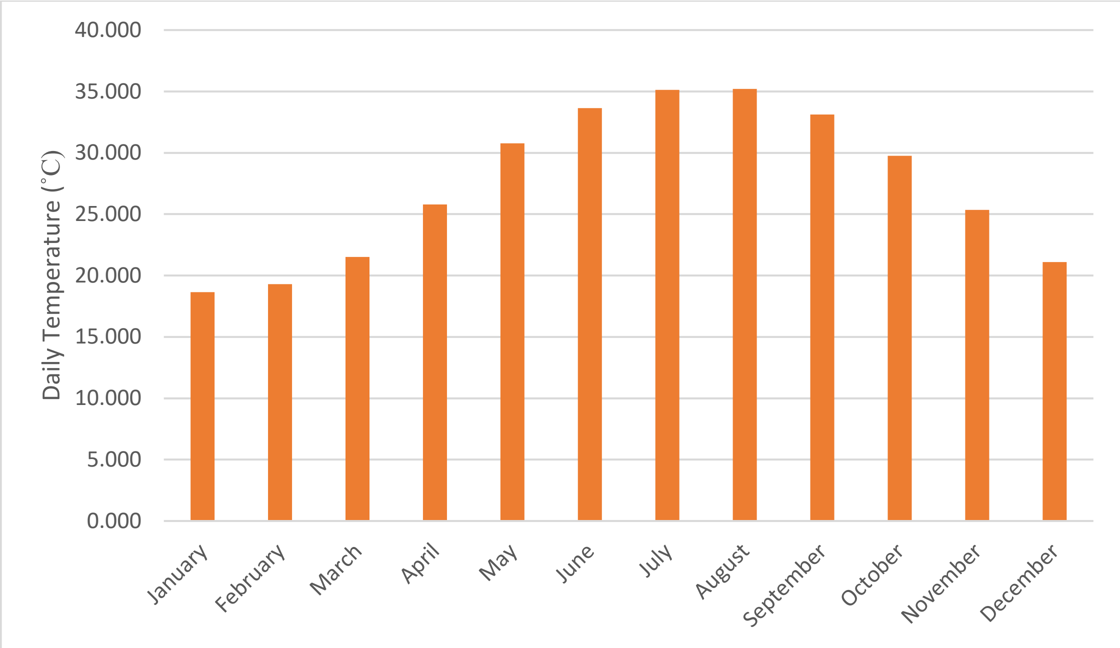


Fig. 5-8. 22 years of average monthly temperature data for the location from 1983-2005 [73]

5.5. Heuristic Design Calculations

The proposed grid-connected PV and diesel backup generator system will have the PV to supply the demand by 40% to 50% of the demand. As the demand load is 15826 kWh/day, therefore the PV modules will cover 6330.40 to 7913 kWh/day of that demand. The daily DC load demand from the PV modules are calculated in Table 5-3. The calculations are based on the technical specifications of the chosen PV module in Table 5-1 and the technical specifications of the chosen inverter in Table 5-2.

Table 5-1. Technical specifications of the PV module [74]

Module Type	P_{max} (W)	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)	Area (m2)	Price ($)
SG330P	330	36.40	9.07	45.00	9.78	1.941	220
Nominal Operation Cell Temperature (NOCT)				45±2 °C			
Temperature Coefficient of P_{max}				-0.43 %/°C			
Temperature Coefficient of V_{oc}				-0.32 %/°C			
Temperature Coefficient of I_{sc}				0.047 %/°C			
Operating Temperature				-40°C ~ +85°C			

Table 5-2. Technical specifications for the SMA SC500HE inverter [75]

Module Type	$P_{AC, maz}$ (kVA) @ 25˚C	$V_{AC, Nom}$ (V)	$I_{AC, Nom}$ (A)	$V_{PV,max}$ (V)	$P_{PV, max}$ (kW)	$I_{DC, max}$ (kW)	Area (m2)
SC500HE	550	270 ± 10%	1070	820	560	1.242	20.236
Efficiency				98.4%			
Operating Temperature				-20˚C to 50˚C			

Table 5-3. Total daily DC energy and load demand

Total AC demand (kWh/day)	Inverter Efficiency (%)	Total DC demand (kWh/day)	DC system voltage (V)	Total DC Load (kAh/day)	Safety Factor (5%)	Total DC load (kAh/day)
6330.4 – 7913	98.4	6433.34 – 8041.67	560	11.48 – 14.36	1.05	12.05 – 15.07

From Table 5-3, it suggests that the total daily AC demand required to enable the PVs to meet 40% to 50% of the total daily load demand ranges from 12.05 – 15.07 kAh/day. Taking into account both daily demand requirement, the PV is designed by considering three tilt angles that are equal to latitude, latitude + 15˚ and latitude - 15˚ based on [73]. The current calculations for all these three tilt angles are done via equation (5.18):

$$Calculated\ Current = \frac{Total\ daily\ DC\ load}{Peak\ sun\ hours\ per\ day} \tag{5.18}$$

Different tilt angle will result in different peak sun hours in each month of the year, therefore the calculated current equation will be computed for each month for all the three chosen tilt angles as shown in Table 5-4, Table 5-5 and Table 5-6.

Table 5-4. Calculated current at tilt angle = latitude (26˚)

Tilt angle (26˚ + 0˚ = 26˚)			
Month	Total DC Demand (kAh/day)	Peak sun (hrs/day)	Calculated Current (kA)
January	12.05 – 15.07	4.5	2.68 – 3.35
February	12.05 – 15.07	5.05	2.39 – 2.99
March	12.05 – 15.07	5.51	2.19 – 2.74
April	12.05 – 15.07	5.87	2.06 – 2.57
May	12.05 – 15.07	6.38	1.89 – 2.37
June	12.05 – 15.07	6.75	1.79 – 2.24
July	12.05 – 15.07	6.48	1.86 – 2.33
August	12.05 – 15.07	6.63	1.82 – 2.28
September	12.05 – 15.07	6.79	1.78 – 2.22
October	12.05 – 15.07	6.33	1.91 – 2.39
November	12.05 – 15.07	4.98	2.42 – 3.03
December	12.05 – 15.07	4.28	2.82 – 3.53

Table 5-5. Calculated current at tilt angle = latitude – 15 (11˚)

Tilt angle (26˚ - 15˚= 11˚)			
Month	Total DC Demand (kAh/day)	Peak sun (hrs/day)	Calculated Current (kA)
January	12.05 – 15.07	3.99	3.03 – 3.78
February	12.05 – 15.07	4.65	2.60 – 3.25
March	12.05 – 15.07	5.36	2.25 – 2.82
April	12.05 – 15.07	6.01	2.01 – 2.51
May	12.05 – 15.07	6.87	1.76 – 2.20
June	12.05 – 15.07	7.44	1.62 – 2.03
July	12.05 – 15.07	7.07	1.71 – 2.14
August	12.05 – 15.07	6.96	1.74 – 2.17
September	12.05 – 15.07	6.69	1.81 – 2.26
October	12.05 – 15.07	5.86	2.06 – 2.58
November	12.05 – 15.07	4.44	2.72 – 3.40
December	12.05 – 15.07	3.75	3.22 – 4.02

Table 5-6. Calculated current at tilt angle = latitude + 15 (41˚)

Tilt angle (26˚ + 15˚= 41˚)			
Month	Total DC Demand (kAh/day)	Peak sun (hrs/day)	Calculated Current (kA)
January	12.05 – 15.07	4.75	2.54 – 3.18
February	12.05 – 15.07	5.17	2.34 – 2.92
March	12.05 – 15.07	5.35	2.26 – 2.82
April	12.05 – 15.07	5.41	2.23 – 2.79
May	12.05 – 15.07	5.62	2.15 – 2.69
June	12.05 – 15.07	5.78	2.09 – 2.61
July	12.05 – 15.07	5.63	2.15 – 2.68
August	12.05 – 15.07	5.99	2.02 – 2.52
September	12.05 – 15.07	6.50	1.86 – 2.32
October	12.05 – 15.07	6.43	1.88 – 2.35
November	12.05 – 15.07	5.24	2.30 – 2.88
December	12.05 – 15.07	4.56	2.65 – 3.31

For the reason that the PVs will be required to supply 40% to 50% of the total daily demand and to ensure that the PVs are able to provide the sufficient amount of energy for that, the lowest peak sun hours for each tilt angle is chosen for comparison. This will provide more reliable and available energy to supply the demand. Table 5-7 shows the three worst peak sun hours of the three tilt angles and their calculated currents from the Table 5-4, Table 5-5 and Table 5-6.

Table 5-7. The worst peak sun hours and their calculated current from each tilt angle

Latitude + 0˚		Latitude + 15˚		Latitude - 15˚	
Peak sun (hrs/day)	Design Current (kA)	Peak sun (hrs/day)	Design Current (kA)	Peak sun (hrs/day)	Design Current (kA)
4.28	2.82 – 3.53	4.56	2.65 – 3.31	3.75	3.22 – 4.02

For this study, the selected tilt angle is the one that has the smallest production of current which is at the latitude + 15˚ with calculated current of 2.65 – 3.31 kA for 40% and 50% of coverage of load, respectively. Hence, to design this required current, another factor is needed to be considered which is called derating factor that is affecting the output of the PVs. Derating factor includes shading, dirt and manufacture defects and these are considered for the PV in this study. As a result, the value of derating factor in this study is chosen to be 80% to safely provide the required current in reality. By including this derating factor, the new calculated current will be calculated by equation (5.19). Then, the number of PV modules in parallel can be calculated based on the new calculated current and is represented through equation (5.20); while the number of PV modules in series is calculated based on the DC system voltage as represented via equation (5.21):

$$The\ new\ calculated\ current = \frac{Calculated\ current}{\frac{Derating\ factor}{100\%}} \tag{5.19}$$

$$PV\ parallel\ connection = \frac{The\ new\ calculated\ current}{PV\ current} \tag{5.20}$$

$$PV\ series\ connection = \frac{DC\ systen\ voltage}{PV\ voltage} \tag{5.21}$$

Consequently, the total number of PV modules required for this study based on the parallel and series connections is calculated in equation (5.22):

$$Total\ PV\ modules = PV\ parallel\ connection\ X\ PV\ series\ connection \tag{5.22}$$

To add, the PV rated capacity for 40% and 50% of coverage of demand is calculated by equation (5.23):

$$PV\ rated\ Capacity = total\ number\ of\ PV\ modules\ X\ PV\ module\ capacity \tag{5.23}$$

Table 5-8. The PV modules requirement calculations

Total DC Demand (kAh/day)	12.05 – 15.07	Nominal DC Voltage (V)	560
Peak sun (hrs/day)	4.56	Rated Module Voltage (V)	36.4
Calculated current (kA)	2.65 – 3.31	Calculated Series Modules	15.39
Derating Factor (%)	80	Series Modules Required	16
New Calculated Current (kA)	3.32 – 4.14	Total Modules	5872 – 7312
PV Current (A)	9.07	PV array Capacity for 40% (kW)	1937.76
Calculated Parallel Modules	366.05 – 456.45	PV array Capacity for 50% (kW)	2412.96
Parallel Modules Required	367 – 457		

Table 5-8 shows all the results of the above calculations for the PV modules requirement. In order to meet the daily AC load demand with these PV capacities, the inverter input values provided by the technical specifications of the inverter shown in Table 5-2 is needed to be met by the PV arrays output. In addition, the inverter output also needs to meet the requirement of the AC daily load. As a consequence, the PV modules will be divided into sub-arrays to meet the inverter input requirements and the inverters will be connected in parallel to increase the power output. The values of PV voltage and current are based on the input requirements of the system in general and the inverter in particular. Each sub-array of the PV modules is calculated via equation (5.24) for parallel connections and in equation (5.25) for series connections:

$$Parallel\ PV\ sub - array\ connections = \frac{I_{DC,inverter\ input}}{I_{PV,module}} \tag{5.24}$$

$$Series\ PV\ sub - array\ connections = \frac{V_{DC,inverter\ input,system\ voltage}}{V_{PV,module}} \tag{5.25}$$

The values chosen for the voltage input for the inverter is equal the DC system voltage which is 560 V and the input current is chosen to be 1000 A to provide the maximum output of the inverter at 550 kVA. Therefore, the results of these as follows:

1- Parallel PV sub-array connections is equal to 110 based on (5.24).
2- Series PV sub-array connections is equal to 15 based on (5.25).
3- Total PV sub-array is 1650 based on (5.22).
4- Total PV sub-array capacity is 554.5 kW based on (5.23).

As the inverter maximum output is 550 kVA, hence the number of parallel inverter needed is calculated by equation (5.26) using Table 5-8:

$$Parallel\ Inverter\ connections = \frac{PV_{array\ capacity\ for\ 40\%\ and\ 50\%\ of\ load}}{P_{\ inverter\ output}} \tag{5.26}$$

As a consequence, Fig. 5-9 shows the parallel connection that the inverters will be connected in and it varies in the number of connected inverters depending on what the percentage of the AC load needed to be covered by PVs as follows:

1- To cover 40% of the daily load by PVs, the parallel inverter connections is equal to 3.55 which means 4 connections at minimum to sufficiently provide 1937.76 kW, but as the total PV sub-array capacity is 554.5 kW, then the total PV arrays will provide 2218 kW.

2- To cover 50% of the daily load by PVs, the parallel inverter connections is equal to 4.42 which means 5 connections at minimum to adequately produce 2412.96 kW, but the PV will output 2772.5 kW due to the total capacity of the PV sub-array.

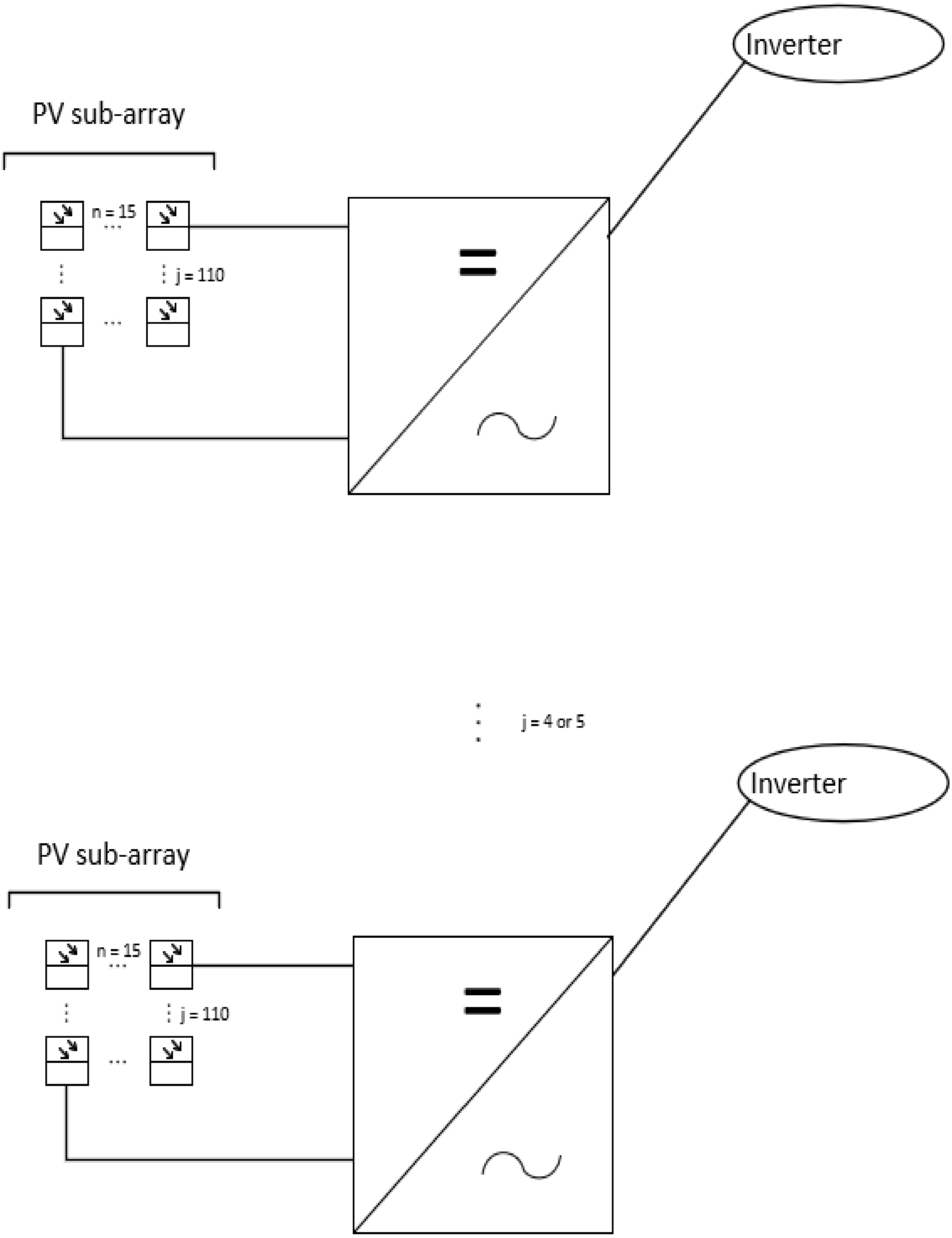


Fig. 5-9. The sub-array PV connections with the parallel inverters

5.6. Components Sizing in HOMER

5.6.1. PV Sizing

This thesis includes the PV module in the second system configuration, in addition to the first system that is the grid system with standby diesel backup generator, to testify the feasibility of having solar energy added to the existing system. The different PV kilowattage sizing has been chosen in HOMER to be 2218 kW (554.5 kW x 4 parallel sub-arrays as discussed in the heuristic calculations) and 2772 kW (554.5 x 5 parallel sub-arrays) in order to find an optimal sizing and sufficient amount of power to supply 40% to 50% of the load demand. These rating are chosen taking into account economic and technical parameters as well as the heuristic calculations done for the PV and inverter. Also, taking into account the effects of air temperature of the location on the PV modules, this requires increasing the size of the PV in order to ensure producing adequate energy to supply the load.

The ground reflectance set to be 20% as default. To add, the tilt angle (degrees West of South) is set to be 41.43 degrees based on the heuristic calculations as well as the azimuth set to be 0 degree by default in HOMER. As the temperature effects are included in the simulations, Fig. 5-10 provides the effects of the ambient temperature on the output of the PV panels.

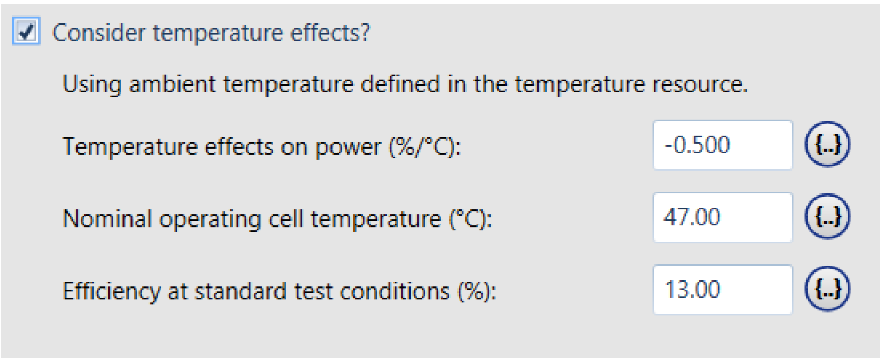


Fig. 5-10. Ambient temperature of the location effects on PV panels

Table 5-9 shows the economic specifications of the PV module for the system. A 330 watt Solar Panel Peimar Poly XL is chosen for this system [76]. The installation and shipping costs assumed to be 10% and 25% of the panel price for 330W which costs $220.00 to calculate the total costs of the panel. Then, PV costs per kW calculated based on the total calculated costs of the 330W panel. To add, the O&M costs assumed to be zero and the replacement assumed to be 20% less than the capital cost of the PV per kW. The Lifetime for the PV modules is chosen to be 20 years.

Table 5-9. Economic specifications of the PV module [76]

330 watt Solar Panel Peimar Poly XL	
Panel price	$220.00
Installation price (10%)	$22.00
Shipping (25%)	$55.00
Total price for 330 W	$297.00
Cost of PV per kW	900.00 $/kW
O&M cost	$0.00
Replacement	720.00 $/kW
Lifetime	20 years

In [70], HOMER Pro calculates the output power of the PV modules including the temperature effects using the expression in equation (5.27):

$$P_{PV} = Y_{PV} f_{PV} \left[\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right]\left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right] \tag{5.27}$$

where:

Y_{PV} is the rated capacity of the PV array under Standard Test Conditions (STC) [kW],

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

$\bar{G}_T$ is the solar radiation incident on the PV array in the current time step [kW/m^2],

$\bar{G}_{T,STC}$ is the incident radiation at STC [1 kW/m^2],

α_P is the temperature coefficient of power [%/˚C],

T_c is the PV cell temperature in the current time step [˚C],

$T_{c,STC}$ is the PV cell temperature under STC [25˚C].

If the ambient temperature of the location is neglected then HOMER will use equation (5.28):

$$P_{PV} = Y_{PV} f_{PV} \left[\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right] \tag{5.28}$$

5.6.2. Inverter Sizing

As the PV module is connected to the DC bus and the demand is connected to the AC bus, an inverter is necessary to be added to the system to convert the power generated by the PV into the AC bus to supply the required load. Therefore, to meet the total of 2000 kW and 2500 kW inverter output, the chosen sizes of the inverter are 4 and 5 units of 500 kW, respectively, based on the heuristic calculations which are in parallel.

A SMA SC500HE grid tied inverter 3-Phase 500 kW is chosen for this system [75]. The installation and shipping costs assumed to be 10% and 25% of the inverter price for 500 kW which costs $134,223.00 to calculate the total costs of the inverter. Then, the cost of the inverter per kW is calculated based on the total calculated cost of the 500 kW inverter. To add, the O&M costs is assumed to be 5% of the cost of inverter per kW and the replacement is assumed to be the same as the initial cost. The inverter comes with a 5 years warranty, therefore the chosen lifetime for the inverter is 5 years [77]. Table 5-10 shows the economic specifications of the selected inverter for the system.

Table 5-10. Economic specifications for the SMA SC500HE inverter [77]

SMA SC500HE grid tied inverter 3-Phase 500kW	
Inverter price	$134,223.00
Installation price (10%)	$13,422.30
Shipping (25%)	$33,555.75
Total price for 792 kW	$181,201.05
Cost of inverter per kW	362.40 $/kW
O&M cost (5%)	$18.12
Replacement	362.40 $/kW
Lifetime	5 years

5.6.3. Diesel Generator

This thesis considers the two diesel generators that are supplying the critical load with total power capacity of 1350 kW as each of them has a rating of 750 kVA. In this study, the power factor for the generators output power is assumed to be at 0.9 as HOMER Pro only deals with kilowattages rating (real power). Hence, converting kVA to kW is a necessary step to be able to simulate in HOMER.

The diesel generator is used in two system configurations that are considered in this study. HOMER Pro provides a range of generic generators with different sizes. However, in the simulation a small generic generator is used and modified to meet the requirements for the research.

Fuel costs play an important role in the total cost of generating electricity from the generator. HOMER determines the fuel costs using a pre-set fuel curve that is in straight line as in Fig. 5-11.

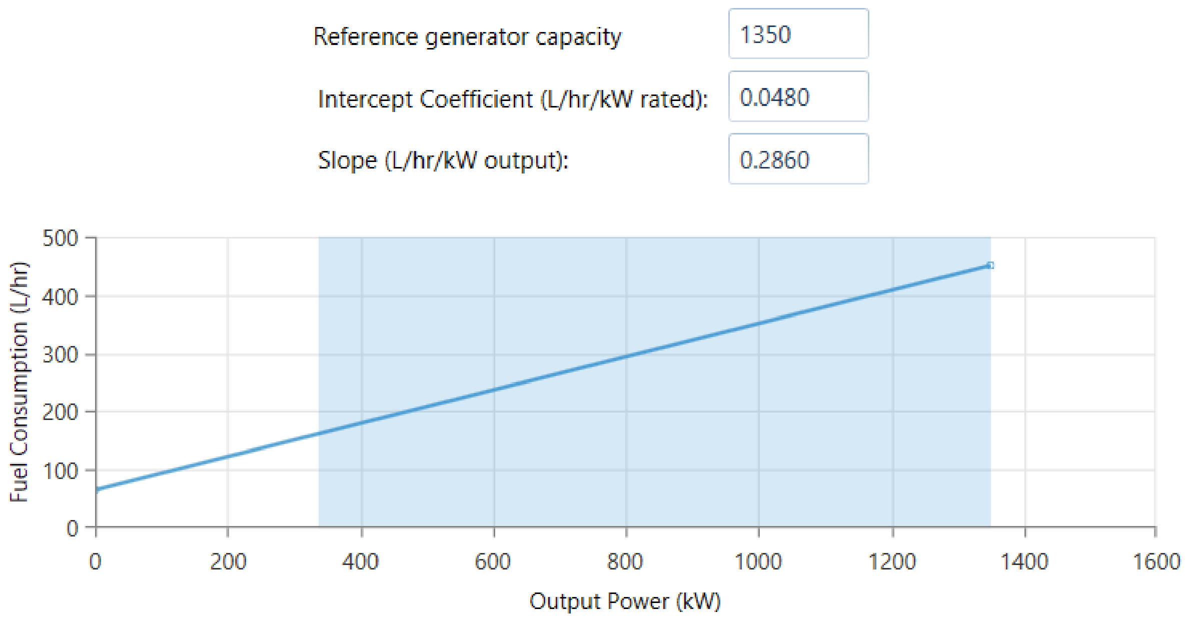


Fig. 5-11 Fuel curve

The capacity chosen for the diesel generator set to be 1350 kW to meet the electricity demand. In Fig. 5-11, the shaded area is where the generator allowed to operate. The minimum power output that the generator can operate at is set to be 25% of the maximum power output that is 337.5 kW. In addition, HOMER calculates the total fuel costs by multiplying the total fuel consumptions rate (L/hr) by the fuel cost per litter ($/L) [70]. The total fuel consumptions are calculated via equation (5.29):

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{5.29}$$

where:

F is fuel consumption rate [L/hr],

F_0 is generator fuel curve intercept coefficient [L/hr/kW_{rated}],

F_1 is generator fuel curve slope [L/hr/kW_{output}],

Y_{gen} is rated capacity of the generator [kW],

P_{gen} is output of the generator in this time step [kW].

HOMER determines the generator's fixed and marginal cost of energy to be used when simulating the system operation [69]. The fixed cost is the cost per hour of operating the generator without producing any energy. The marginal cost is the incremental cost per kilowatt-hour of generating energy from the generator. The fixed cost is calculated by equation (5.30):

$$c_{gen,fixed} = c_{om,gen} + \frac{C_{rep,gen}}{R_{gen}} + F_0 Y_{gen} c_{fuel,eff} \tag{5.30}$$

where:

$c_{om,gen}$ is the O&M cost [$/hr],

$C_{rep,gen}$ is the generator replacement cost [$],

R_{gen} is the generator lifetime [hours],

F_0 is the fuel curve intercept coefficient [L/hr/kW_{rated}],

Y_{gen} is the capacity of the generator [kW],

$c_{fuel,eff}$ is the effective price of fuel [$/L], and it includes the cost penalties associated with the emissions of pollutants.

Equation (5.31) shows how the marginal cost of energy for the generator is calculated as follows:

$$c_{gen,mar} = F_1 c_{fue,eff} \tag{5.31}$$

where:

F_1 is the fuel curve slope [L/hr/kW_{output}].

Technical and economic specifications for the generator are shown in Table 5-11. In the table, the lifetime of the diesel generator is specified in hours of operation as the generator lifetime is largely dependent on its operation hours [70]. The capital and replacement costs of the diesel generator are obtained from [78]. The costs associated with installation and labour in Saudi Arabia are included in the capital and replacement costs [37, 79].

Table 5-11. Technical and economic specifications for Diesel Backup Generator

Diesel Backup Generator (DBG)	
Capital cost ($/kW)	1521
Replacement cost ($/kW)	1521
Operation and Maintenance cost ($/h)	0.05
Lifetime (h)	15000
Minimum load supply (%)	25

5.7. Grid

In HOMER Pro, there are four different considerations for the grid to select from when grid is included in the simulation. These are called simple rates, real time rates, scheduled rates and grid extension. The last three grid options are provided under an added-on module called Advanced Grid Module which needs to be purchased. To use the simple rates, all what needed is the price of purchasing energy from grid and the sellback rate. However, in real time rates and scheduled rates, there are more options to include to make the simulations more realistic, for instance, different pricing periods can be defined in these choices as well as reliability of the grid. Whereas, in the simple rates, these options are not included. In the grid extension option, capital cost for the grid extension ($/km), operations and maintenance ($/year/km) as well as purchase rates from the grid ($/kWh) are required.

This study is considering the reliability of the grid by including grid outages that occur frequently in the past years as shown in Chapter 4 as well as including different purchase and sell rates depending on different hours during a certain day of the year. This is to increase the ability of imitating the existing system with different simulations that can affect the feasibility of adding solar energy to the system. Therefore, from the grid choices provided by HOMER Pro, the scheduled rates option was chosen as it fulfils all the necessary aspects that needed to be included in the simulations. The applied rates for the grid price are based on the consumption rates previously discussed in Chapter 4. Also, an estimation is made for the peak, off-peak and shoulder periods. Table 5-12 summarises the prices included for the grid in the simulations. These considered prices are three different sellback rates to the grid as follows:

1- Selling energy back to the grid by half of buying from the grid.
2- Selling energy to the grid with the same price of purchasing from the grid.
3- Selling electricity with 5% more than the purchase rates from the grid.

Table 5-12. The prices of purchasing from and selling to the grid

Sellback rates	Purchase price ($)		Sellback price ($)	
First sellback rate	Off-peak	0.085	Off-peak	0.043
	Shoulder	0.095	Shoulder	0.048
	Peak	0.100	Peak	0.050
Second sellback rate	Off-peak	0.085	Off-peak	0.085
	Shoulder	0.095	Shoulder	0.095
	Peak	0.100	Peak	0.100
Third sellback rate	Off-peak	0.085	Off-peak	0.089
	Shoulder	0.095	Shoulder	0.100
	Peak	0.100	Peak	0.105

These rates are scheduled at different times of the day and the year. For example, for the summer periods (May-Oct), the peak is assumed to be from 12-6 pm, the shoulder period to be from 10-11 am and 7-8 pm and the rest of the day hours are off-peak. Whereas, in winter (Jan-Apr and Nov-Dec), the peak considered to be from 7 pm until 12 am, the shoulder hours from 5-6 pm and 1-2 am and the rest of the hours are off-peak as shown in Fig. 5-12.

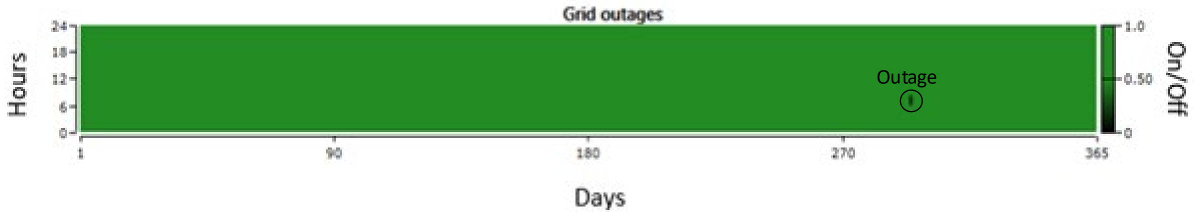
	Price $/kWh	Sellback $/kWh
Off-peak	0.0850	0.0430
Peak	0.1000	0.0500
Shoulder	0.0950	0.0480

Fig. 5-12. Grid rate schedule

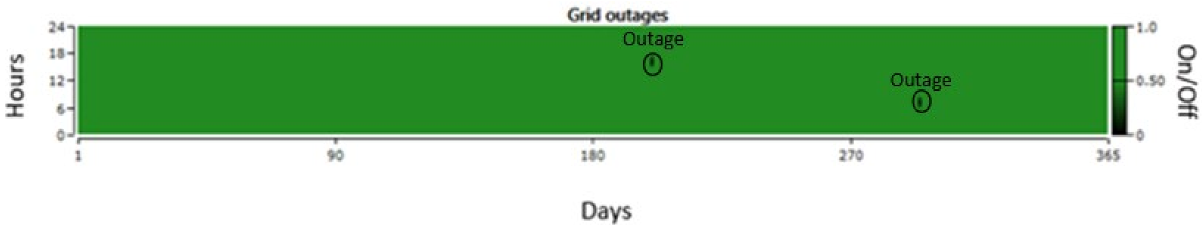
As there were some grid power outages occurred during the last few years, three different grid power outage scenarios are included to evaluate the feasibility of having PV system added to the existing system (Grid-Diesel backup generator). Hence, the three considered power outages scenarios for the systems are:

1- Once a year for 2 hours.
2- Twice a year for 2 hours.
3- Thrice a year for 2 hours.

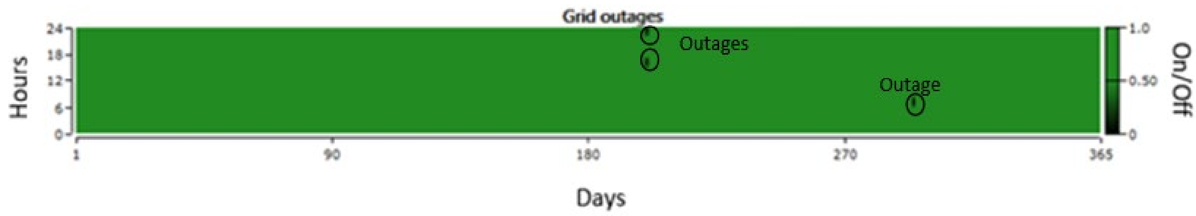
These outage scenarios are based on the previous average power outages that occurred in Dammam and also to anticipate if the outage lasts longer or happen more frequently. Fig. 5-13 shows where each power outage occurs during the year in the simulation for each scenario. Fig. 5-13a represents outage of once per year, Fig. 5-13b for two outages per year and Fig. 5-13c for three outages per year. It is important to note that these outages are still probabilistic in nature. Furthermore, the chosen outages for this research are based on the historical power outages in terms of how frequently they are occurring per year, but randomly generated by HOMER in terms of when they are happening during the year.



a)



b)



c)

Fig. 5-13. a) Power outage once a year, b) power outage twice a year and c) power outage thrice a year

For the existing system (grid and diesel backup generator), the three scenarios of the grid power outages will be analysed. When the PV is added to the existing system, there will be three added sensitive analysis which are reliant on the three sellback rates to the grid as in Table 5-12. These rates included in the analysis of the grid-connected PV system due to the expectancy of producing excess energy from the PVs from which the grid can buy energy.

5.8. Summary

To sum up, HOMER Pro software is detailed and the way that this software decides whether or not a particular system is an optimum solution is discussed. Also, the controller strategies in HOMER are discussed, and from all the provided controllers, ML and CC dispatches strategies are chosen to be used. Moreover, the economic and constraints aspects are detailed.

The location of the load profile is one of the hospital buildings in Dammam, Saudi Arabia. This load profile is 15,826 kWh/day with a peak load of 1350 kW. This load will be supplied by two system configurations which will be the existing system (grid with diesel backup generator) and the proposed grid-connected PV system with diesel backup generator.

Heuristic design calculations are completed after choosing a PV module and an inverter model to be used for the proposed grid-connected PV system. Hence, these calculations result in having new outputs for the PV with 2218 kW to 2772.5 kW to cover 40% to 50% of the load, respectively, and 2000 kW and 2500 kW for the inverter. Therefore, these outputs of both PVs and inverters are used in HOMER for sizing the PV and inverter. For the diesel sizing, it is equivalent to the same size of the existing diesel generators.

Three scenarios which are dependent on the grid power outage are detailed for all the system configurations based on the information provided in Chapter 4. Nevertheless, for the grid-connected PV system only, there are three added sensitive analysis which are dependent on the sellback rate to the grid when the PV produces higher energy than the load.

6. Discussion and Analysis of System configurations

6.1. Overview

Based on the provided load profile in Chapter 5, with the use of solar resource data, diesel generator data, the heuristic calculations for both PV module sizing and inverter sizing, as well as grid data, different system configurations are designed using HOMER Pro. In this chapter, two system configurations designed are going to be analysed and discussed. The first system is designed to be the same as the existing system (grid with diesel backup generator) for the location in order to better understand the possible benefits that the PVs will provide when included to the existing system. The second system is grid-connected PV system with diesel backup generator. Both systems will be examined by three scenarios of grid power outages (three sensitive analysis), but the system with the inclusion of PVs will include another three sensitive analysis which are considering three different sellback rates from the excess energy provided by PVs to the grid. Then, there will be a comparison between the optimum systems from both system configurations that are chosen by HOMER Pro in terms of economics, more specifically in three main aspects which are the total NPC, LCOE and the annual operating costs. Next, the same optimum systems will be compared in terms of their resultant emissions of pollutants, specifically CO_2, SO_2 and NO_x. Finally, a summary of all findings from all the analysis and discussion will be written.

6.2. Grid with Diesel backup generator

Grid with diesel backup generator system is modelled as shown in Fig. 6-1. The diesel generator capacity is chosen to be 1350 kW which equals to the output of the combination of the real existing diesel generators as mentioned previously.

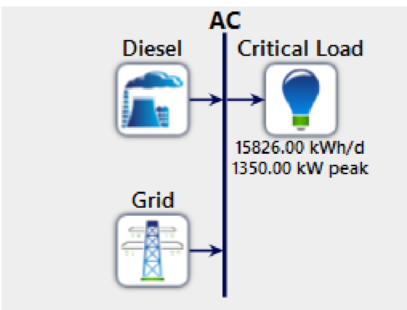


Fig. 6-1. Schematic system for Grid and Diesel backup generator

Two methods of dispatching in HOMER is considered when the simulations and optimisation are calculated which are Charge Cycling strategy (CC) and MATLAB Link strategy (ML). The strategy of the ML for this system for all the three scenarios is to supply the load by the grid capacity whenever it is available. Nonetheless, whenever a power outage occurs from the grid (grid is down), it runs the diesel generators to support the load. While running the diesel, the MATLAB code checks if the load required at this moment is higher or lower than the minimum operating power of the diesel. Hence, if the load is lower than the operating power of the diesel, the diesel runs at its minimum operating power which is in all simulations chosen to be 25% of the diesel maximum power available (337.5 kW). Whereas, if the load is higher than the minimum operating, it runs the diesel at the same load requested. A flowchart of the MATLAB code is shown in Fig. 6-2. This modelled system is simulated considering the three scenarios of the grid power outages which are once, twice and thrice a year and the optimum results chosen by HOMER are shown in Fig. 6-3.

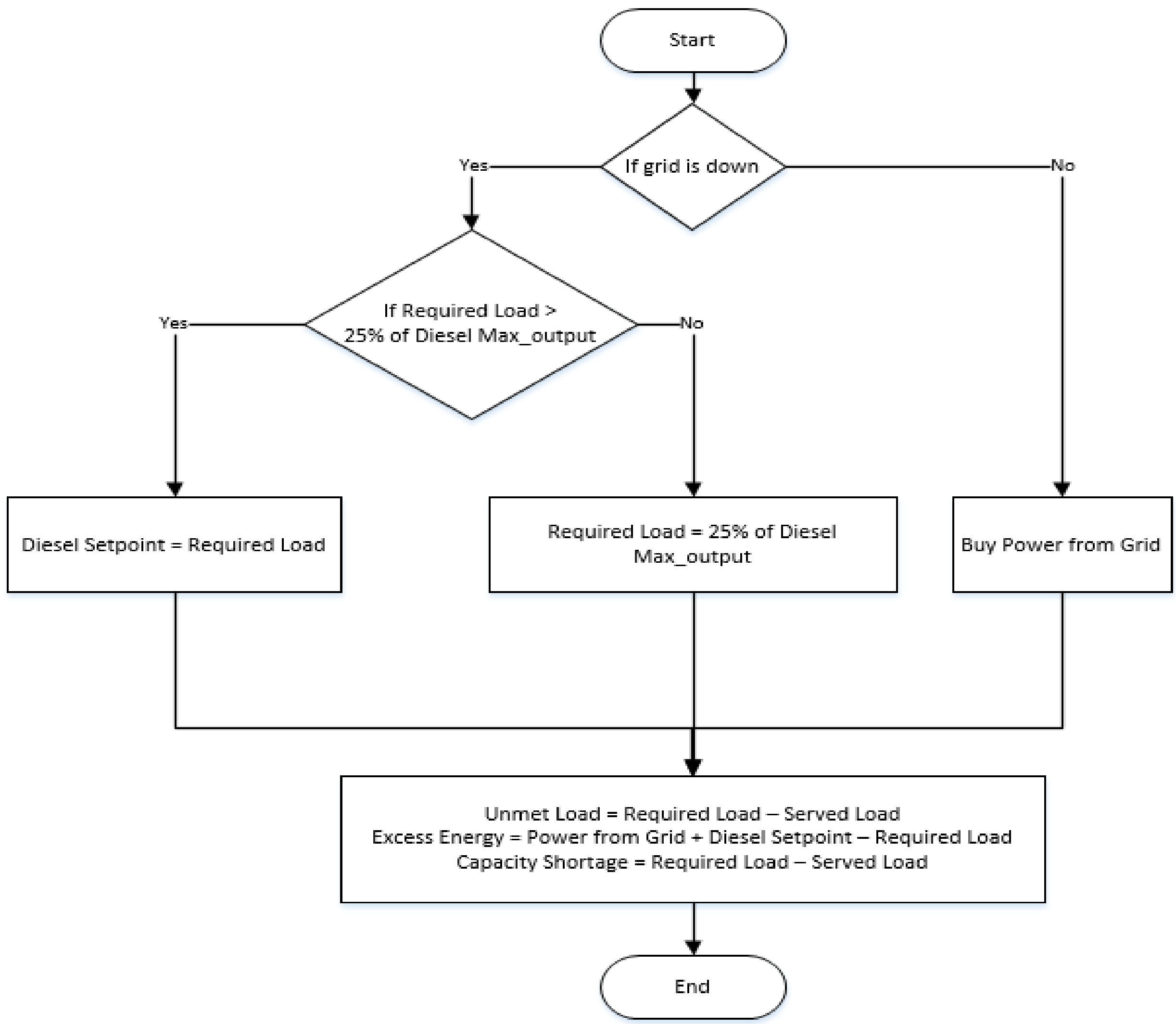


Fig. 6-2. Flowchart of the MATLAB Code for the system

Sensitivity			Architecture						Cost			
Grid Failure Frequency (1/yr)	Grid Variation Repair Time (h)	Grid Mean Repair Time (h)	⚠			Diesel (kW)	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)
1.00	5.00	2.00				1,350	999,999	CC	$0.0988	$11.1M	$465,391	$2.05M
2.00	5.00	2.00				1,350	999,999	CC	$0.0988	$11.1M	$465,616	$2.05M
3.00	5.00	2.00				1,350	999,999	CC	$0.0989	$11.1M	$465,909	$2.05M

Fig. 6-3. Optimum results of the three scenarios of different grid power outages

For all the three scenarios, the systems will be discussed regarding the economic values, the diesel operations when the power outage from the grid occurs and which system of the three scenario systems results in the optimum system.

6.2.1. Results of scenario one for the system

The results of CC dispatch are chosen to be the optimum system solution by HOMER and its results shown in Fig. 6-4. The results provide an annual operating cost of $465,391, total NPC of $11.1M and LCOE of 0.0988 $/kWh.

Architecture						Cost				System
⚠			Diesel (kW)	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
			1,350	999,999	CC	$0.0988	$11.1M	$465,391	$2.05M	0

Fig. 6-4. Scenario one with CC dispatch result

HOMER decides to choose the CC dispatch strategy to be the one that provides the optimum results, and the ML dispatch also delivers the exact same outcomes as the CC. Fig. 6-5 displays the ML results in comparison with the CC results.

Architecture						Cost				System
⚠			Diesel (kW)	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
			1,350	999,999	CC	$0.0988	$11.1M	$465,391	$2.05M	0
⚠			1,350	999,999	ML	$0.0988	$11.1M	$465,391	$2.05M	0

Fig. 6-5. Scenario one with ML dispatch result

The costs of this system are shown in Fig. 6-6, and the only capital cost of this system is the capital cost of diesel generator that is $2,053,350.00. Fig. 6-6 shows the detailed total NPC, LCOE and annual operating cost which are $11,138,140.00, 0.09878 $/kWh and 465,390.80 $/year, respectively. Moreover, this figure clearly indicates that the total O&M costs of the system in this scenario is $10,330,995.95. To add, the O&M costs of the grid ($10,256,626.06) and the other O&M costs ($71,734.58) which are associated with the costs of the emissions from both the grid and diesel generator play the significant role in increasing the cost of the system in general. Whereas, the salvage cost of the diesel generator (-$1,247,051.93) reduced the overall NPC. The salvage calculation includes the replacement cost of the component multiplied by the ratio of the remaining life of the component and the lifetime of the component during the project life.

Total NPC:	$11,138,140.00
Levelized COE:	$0.09878
Operating Cost:	$465,390.80

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$2,635.31	$849.71	-$1,247,051.93	$809,783.09
Grid	$0.00	$0.00	$10,256,626.06	$0.00	$0.00	$10,256,626.06
Other	$0.00	$0.00	$71,734.58	$0.00	$0.00	$71,734.58
System	$2,053,350.00	$0.00	$10,330,995.95	$849.71	-$1,247,051.93	$11,138,143.73

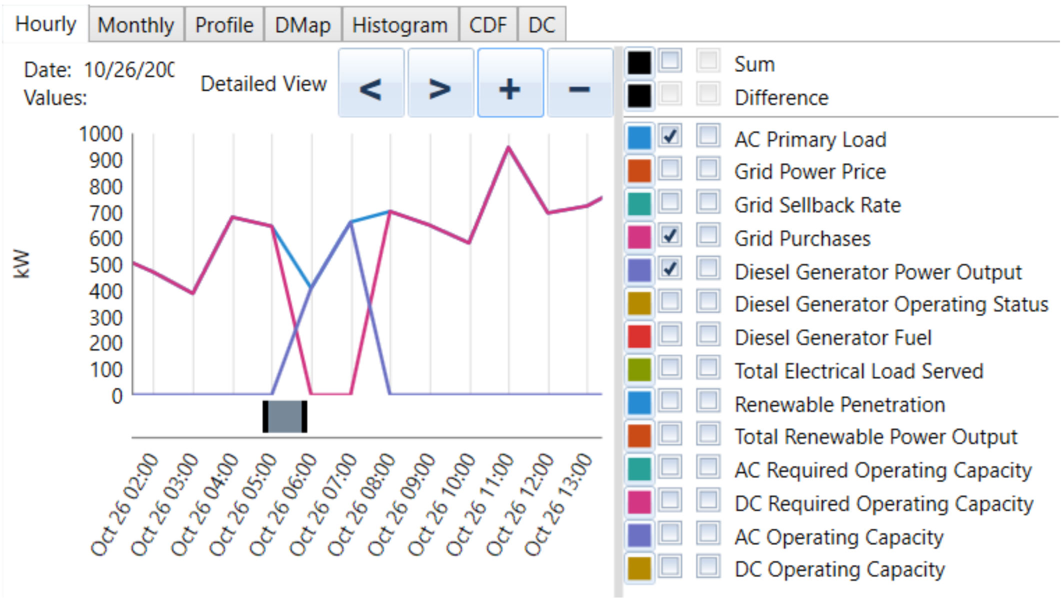
Fig. 6-6. The costs of each component of the system in scenario one and the detailed values of total NPC, LCOE and operating cost

Fig. 6-7 shows that the diesel generator runs for 2 hours when the grid power outage occurs. The total energy of the diesel generator is 1,069 kWh/year, the fuel consumption is 435 L/year, the O&M cost of the diesel is 135 $/year and the fuel cost is 43.5 $/year.

	Diesel				
	Hours	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)
CC	2.00	1,069	435	135	43.5
ML	2.00	1,069	435	135	43.5

Fig. 6-7. Diesel generator output and its costs

As the diesel generator runs only when the grid is down, Fig. 6-8a shows when the diesel is operated and what the power outputs of the diesel are. Because the generator runs for only two hours, at the first hour it runs at 407.87 kW at 6 am and the second hour at 660.96 kW at 7 am as shown in Fig. 6-8b and Fig. 6-8c.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Values:
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Difference
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
AC Required Operating Capacity
DC Required Operating Capacity
AC Operating Capacity
DC Operating Capacity
kW
1000
900
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500
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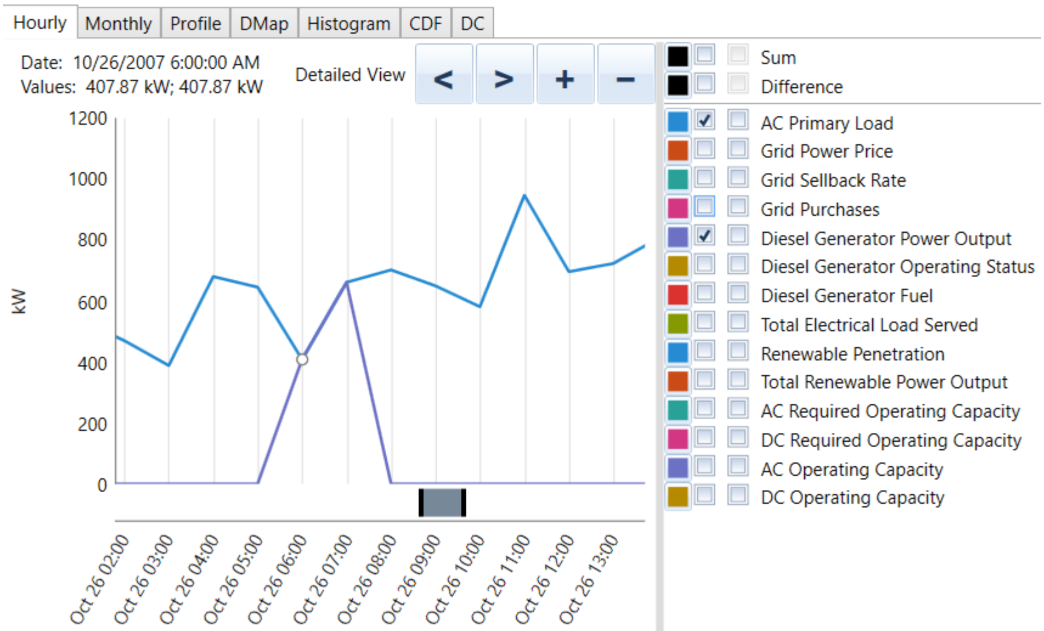
a)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AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
AC Required Operating Capacity
DC Required Operating Capacity
AC Operating Capacity
DC Operating Capacity
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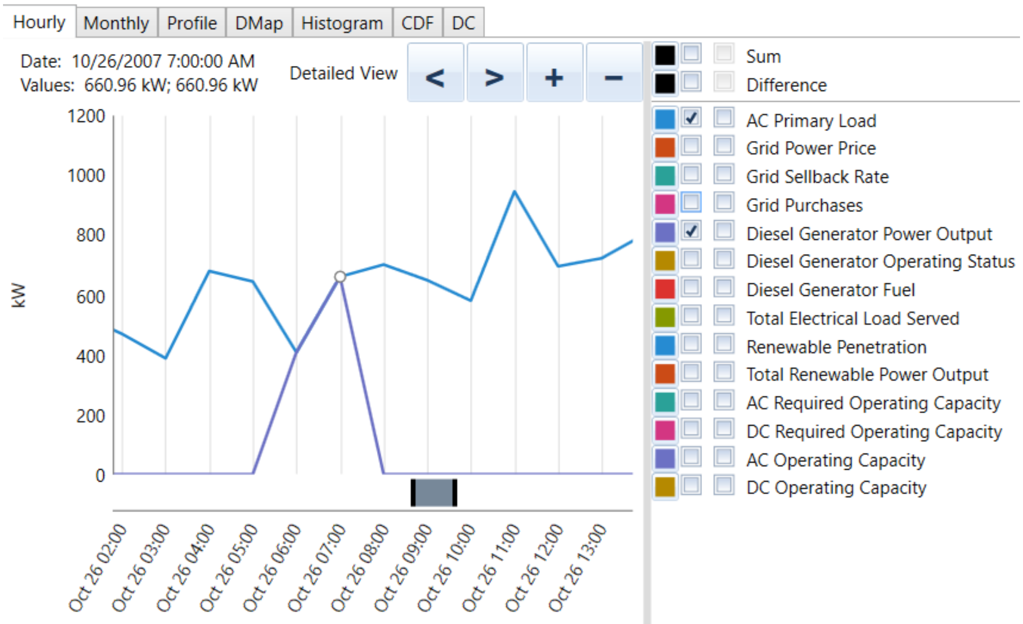
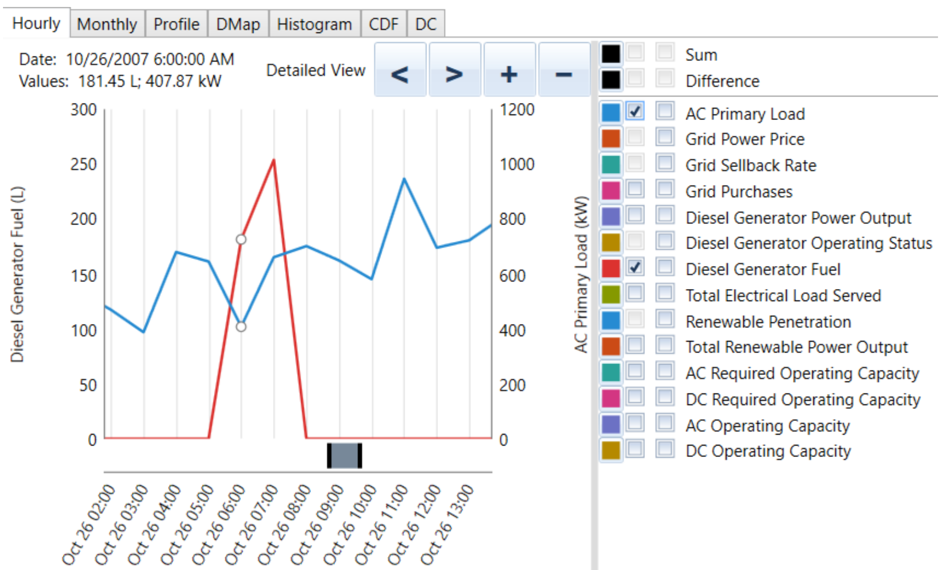
b)



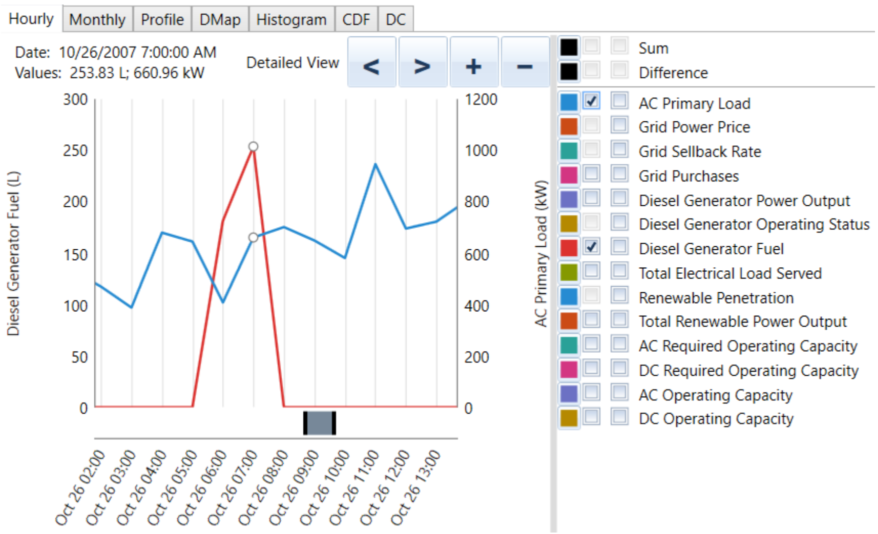
c)

Fig. 6-8. a) Diesel generator running period, b) the minimum power output of the diesel and c) the maximum power output of the diesel

Fig. 6-9a and Fig. 6-9b show how many litres of the fuel is consumed during the operation of the diesel generator in this scenario. In Fig. 6-9a, the minimum fuel consumption is 181.45 L when the diesel operates at 407.87 kW and in Fig. 6-9b, the maximum is 253.83 L when the output of the diesel is at 660.96 kW.



a)



b)

Fig. 6-9. Fuel consumption during the diesel generator operation with a) the minimum value of fuel consumption and b) the maximum of fuel consumption.

6.2.2. Results of scenario two for the system

Although the HOMER optimization chooses the CC strategy to be the one that gives the optimum solution for the system, both ML and CC strategies produces the exact results as shown in Fig. 6-10. In addition to this, even if the COE and total NPC seem to have the same values, Fig. 6-11 indicates the slight difference between this scenario and the first.

Architecture						Cost				System
			Diesel (kW)	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
			1,350	999,999	CC	$0.0988	$11.1M	$465,616	$2.05M	0
			1,350	999,999	ML	$0.0988	$11.1M	$465,616	$2.05M	0

Fig. 6-10. Scenario two with CC and ML dispatch results

In Fig. 6-11, the total NPC in scenario two is increased as in scenario one was $11,138,140.00, while in scenario two is $11,142,540.00. This is due to the increase of the operating costs which becomes $465,616.20, whereas in scenario one it was $465,390.80. Hence, the LCOE is also increased and becomes 0.09882 $/kWh, but in scenario one it was 0.09878 $/kWh. In the same figure, it is clearly seen that due to the increase of the diesel operating hours as the power outage occurs 4 hours in this scenario, the diesel generator's O&M costs and the fuel costs are increased too with the values of $5,270.61 and $2,172.29 in the same order, and the other O&M costs are raised with $71,745.73. In spite of the fact that the O&M costs of the diesel generator and the other O&M costs are elevated, the O&M of the grid reduced ($10,252,886.23) which results in having total O&M costs of $10,329,902.57 that is lower than the total O&M costs of the scenario one ($10,330,995.95). As the diesel generator runs for more hours in this scenario, so the salvage cost of the diesel generator is decreased, and it is lowered to -$1,242,881.18, where in scenario one it is -$1,247,051.93.

Total NPC:	$11,142,540.00
Levelized COE:	$0.09882
Operating Cost:	$465,616.20

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$5,270.61	$2,172.29	-$1,242,881.18	$817,911.71
Grid	$0.00	$0.00	$10,252,886.23	$0.00	$0.00	$10,252,886.23
Other	$0.00	$0.00	$71,745.73	$0.00	$0.00	$71,745.73
System	$2,053,350.00	$0.00	$10,329,902.57	$2,172.29	-$1,242,881.18	$11,142,543.68

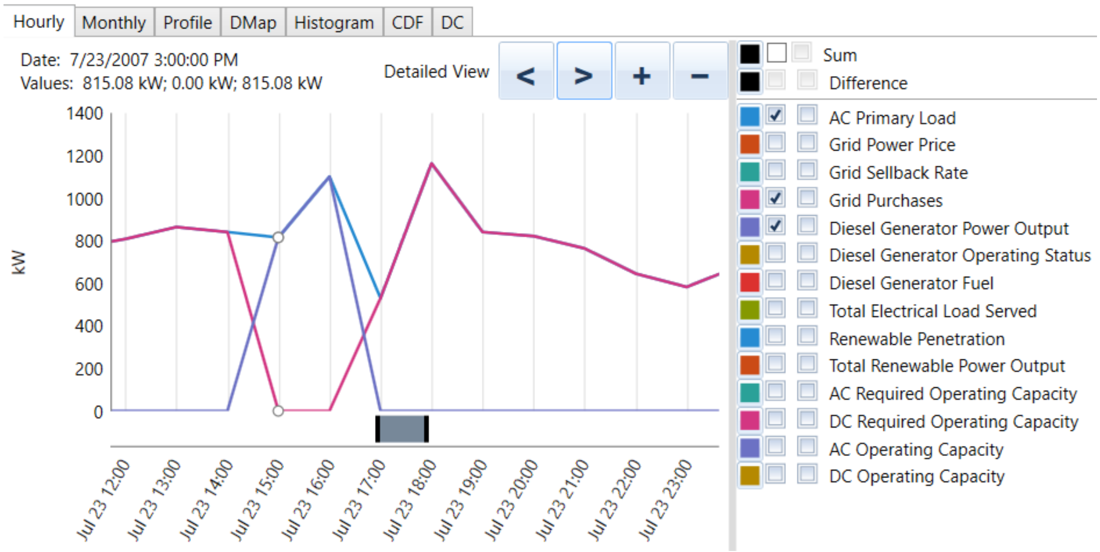
Fig. 6-11. The costs of each component of the system in scenario two and the exact values of total NPC, LCOE and operating cost

The diesel generator produces 2,985 kWh/year that associates with fuel consumption of 1,113 L/year. The O&M costs from the diesel generator is 270 $/year and the fuel cost of this generator production is 111 $/year. Fig. 6-12 summarises the diesel generator output and displays that the generator runs for 4 hours in this scenario as the power outage happens for that period of time.

	Diesel				
	Hours	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)
CC	4.00	2,985	1,113	270	111
ML	4.00	2,985	1,113	270	111

Fig. 6-12. Diesel generator output and its costs

Fig. 6-13 indicates where the first operation of the diesel generator in this scenario and the second time of operation as in this scenario it operates twice for 2 hours because of the duration of the outage is 4 hours in total annually. Fig. 6-13a and Fig. 6-13b show the values of the power outputs of the generator in the first operation period which are 815 kW at 3 pm and 1100.74 kW at 4 pm. The values of the second operation are 407.78 kW and 660.96 kW as displayed in Fig. 6-13c and Fig. 6-13d, respectively.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CDF
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Detailed View
Sum
Difference
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
AC Required Operating Capacity
DC Required Operating Capacity
AC Operating Capacity
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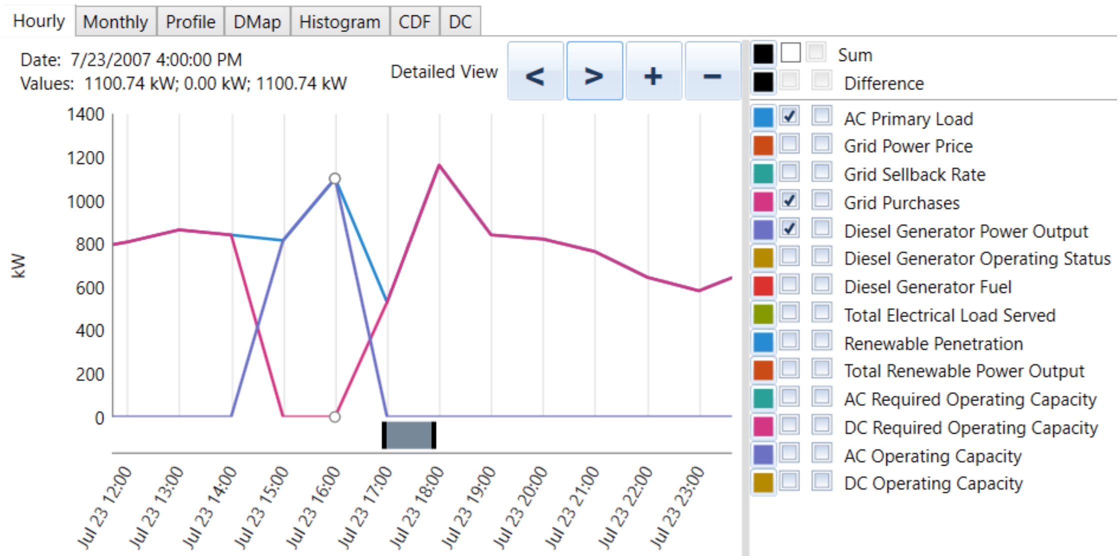
a)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CDF
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Sum
Difference
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
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DC Required Operating Capacity
AC Operating Capacity
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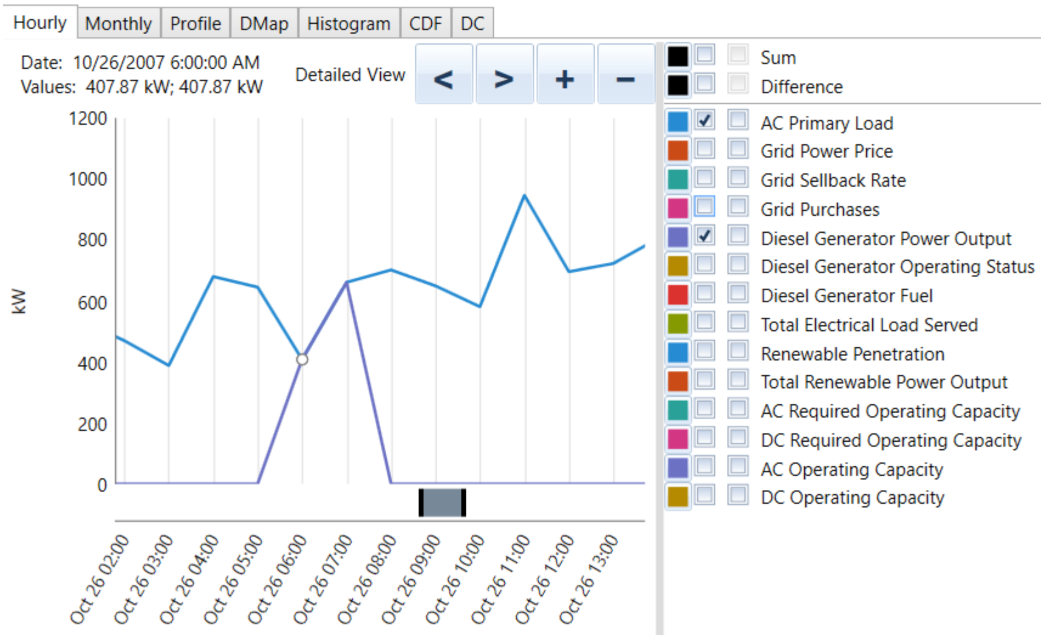
b)



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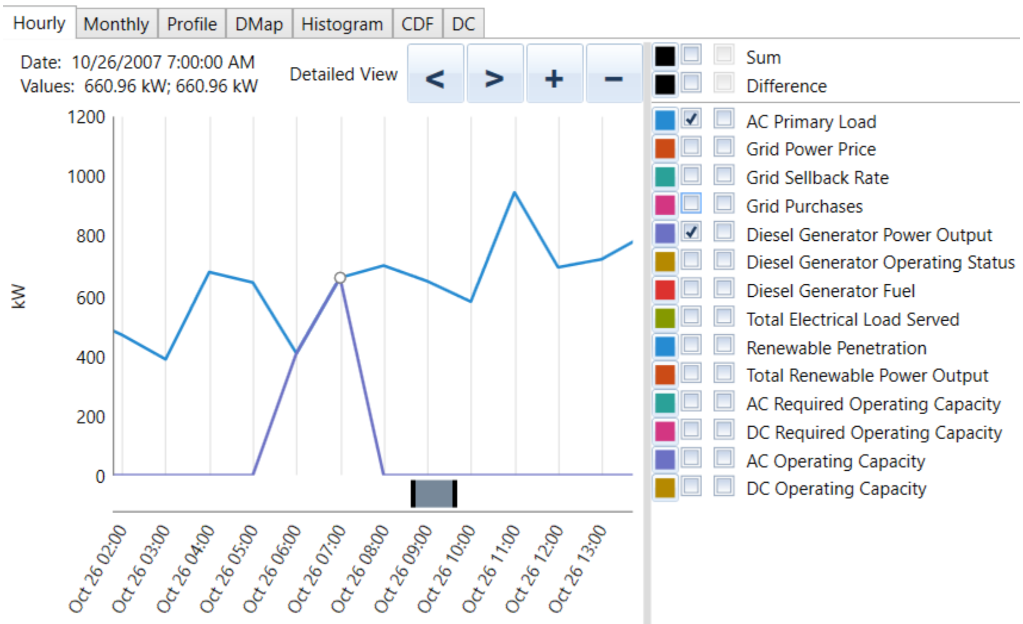
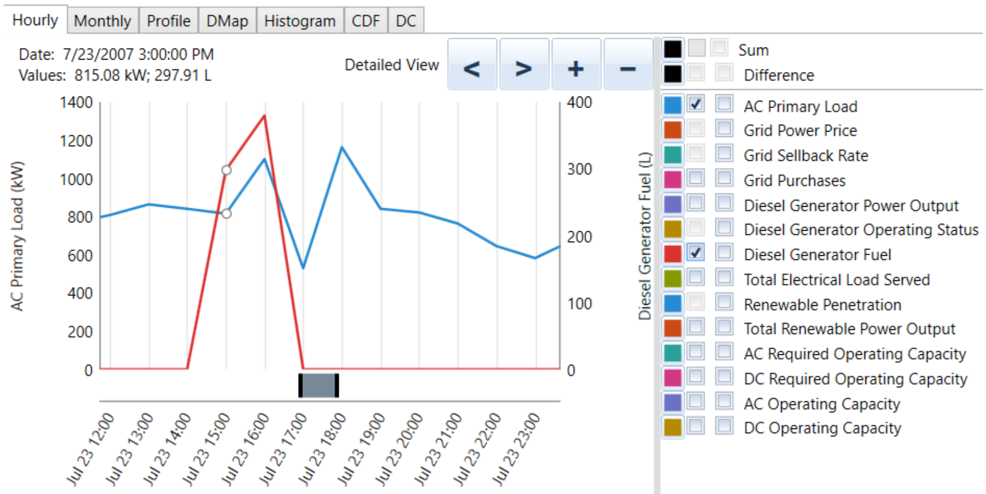


d)

Fig. 6-13. a) The minimum value of first operation of Diesel generator, b) the maximum power output of the diesel at the same operation period, c) the minimum power output of the diesel in the second operation period and d) the maximum power output of the same operation period.

The fuel consumption of the diesel generator in this scenario is higher than the first scenario as more hours required from the generator to run in case of the power outage occurrence. Fig. 6-14a and Fig. 6-14b provide the values of the fuel consumption in the first operation period which are 297.91L and 379.61L. The values of the fuel consumption of the second operation period are 181.45 L and 253.83 L as in scenario one and shown in Fig. 6-14c and Fig. 6-14d, respectively.



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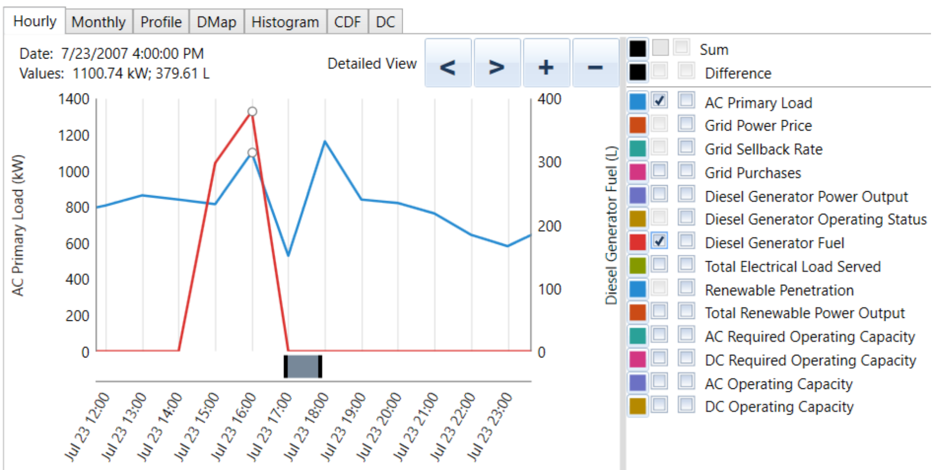

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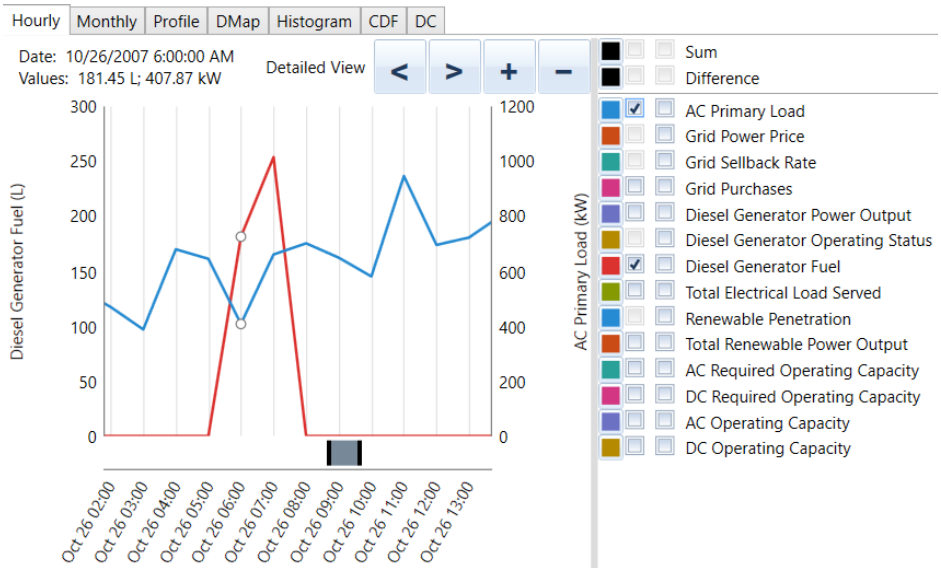

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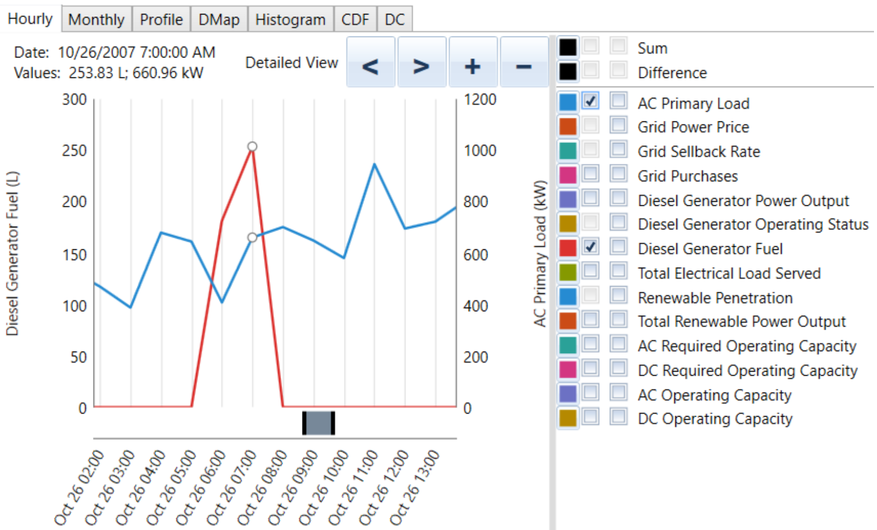


d)

Fig. 6-14. Fuel consumption during the diesel generator operation with a) the minimum value of fuel consumption in the first operation period and b) the maximum of fuel consumption in the same period, c) the minimum value of fuel consumption in the second operation period and d) the maximum value of fuel consumption in the same period.

6.2.3. Results of scenario three for the system

Both strategies (CC and ML) provide the same results, but HOMER prefer to choose the CC strategy to be the one to represent the optimum solution for the system. Fig. 6-15 indicates a slight increase in the COE, even if the total NPC seems to be the same, Fig. 6-16 illustrates the more detailed costs.

Architecture						Cost				System
			Diesel (kW)	Grid (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
			1,350	999,999	CC	$0.0989	$11.1M	$465,909	$2.05M	0
⚠			1,350	999,999	ML	$0.0989	$11.1M	$465,909	$2.05M	0

Fig. 6-15. Scenario two with CC and ML dispatch results

Fig. 6-16 displays the detailed costs of the total NPC, LCOE, operating cost as well as the costs of each component of the system. It can clearly be seen that the total NPC, LCOE, operating cost, diesel O&M costs and other O&M costs are increased in scenario three from their values in scenario one. For the first scenario, the total NPC, LCOE and operating cost are $11,138,140.00, 0.09878 $/kWh, $465,390.00, respectively, whereas in the third scenario becomes $11,148,260.00, 0.09887 $/kWh and $465,909.00 in order as shown in Fig. 6-16.

Notwithstanding, the total O&M and the grid O&M costs and the total salvage are reduced in scenario three compared with scenario one. In scenario one, the total O&M is $10,330,995.95, while in scenario three is $10,330,510.59. The grid O&M is $10,256,626.06 in scenario one, whilst in scenario three becomes $10,250,849.40. The total salvage in first scenario is -$1,247,051.93, but in the third scenario is -$1,238,710.44.

Total NPC:	$11,148,260.00
Levelized COE:	$0.09887
Operating Cost:	$465,909.10

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$7,905.92	$3,110.61	-$1,238,710.44	$825,656.09
Grid	$0.00	$0.00	$10,250,849.40	$0.00	$0.00	$10,250,849.40
Other	$0.00	$0.00	$71,755.27	$0.00	$0.00	$71,755.27
System	$2,053,350.00	$0.00	$10,330,510.59	$3,110.61	-$1,238,710.44	$11,148,260.76

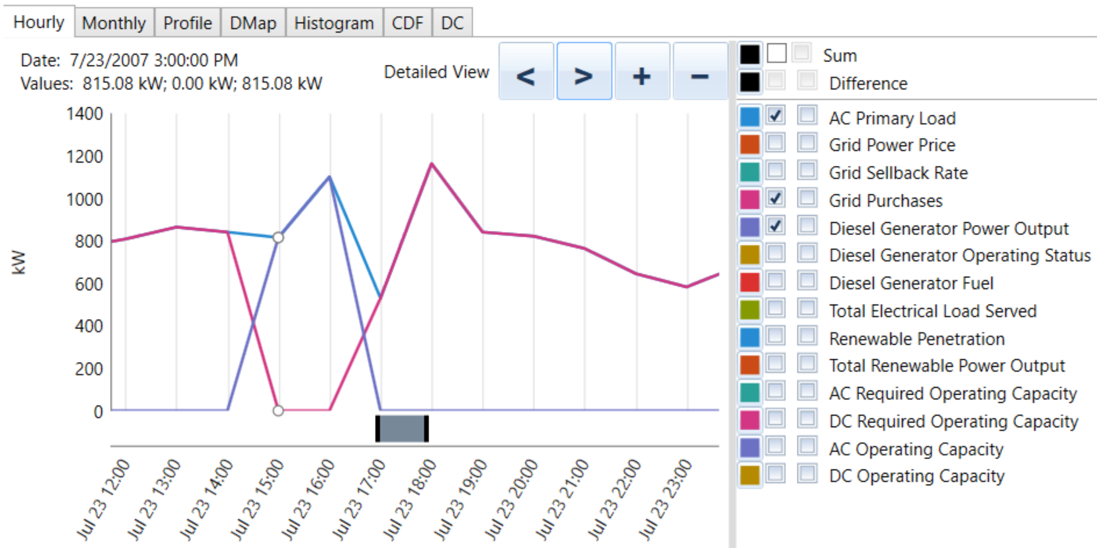
Fig. 6-16. The costs of each component of the system in scenario two and the exact values of total NPC, LCOE and operating cost

Fig. 6-17 provides a summary of the annual diesel generator output and its costs. As in this scenario the diesel runs for 6 hours per year, the total production of the diesel generator is 4,212 kWh/year with total fuel consumption of 1594 L/year as shown in the same figure. The diesel O&M cost and the fuel cost are 405 and 159 $/year as in Fig. 6-17.

	Diesel				
	Hours	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)
CC	6.00	4,212	1,593	405	159
ML	6.00	4,212	1,593	405	159

Fig. 6-17. Diesel generator output and its costs

Fig. 6-18 summarises all the operation periods of the diesel generator in this scenario. The only difference in this scenario from scenario one and two is that the diesel runs twice during July. As well, the extra 2 hours of the diesel operation in this scenario happen in the same day of the first operation period at 10 pm and 11 pm, with the values of 645.22 kW at 10 pm and 582.33 kW at 11 pm before it return to shut down at 12 pm as depicted in Fig. 6-18c and Fig. 6-18d in the same order.



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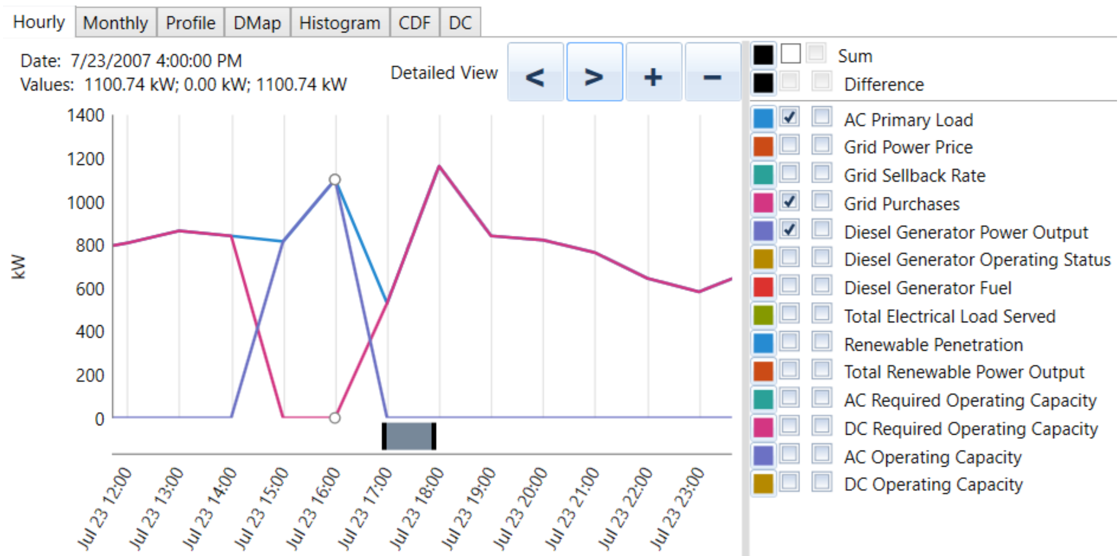

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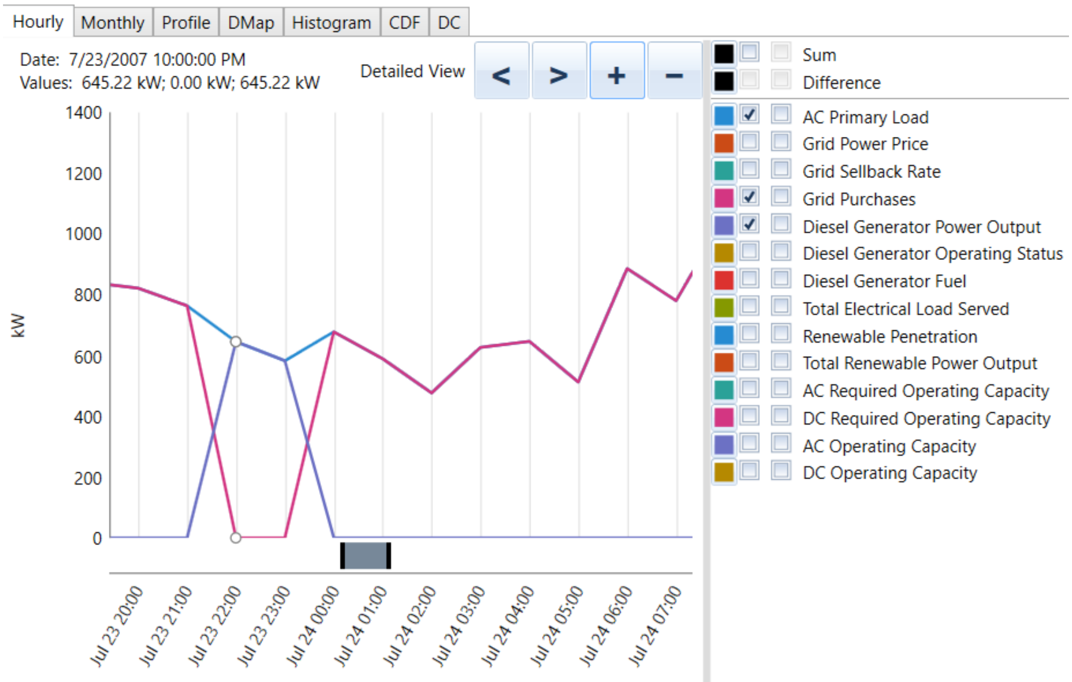

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Sum
Difference
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
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DC Required Operating Capacity
AC Operating Capacity
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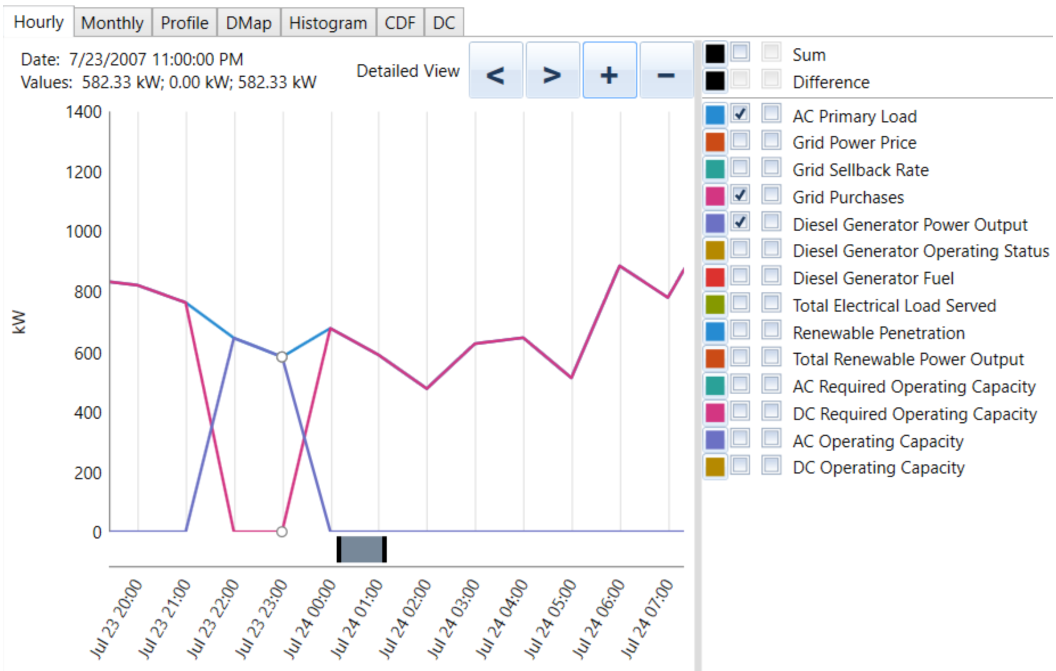

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Difference
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
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DC Required Operating Capacity
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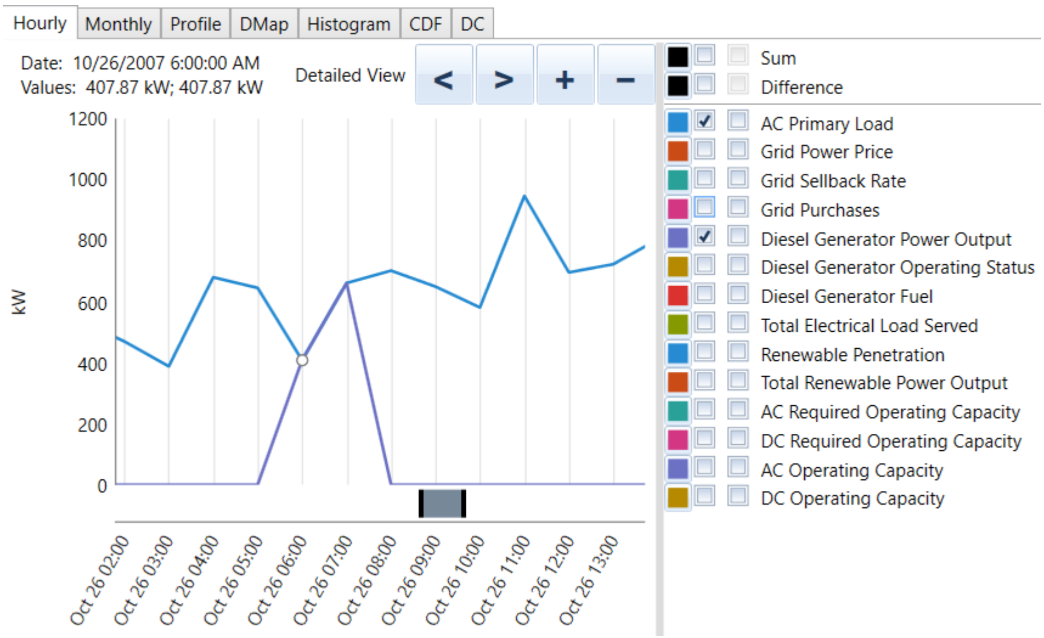

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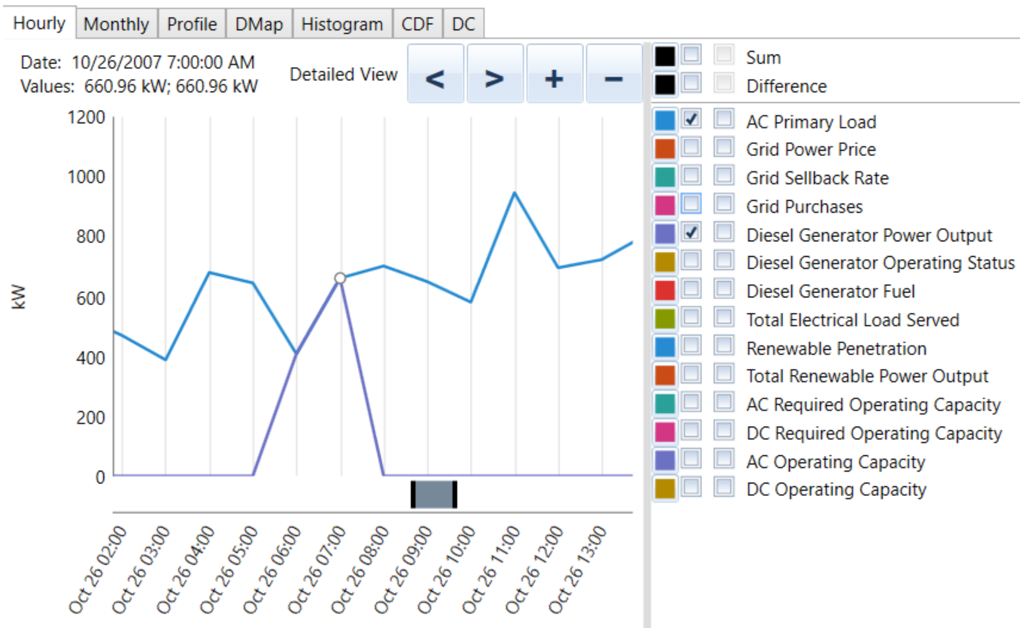
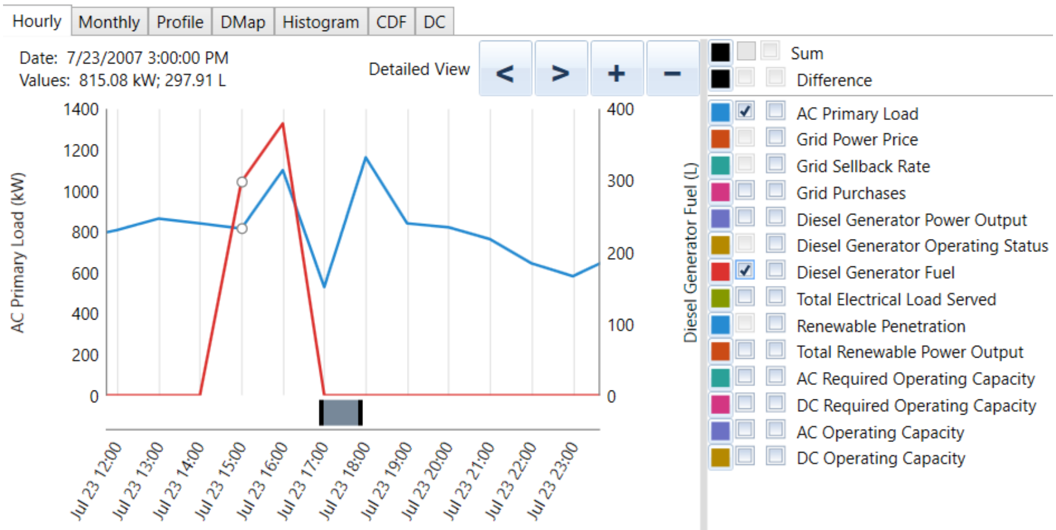


f)

Fig. 6-18. a) The minimum power output of the first operation period of the diesel generator, b) the maximum power output in the same period, c) the maximum value of second operation of Diesel generator, d) the minimum power output of the diesel at the same operation period, e) the minimum power output of the diesel in the third operation period and f) the maximum power output of the same operation period.

Also, the only difference in the fuel consumption happens when the generator operates the extra 2 hours in 23rd of July from 10 pm until 12 pm. Fig. 6-19 summarises all the periods of the fuel consumptions in this scenario. The maximum value of the fuel consumption in the second operation period of the diesel generation in this scenario is 249.33 L at 10 pm and the minimum is 231.35 L at 11 pm as shown in Fig. 6-19c and Fig. 6-19d.



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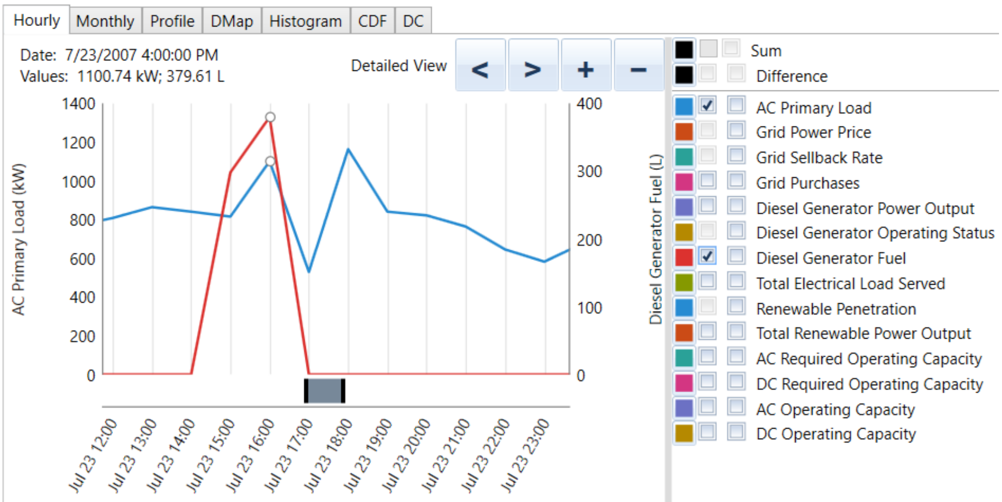

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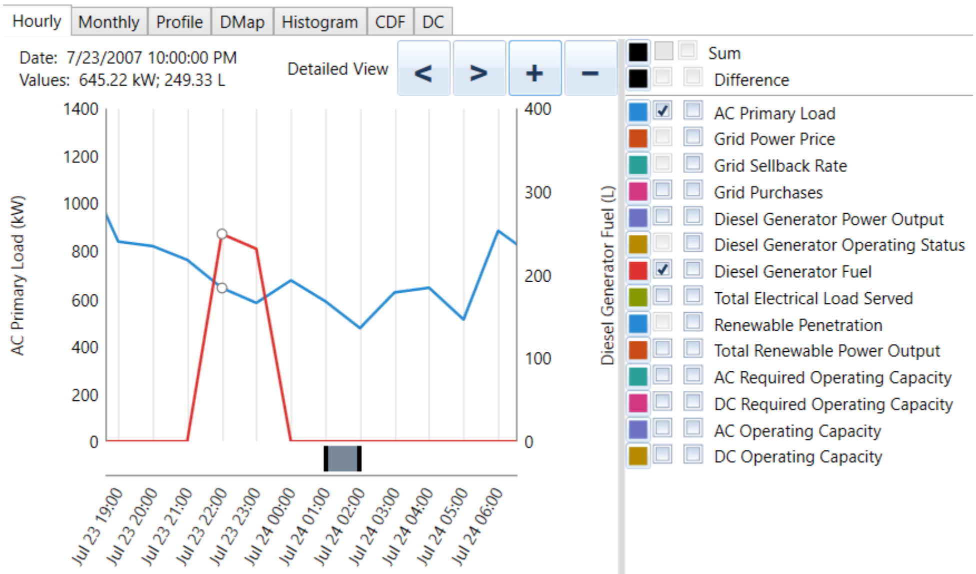
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Difference
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Grid Sellback Rate
Grid Purchases
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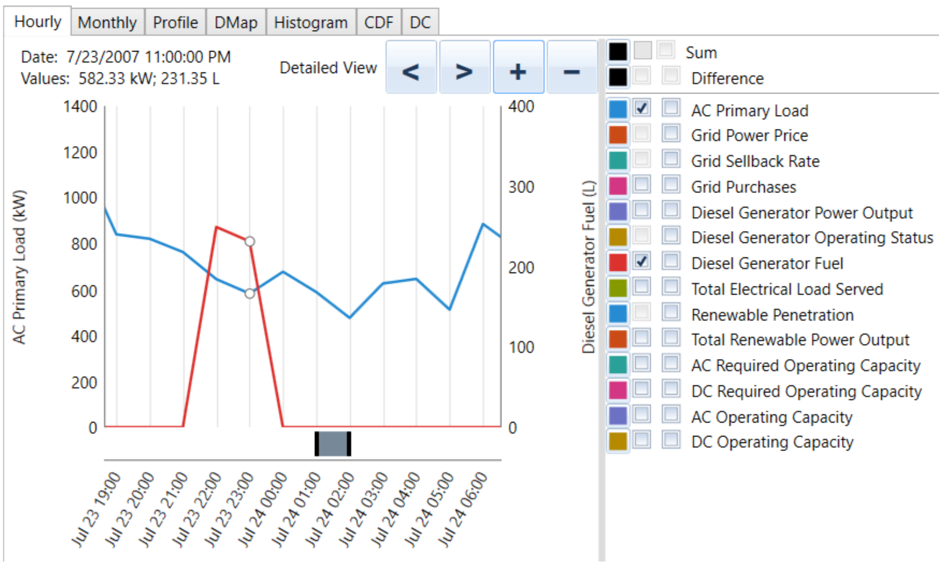
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
AC Required Operating Capacity
DC Required Operating Capacity
AC Operating Capacity
DC Operating Capacity
AC Primary Load (kW)
Diesel Generator Fuel (L)

c)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CDF
DC
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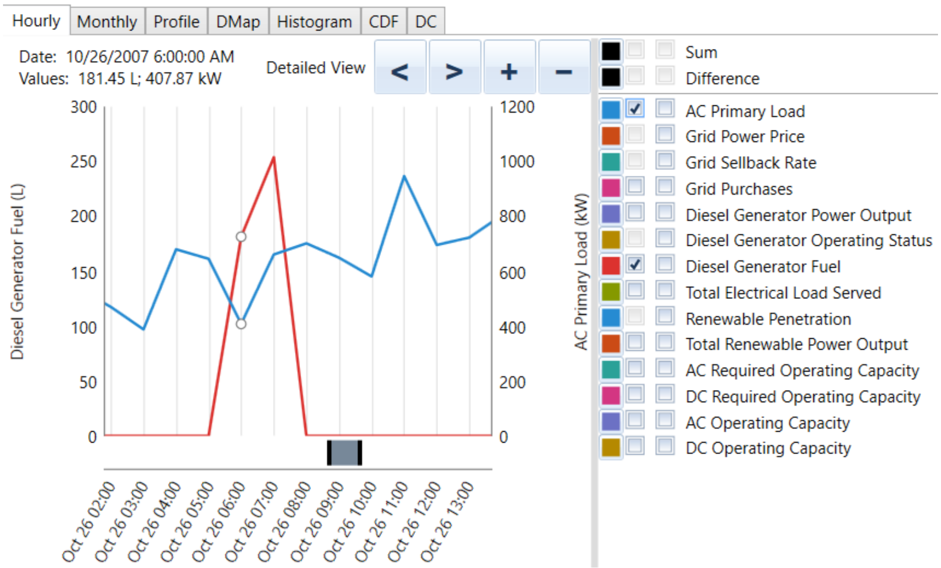
Sum
Difference
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Diesel Generator Power Output
Diesel Generator Operating Status
Diesel Generator Fuel
Total Electrical Load Served
Renewable Penetration
Total Renewable Power Output
AC Required Operating Capacity
DC Required Operating Capacity
AC Operating Capacity
DC Operating Capacity
AC Primary Load (kW)
Diesel Generator Fuel (L)

d)



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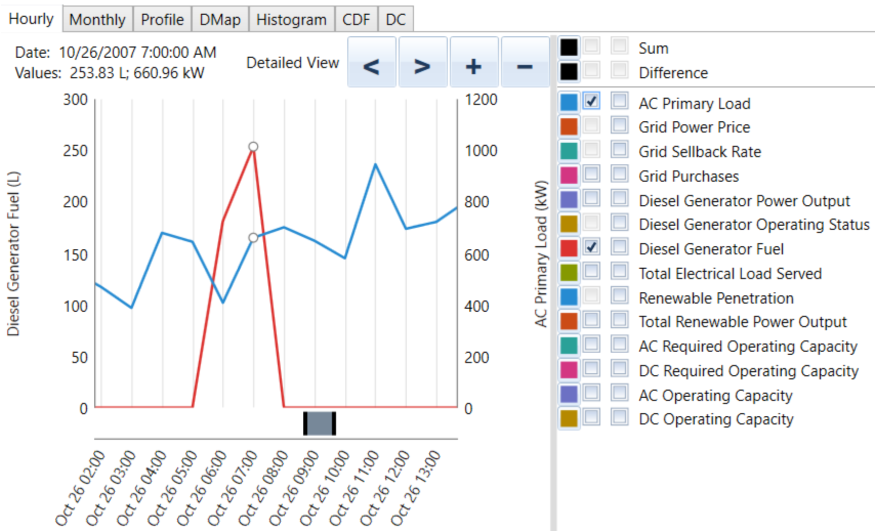


f)

Fig. 6-19. Fuel consumption during the diesel generator operation with a) the minimum value of fuel consumption in the first operation period and b) the maximum of fuel consumption in the same period, c) the maximum value of fuel consumption in the second operation period, d) the minimum value of fuel consumption in the same period, e) the maximum fuel consumption in the third operation period and f) the minimum fuel consumption in the same operation period.

Table 6-1 provides the summary of the economics of the grid with diesel backup generator system in all scenarios. This table shows that the third scenario results in having the highest total NPC, LCOE and annual operating costs. In terms of total O&M costs the second scenario gives the lowest total O&M costs among the other scenarios with $10,329,902.57. This is because the decrease in the grid O&M costs is higher than the increase of the diesel O&M and other O&M costs. Hence, for this system, the scenario that offers the lowest system costs is when the grid power outage happens once a year which is the first scenario.

Table 6-1. The summary of the economics of the grid with diesel backup generator system in all scenarios

Costs of each scenario	Scenario 1	Scenario 2	Scenario 3
Total NPC ($)	11,138,140.00	11,142,540.00	11,148,260.00
LCOE ($/kWh)	0.09878	0.09882	0.09887
Operating Costs ($/year)	465,390.00	465,616.20	465,909.00
Total O&M ($)	10,330,995.95	10,329,902.57	10,330,510.59
Grid O&M ($)	10,256,626.06	10,252,886.23	10,250,849.40
Diesel O&M ($)	2,635.31	5,270.61	7,905.92
Other O&M ($)	71,734.58	71,745.73	71,755.27

6.3. Grid-connected PV with Diesel backup

Grid-connected PV with diesel backup generator system is modelled as shown in Fig. 6-20. The diesel generator capacity is still the same as 1350 kW and the PVs are chosen to be 2218 kW and 2772 kW to cover a 40% and 50% of the critical load in the system. These values are chosen depending on the heuristic calculations in Chapter 5.

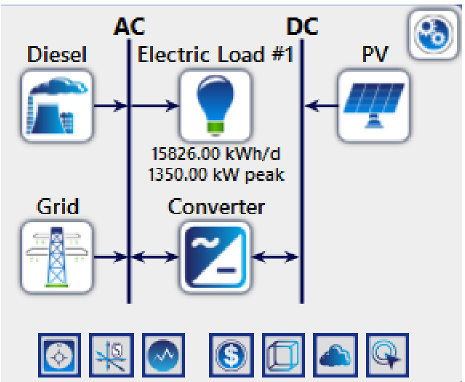


Fig. 6-20. Schematic system for grid-connected PV with Diesel backup

The CC and ML strategies are also used as the controllers for this system. In the ML strategy, MATLAB code is written to decide when to operate the PV, grid and diesel generator. First, it checks whether or not the PV output is higher than the load requested, therefore if PV is higher, then it runs the PV and any excess energy is going to be sold to the grid. If the PV is less than the load, it runs the grid with the remaining load that is not supported by the PV; and hence, in this case there is no excess energy to be sold to the grid. In case of the grid power outage, the MATLAB code checks if load is higher than the minimum operating power of the generator

(25% of the maximum power output of the diesel generator) and PV is output is zero, then it runs the generator with the power equal to the load. However, if the load is equal to the minimum operating power of the generator and PV is less than the load, then it runs the generator with the remaining power from subtracting the load from the PV output. In this stage, the code checks again whether or not the remaining power is less than 25% of the maximum power output of the generator. Thus, if it is less than that value, it runs the diesel with the minimum allowed power output. Next step, the MATLAB code checks if the load is less than 25% of the maximum power output of the diesel generator and the PV output is zero. If that is the case, the code makes the diesel run with the minimum operating power output. Lastly, the code checks if the load is less than the minimum allowed power output of the generator and the PV is less than the load. If that case happens, then it runs the generator with the 25% of the maximum power output of the generator, then it calculates the excess energy by subtracting the sum of the generator output and PV output from the load requested at this point. A flowchart of this MATLAB code is illustrated in Fig. 6-21.

This modelled system is simulated considering the three scenarios of the grid power outages which are once, twice and thrice a year. Nevertheless, due to having renewable energy source added to this system, an additional sensitivity analysis included in this case which is the price of the sellback rate to the grid when the PV output is higher than the load requested by the system. These rates are assumed to be a) half of the grid energy price, b) the sellback rate and the grid energy price are equal and c) the sellback rate is 5% higher than the grid energy price.

Fig. 6-22 displays the optimum solutions chosen by HOMER for these three scenarios with the different sellback rates to the grid. Fig. 6-22a shows the optimum solutions chosen for the three scenario with sellback rate that is half of the grid energy price and the optimum results chosen for the scenarios with sellback rate that is equivalent to the grid energy price is provided in Fig. 6-22b. In Fig. 6-22c, the results of the optimum systems given by HOMER for the scenarios when the sellback rate is higher than the grid power price by 5%.

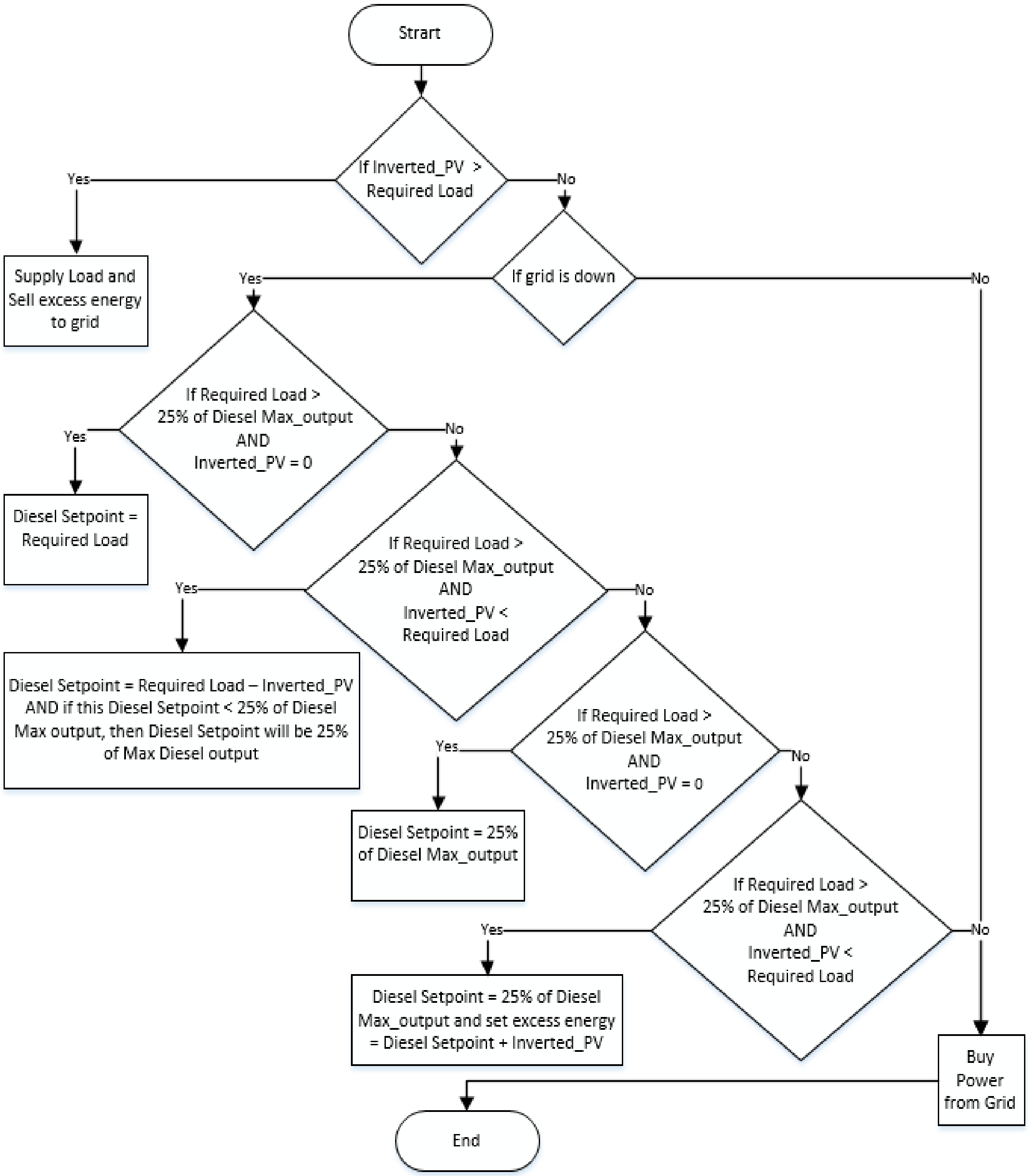


Fig. 6-21. Flowchart of MATLAB code for the system

Sensitivity			Architecture						
Grid Failure Frequency (1/yr)	Grid Variation Repair Time (h)	Grid Mean Repair Time (h)	PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)
1.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0682
2.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0680
3.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0680

a)

Sensitivity			Architecture					
Grid Failure Frequency (1/yr)	Grid Variation Repair Time (h)	Grid Mean Repair Time (h)	PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)
1.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0582
2.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0580
3.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0580

b)

Sensitivity			Architecture					
Grid Failure Frequency (1/yr)	Grid Variation Repair Time (h)	Grid Mean Repair Time (h)	PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)
1.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0572
2.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0570
3.00	5.00	2.00	2,772	1,350	999,999	2,000	ML	$0.0570

c)

Fig. 6-22. Optimum results of the three scenarios with a) sellback rate half of the grid energy price, b) sellback rate equivalent to the grid energy price and c) sellback rate higher than the grid energy price by 5%

For the three scenarios, the optimum systems chosen by HOMER are the ones that are going to be discussed for each sellback rate. Thus, nine systems will be analysed in the following sub-sections. These systems will be discussed in regards with the economics, whether or not the diesel generator needed to be operated, the coverage of the power outage from the grid and the optimum scenario system among others.

6.3.1. Results of scenario one for the system

6.3.1.1. Sellback rate half of the grid energy price

In this situation, the ML strategy is chosen by HOMER to be the one that results in the optimum system as shown in Fig. 6-22a. This system consists of 2772 kW PV, 2000 kW inverter, the grid and 1350 kW diesel backup generator. Fig. 6-23 summarises the results of the optimum system having COE of 0.0682 $/kWh, total NPC of $9.91M, operating cost of 239,725 $/year and initial cost of $5.23M. In addition, the renewable fraction is 54.1% as expected from the heuristic calculations in order to cover 50% of the requested load by using PV, the size of the PV needs to be 2772.5 kW.

Architecture										Cost				System
					PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
					2,772	1,350	999,999	2,000	ML	$0.0682	$9.91M	$239,725	$5.23M	54.1

Fig. 6-23. Optimum result of scenario one with sellback rate is half of the grid energy price

Fig. 6-24 shows the detailed costs of the systems including the LCOE of 0.06816 $/kWh, total NPC of $9,910,169.00 and the operating cost of 239,725.50 $/year. What's more, it is clear that the PV initial capital cost is the highest among the other components in the system with value of $2,495,250.00 and the lowest is the inverter with an initial cost of $681,940.00. in terms of the replacement cost, the only components that required replacement during the simulations is the PV and inverter in which the PV has the highest cost of replacement with $1,343,078.35 and the inverter with $458,821.18. However, the grid O&M cost results in having the highest O&M cost among others with the value of $4,634,314.12 and the lowest is the other O&M cost with value of $21,655.56.

In this situation and this optimum system, the diesel generator is not used at all even when the grid power outage happens as the PV covers that outage as it occurs while the PV has an output power higher than the load requested at that point as it will be seen later. Hence, the highest salvage in this system is coming from the diesel generator with -$1,219,942.10 followed by the PV with -$912,298.45.

Total NPC:	$9,910,169.00
Levelized COE:	$0.06816
Operating Cost:	$239,725.50

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$0.00	$0.00	-$1,219,942.10	$833,407.90
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$4,634,314.12	$0.00	$0.00	$4,634,314.12
Other	$0.00	$0.00	$21,655.56	$0.00	$0.00	$21,655.56
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$5,321,628.45	$0.00	-$2,443,899.10	$9,910,168.88

Fig. 6-24. The costs of each component of the system in scenario one with the first sellback rate and the detailed values of total NPC, LCOE and operating cost

As the power energy outage happen in October and in the same time that the PV has an output that cover the load requested, then the diesel is not operated. Therefore, Fig. 6-25 shows how the PV is covering the load in the moment of the power outage from the grid which is at 6 am to 7 am on October 26th.

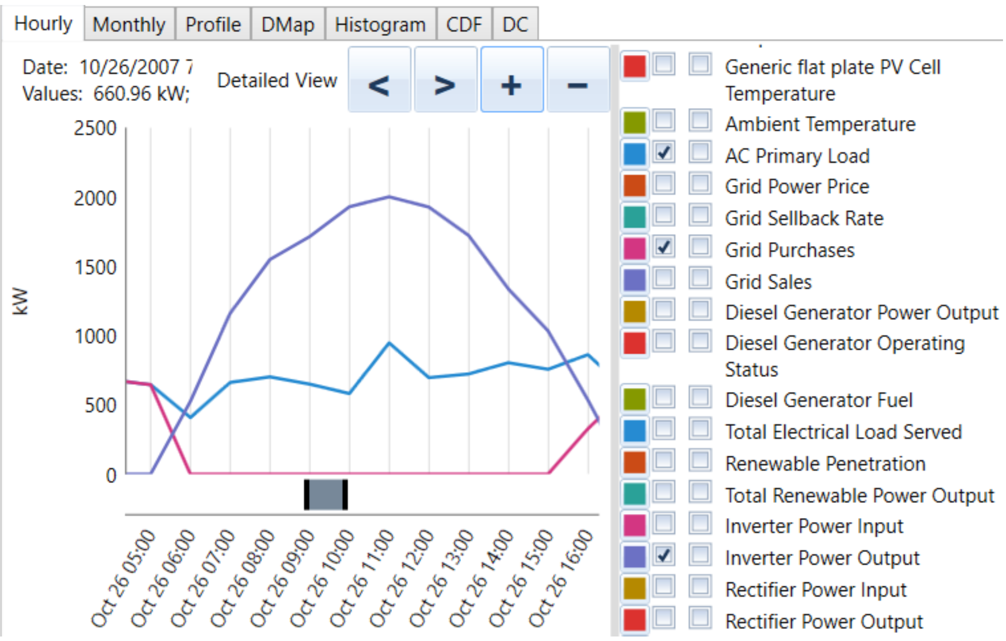


Fig. 6-25. PV is covering the power outage from the grid

6.3.1.2. Sellback rate equal to the purchase price

Also, when the sellback rate is equivalent to the price of energy from the grid, HOMER optimisation results show that ML strategy control leads to the optimum system as shown in Fig. 6-22b. Even when the sellback rate is set to be the same as the price of buying energy from the grid, HOMER is still choosing the same kilowattage outputs for all the component of the previous system in scenario one as shown in Fig. 6-26. In the same figure, it is noticeably that the COE becomes 0.0582 $/kWh, 14.66% reduction in the price of energy compared to the previous sellback rate with the COE of 0.0682 $/kWh. To add, the NPC of this system is $8.46M, whereas it was previously equal to $9.91M, and this is another huge difference with almost the same percent reduction (14.63%). Furthermore, this results in having an operating cost of 165,426 $/year, 74,299 $/year (30.99%) decrease compared to the previous system that had the operating cost of 239,725 $/year. However, the initial cost and renewable fraction are relatively the same with the previous system at $5.23M and 54.1%, respectively.

Architecture					Cost				System
PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
2,772	1,350	999,999	2,000	ML	$0.0582	$8.46M	$165,426	$5.23M	54.1

Fig. 6-26. Optimum result of scenario one with sellback rate is equivalent to the grid energy price

The detailed costs of this system and its component costs are all provided in Fig. 6-27. Therefore, the exact values of LCOE, total NPC and operating cost of the system are 0.05819 $/kWh, $8,459,785.00 and 165,426 $/year, respectively. Moreover, obviously the PV is the largest contributor in increasing the initial capital cost of the investment followed by the generator that is in fact the generator is not used in this scenario as the shortage of power happens during the morning where the PV has a large power output that covers that capacity demand. In term of replacement cost, the PV is the most expensive component to be replaced ($1,343,078.35) and inverter comes after, but with less than half million ($458,821.18).

In terms of the O&M costs, the grid O&M costs are still the highest with ($3,183,930.24), but it is lower than the previous situation where the sellback rate is half the price of grid energy price ($4,634,314.12). The inverter O&M costs come after the grid with $665,658.77, and the lowest O&M costs are coming from the other O&M costs with $21,655.56. The O&M costs of the inverter and the other O&M costs are still equivalent to the resulted costs in the previous situation.

To add, there is no fuel costs as the diesel generator is not used in this situation. This is because the PV covered the power outage that occurs in this scenario as previously stated. Therefore, the highest salvage is coming from the generator with -$1,219,942.10. Then, the PV comes second with -$912,298.45 and the inverter has the lowest salvage with -$311,658.55. The salvage values for these components are still the same as the previous situation where the sellback rate is half of the price of purchasing energy from the grid.

Total NPC:	$8,459,785.00
Levelized COE:	$0.05819
Operating Cost:	$165,426.00

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$0.00	$0.00	-$1,219,942.10	$833,407.90
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$3,183,930.24	$0.00	$0.00	$3,183,930.24
Other	$0.00	$0.00	$21,655.56	$0.00	$0.00	$21,655.56
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$3,871,244.56	$0.00	-$2,443,899.10	$8,459,784.99

Fig. 6-27. The costs of each component of the system in scenario one with the second sellback rate and the detailed values of total NPC, LCOE and operating cost

6.3.1.3. Sellback rate 5% higher than the purchase price

As the sellback rate becomes higher than the grid price of energy, HOMER optimisation results provide that ML strategy control leads to the optimum system as shown in Fig. 6-22c. It is clearly seen that the outputs of all components chosen to be the same as the first situation by HOMER as in Fig. 6-28. Nevertheless, this rate of sellback results in having the lowest COE, total NPC and operating cost which are 0.0572 $/kWh, $8.32M and 158,125 $/year in this order. These costs are lower than the first situation costs, as this COE is 16.13% lower than the first situation COE, this total NPC is lower by 16.04% and the operating cost by 34.04%. These are very huge reductions in the total cost, especially the reduction of the operating costs. The renewable fraction and initial cost are still the same as the first situation as displayed in Fig. 6-28.

Architecture										Cost				System
					PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
					2,772	1,350	999,999	2,000	ML	$0.0572	$8.32M	$158,125	$5.23M	54.1

Fig. 6-28. Optimum result of scenario one with sellback rate is 5% higher than the grid energy price

Fig. 6-29 provides the detailed cost of this system and its all components costs. Hence, the LCOE is given as 0.05721 $/kWh, the total NPC is $8,317,271.00 and the operating cost is

158,125.40 \$/year. It is still that the PV is the huge contributor in having very expensive initial cost followed by the generator which is still not used in this situation. Furthermore, the PV replacement cost is still the huge contributor in making the system total NPC is still high.

In this situation, inverter O&M costs and the other O&M costs are still the same as the previous two situations. Nonetheless, the grid O&M costs in this situation is lower than the previous situations with a value of \$3,041,416.30 which is less than the first and second situation by 34.37% and 4.48%, respectively. Thus, the total O&M costs of the system is \$3,728,730.62 that is lower than the total O&M of the first and second situations with 29.93% and 3.68% in this order.

The salvage costs are still the same as the previous situations. Thus, the diesel is still resulting in providing the highest salvage with -\$1,219,942.10 followed by the PV with -\$912,298.45. Lastly, the inverter salvage is -\$311,658.55.

Total NPC:	$8,317,271.00
Levelized COE:	$0.05721
Operating Cost:	$158,125.40

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$0.00	$0.00	-$1,219,942.10	$833,407.90
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$3,041,416.30	$0.00	$0.00	$3,041,416.30
Other	$0.00	$0.00	$21,655.56	$0.00	$0.00	$21,655.56
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$3,728,730.62	$0.00	-$2,443,899.10	$8,317,271.05

Fig. 6-29. The costs of each component of the system in scenario one with the third sellback rate and the detailed values of total NPC, LCOE and operating cost

6.3.2. Results of scenario two for the system

6.3.2.1. Sellback rate half the purchase price

As well, in this scenario and situation, HOMER chooses that the ML strategy results in the optimum solution for the situation as display in Fig. 6-22a. The values of the kilowattage outputs of all components are the same as in the first scenario which is 2772 kW PV, 2000 kW inverter and 1350 kW diesel generator. The renewable fraction is still at 54.1% as shown in Fig. 6-30. This figure provides a summary of the COE with \$0.0680, total NPC with \$9.88M, operating cost of 238, 258 $/year and initial cost of $5.23M. Noticeably, the COE and operating cost is lower than the first scenario with the same sellback rate which were 0.0682 $/kWh and 239, 725 $/year, respectively.

Architecture					Cost				System
PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
2,772	1,350	999,999	2,000	ML	$0.0680	$9.88M	$238,258	$5.23M	54.1

Fig. 6-30. Optimum result of scenario two with sellback rate is half of the grid energy price

The detailed costs of the system and the costs of the components are shown in Fig. 6-31. This indicates that the LCOE is 0.06797 $/kWh, with total NPC of $9,881,525.00 and operating cost of 238,258.10 $/year. As the system consists of the same components, the initial cost will stay the same for all the situations with total initial capital of $5,230,540.00. Also, the total replacement costs will be the same as in all the situations for this system configuration that is $1,801,899.53.

In this situation, the diesel is operated for one hour due to the power outage that happens while the PV is unable to cover it as shown in Fig. 6-32. The total O&M costs increases due to this usage of the diesel which results in adding a cost of diesel O&M of $1,317.65 as in Fig. 6-31. To add, the inverter still has the same O&M cost with $665,658.77 and the other O&M costs rise and become $21,660.40. However, the grid O&M costs decrease with a value of $1,257 resulting in $4,633,057.12. Hence, the total O&M costs have increased and become $5,321,693.94 because the increase of the total diesel O&M costs are higher than the decrease in the total grid O&M costs.

As the diesel is operated for one hour in this situation, the diesel fuel costs $486.00 in the system. Although the diesel operates for one hour, the salvage of the diesel increases to -$1,249,137.30 and becomes the highest. This followed by the PV with the same value of the previous situations (-$912,298.45) and then the inverter with also the same value of the previous situations (-$311,658.55).

Total NPC:	$9,881,525.00
Levelized COE:	$0.06797
Operating Cost:	$238,258.10

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$1,317.65	$486.00	-$1,249,137.30	$806,016.35
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$4,633,057.12	$0.00	$0.00	$4,633,057.12
Other	$0.00	$0.00	$21,660.40	$0.00	$0.00	$21,660.40
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$5,321,693.94	$486.00	-$2,473,094.30	$9,881,525.17

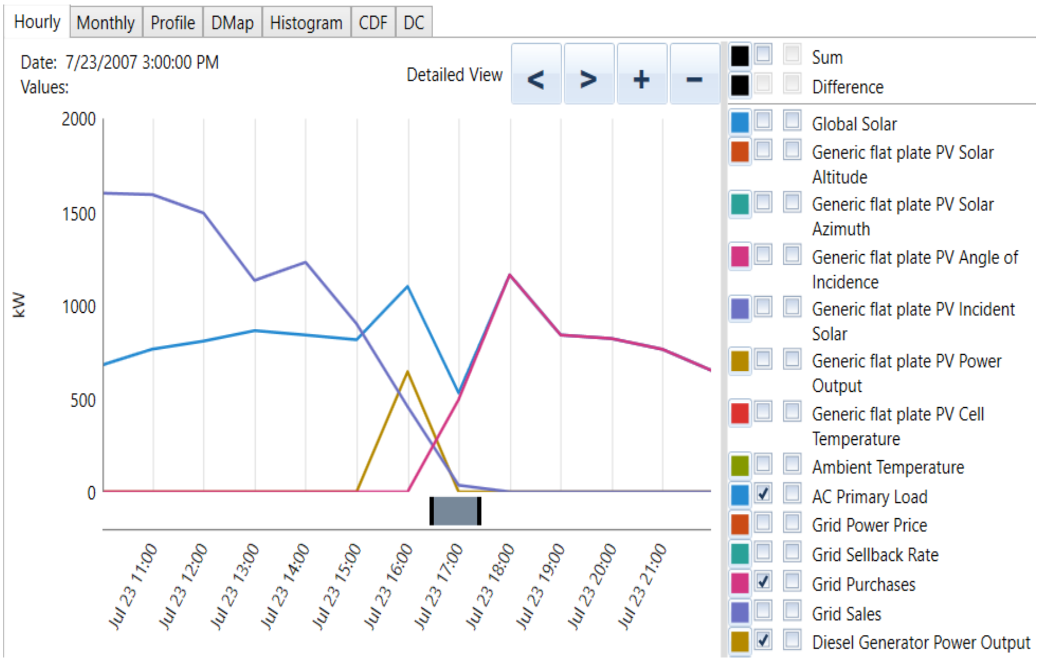
Fig. 6-31. The costs of each component of the system in scenario two with the first sellback rate and the detailed values of total NPC, LCOE and operating cost

Fig. 6-32 provides that the diesel operates for one hour and its total production of 644 kWh. Also, it shows the total fuel used in this situation is 249 L. Moreover, the annual O&M and fuel costs are given with the value of 67.5 $/year and 24.9 $/year in this order.

Diesel				
Hours	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)
1.00	644	249	67.5	24.9

Fig. 6-32. Diesel generator output and its costs

As in this scenario the outage of power happens twice in one year. These outages happen in different time of the year, one of the outage periods is already covered by the PV output where the diesel is not needed to supply as shown in Fig. 6-25. However, in the second period of the power outage, the PV output covers the first hour of the outage and the diesel covers the second hour of the outage as depicted in Fig. 6-33a. Fig. 6-33b provides the power outputs of the inverter with 900.27 kW where the load required is 815.08 when the outage of the grid occurs. Whereas in the second hour where the load required is higher than the inverter output of 1100.74 kW, the diesel runs for this hour at 643.93 kW cooperating with the inverter output of 456.81 kW to supply the load requested as displayed in Fig. 6-33c. When the diesel runs for that hour of power shortage, the needed fuel consumption is 248.96 L as in Fig. 6-34.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Monthly
Profile
DMap
Histogram
CDF
DC
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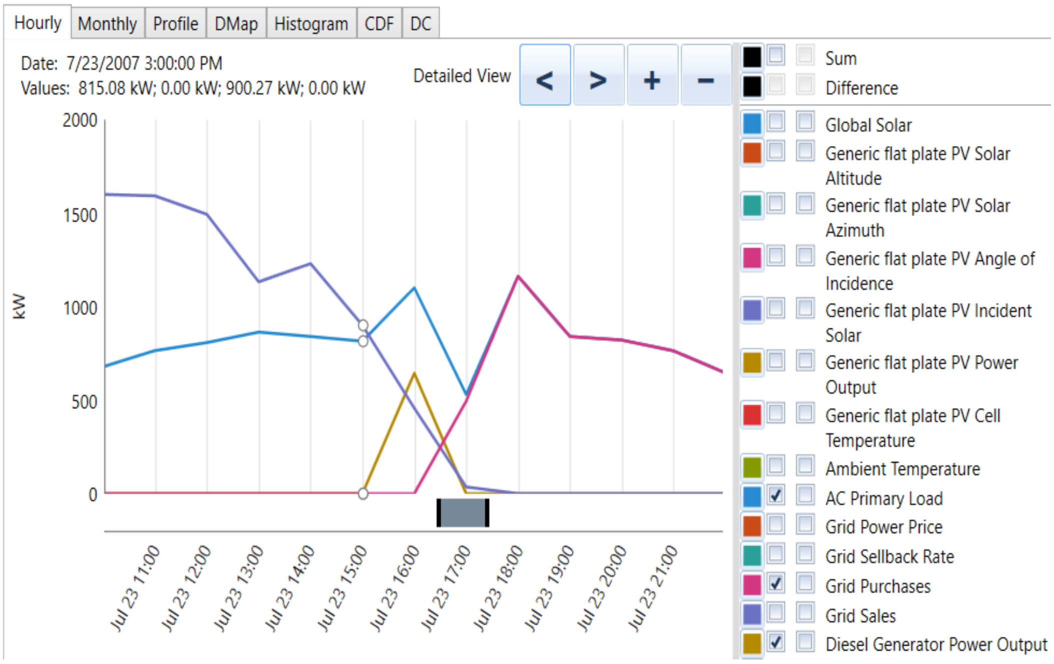
1500
1000
500
0
kW
Jul 23 11:00
Jul 23 12:00
Jul 23 13:00
Jul 23 14:00
Jul 23 15:00
Jul 23 16:00
Jul 23 17:00
Jul 23 18:00
Jul 23 19:00
Jul 23 20:00
Jul 23 21:00
Sum
Difference
Global Solar
Generic flat plate PV Solar Altitude
Generic flat plate PV Solar Azimuth
Generic flat plate PV Angle of Incidence
Generic flat plate PV Incident Solar
Generic flat plate PV Power Output
Generic flat plate PV Cell Temperature
Ambient Temperature
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Grid Sales
Diesel Generator Power Output

a)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Monthly
Profile
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Detailed View
2000
1500
1000
500
0
kW
Jul 23 11:00
Jul 23 12:00
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Jul 23 14:00
Jul 23 15:00
Jul 23 16:00
Jul 23 17:00
Jul 23 18:00
Jul 23 19:00
Jul 23 20:00
Jul 23 21:00
Sum
Difference
Global Solar
Generic flat plate PV Solar Altitude
Generic flat plate PV Solar Azimuth
Generic flat plate PV Angle of Incidence
Generic flat plate PV Incident Solar
Generic flat plate PV Power Output
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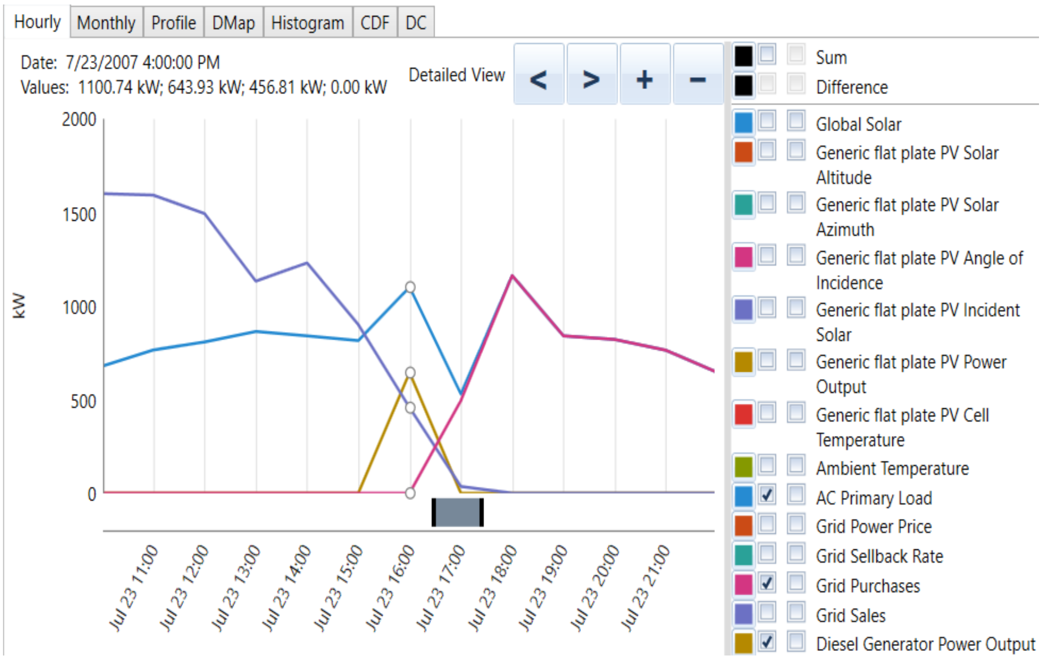
Ambient Temperature
AC Primary Load
Grid Power Price
Grid Sellback Rate
Grid Purchases
Grid Sales
Diesel Generator Power Output

b)



c)

Fig. 6-33. a) PV and diesel covering the power outage, b) inverter output is covering the first hour of outage and c) the power output of the diesel covering the second hour of outage

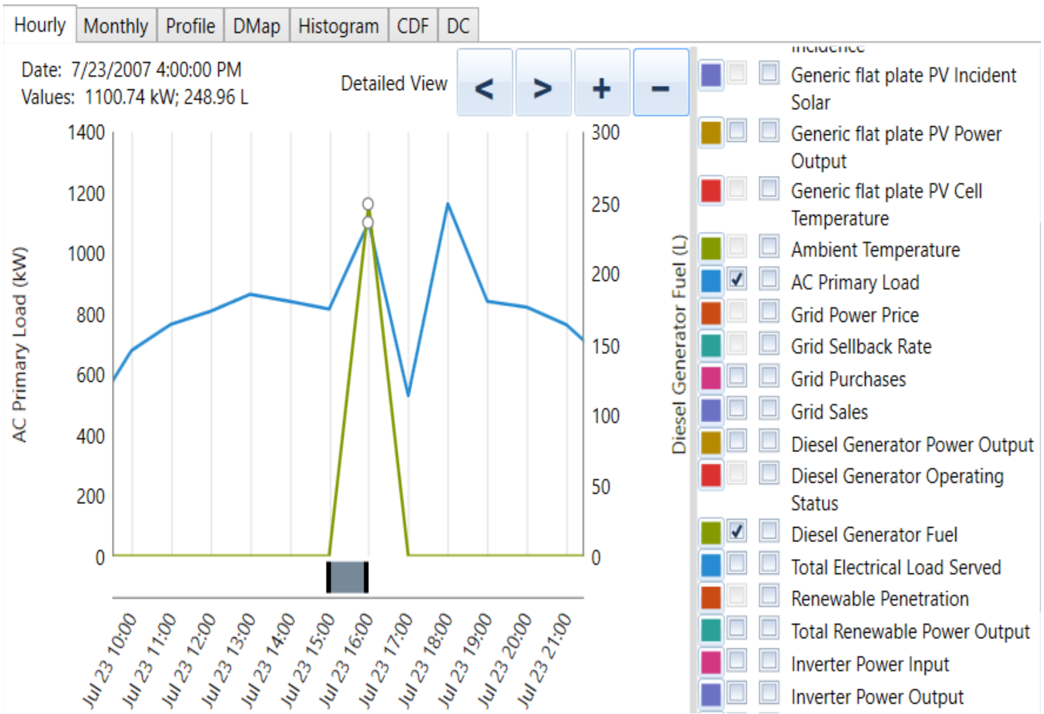


Fig. 6-34 Fuel consumption during the diesel generator operation

6.3.2.2. *Sellback rate equal to the purchase price*

In this situation, the results of ML dispatch are chosen to be the optimum system by HOMER as in Fig. 6-22b. The components still have the same outputs of kilowattages (2772 kW PV, 1350 kW diesel generator and 2000 kW inverter), initial cost ($5.23M) and renewable fraction of 54.1% as the previous situation at sellback rate half the purchase price. Nevertheless, Fig. 6-35 indicates that this situation gives lower values of COE with 0.0580 $/kWh, total NPC with $8.43M and operating cost of 163, 959 $/year. These differs by 14.70% lower in COE, 14.67% lower in total NPC and 31.61% lower in operating cost.

Architecture					Cost				System
PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
2,772	1,350	999,999	2,000	ML	$0.0580	$8.43M	$163,959	$5.23M	54.1

Fig. 6-35. Optimum result of scenario two with sellback rate is equivalent to the grid energy price

Fig. 6-36 shows the detailed costs of the system with the difference of some costs due to this situation of the power outage. In this figure, the costs of LCOE, total NPC and operating cost are shown to be lower than the previous situation as mentioned above with values of 0.05779 $/kWh, $8, 431, 141.00 and 163,958.60 $/year. The initial cost ($5,230,540.00) and replacement cost ($1,801,899.53), however, are still the same as the previous situation.

As the diesel is still operating for only one hour, the total O&M diesel cost is still the same as before with $1,317.65 and the other O&M cost also the same ($21,660.40) as depicted in Fig 6-35. In addition, the total inverter O&M cost is $665,658.77 which is also the same as before. Nonetheless, the total grid O&M costs becomes lower than the previous situation with $3,182,673.23. Thus, this results in lowering the total O&M costs of the system and become $3,871,310.05.

The fuel cost is still the same as before with $486.00 in the system. Also, the diesel still has the highest salvage value of -$1,249,137.30, followed by the PV and then the inverter with -$912,298.45 and -$311,658.55 in this order.

Total NPC:	$8,431,141.00
Levelized COE:	$0.05799
Operating Cost:	$163,958.60

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$1,317.65	$486.00	-$1,249,137.30	$806,016.35
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$3,182,673.23	$0.00	$0.00	$3,182,673.23
Other	$0.00	$0.00	$21,660.40	$0.00	$0.00	$21,660.40
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$3,871,310.05	$486.00	-$2,473,094.30	$8,431,141.28

Fig. 6-36. The costs of each component of the system in scenario two with the second sellback rate and the detailed values of total NPC, LCOE and operating cost

6.3.2.3. *Sellback rate 5% higher than the purchase price*

This sellback rate results in better economics with COE is 16.18% (0.0570 $/kWh) lower than the first sellback rate, the total NPC drops by 16.09% ($8.29M) and operating cost 34.25% (156, 658 $/year) less than the first situation as in Fig. 6-37. The renewable fraction and the initial cost of the system are still the same as shown in the figure. This system is chosen to be the optimum with the ML dispatch strategy by HOMER as in Fig. 6-22c.

Architecture					Cost				System
PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
2,772	1,350	999,999	2,000	ML	$0.0570	$8.29M	$156,658	$5.23M	54.1

Fig. 6-37. Optimum result of scenario two with sellback rate is 5% higher than the grid energy price

These costs are shown in more detailed way in Fig. 6-38. The initial cost and replacement costs are still the same. While, the LCOE, total NPC and operating cost become lower with values of 0.05701 $/kWh, $8, 288, 628.00 and 156, 658.00 $/year, respectively.

In this situation, all the O&M costs are still the same, except the total grid O&M costs which become lower by 34.38% ($3,040,159.30) from the first sellback rate. This results in having lower total O&M costs for the system with $3,728,796.11 as in the figure. The salvage and the fuel costs for the diesel are still the same. Also, the salvage values for the PV and inverter are still the same.

Total NPC:	$8,288,628.00
Levelized COE:	$0.05701
Operating Cost:	$156,658.00

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$1,317.65	$486.00	-$1,249,137.30	$806,016.35
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$3,040,159.30	$0.00	$0.00	$3,040,159.30
Other	$0.00	$0.00	$21,660.40	$0.00	$0.00	$21,660.40
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$3,728,796.11	$486.00	-$2,473,094.30	$8,288,627.35

Fig. 6-38. The costs of each component of the system in scenario two with the third sellback rate and the detailed values of total NPC, LCOE and operating cost

6.3.3. Results of scenario three for the system

6.3.3.1. Sellback rate half the purchase price

In this situation and scenario, HOMER chooses the optimum system to be the same as the previous specifications and also the dispatch which results in having this optimum techno-economic system is ML dispatch as shown in Fig. 6-22a. In Fig. 6-39, the summary of the costs of the system provides that the COE is the same as scenario two with 0.0680 $/kWh, but with higher total NPC and operating cost that are $9.89M and 238,551 $/year respectively. However, the renewable fraction is still the same with 54.1%.

Architecture										Cost				System
					PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
					2,772	1,350	999,999	2,000	ML	$0.0680	$9.89M	$238,551	$5.23M	54.1

Fig. 6-39. Optimum result of scenario three with sellback rate is half of the grid energy price

Fig. 6-40 illustrates the detailed costs of this system as well as the components costs. The LCOE of this system is 0.06800 $/kWh, the total NPC is $9,887,242.00 and the operating cost is 238,551.00 $/year. The initial costs and the replacement costs stay the same as the components of the system are the same.

In this scenario, the diesel runs for three hours as the PV cannot support the power outages that happen for these hours as displayed in Fig. 6-40. Hence, the total O&M costs of the diesel increase to $3,952.96 and the other O&M costs also become $21,669.94. Conversely, the grid

O&M costs decrease and become $4,631,020.29. The only O&M costs that stay the same is the inverter O&M costs with $665,658.77. Due to these changes in the O&M costs, the total O&M costs reach $5,322,301.96 which is higher than the first scenario.

Due to the need for the diesel generator to run for three hours, this leads to increase in the fuel cost of the generator as it reaches $1,424.32. The highest salvage costs in this scenario is coming from the diesel generator with -$1,244,966.55, but the PV and inverter salvage costs are still the same as the first scenario.

Total NPC:	$9,887,242.00
Levelized COE:	$0.06800
Operating Cost:	$238,551.00

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$3,952.96	$1,424.32	-$1,244,966.55	$813,760.72
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$4,631,020.29	$0.00	$0.00	$4,631,020.29
Other	$0.00	$0.00	$21,669.94	$0.00	$0.00	$21,669.94
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$5,322,301.96	$1,424.32	-$2,468,923.55	$9,887,242.26

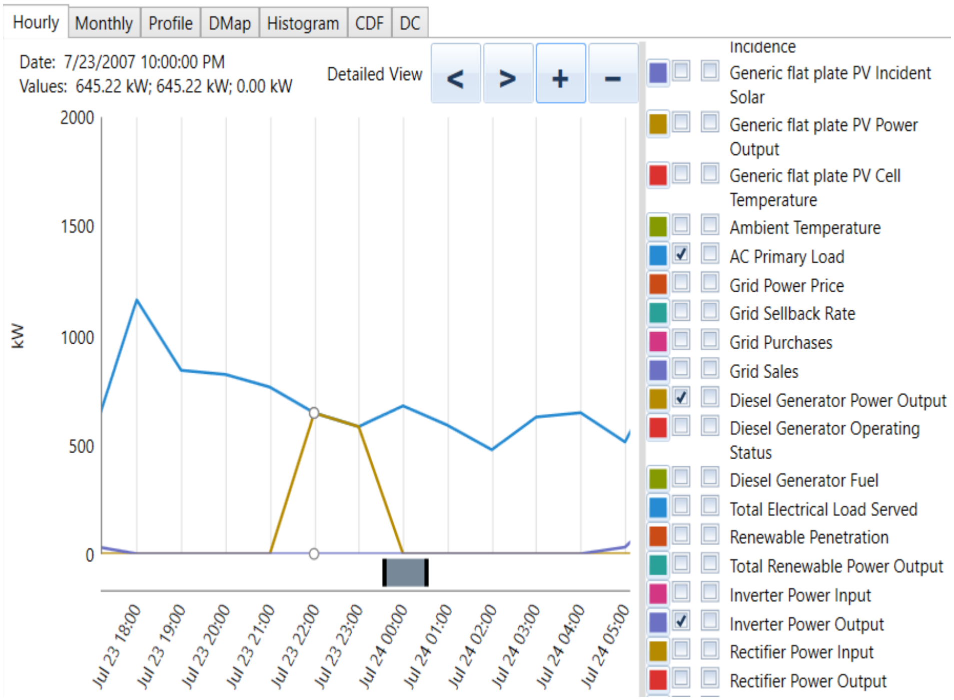
Fig. 6-40. The costs of each component of the system in scenario three with the first sellback rate and the detailed values of total NPC, LCOE and operating cost

It is shown in Fig. 6-41 that the diesel is running for three hours in this scenario with total production of 1,871 kWh. This figure also displaying the amount of fuel litres that the generator is using which is 730 L. Furthermore, the annual O&M costs and fuel costs are 202 $/year and 73.0 $/year in this order.

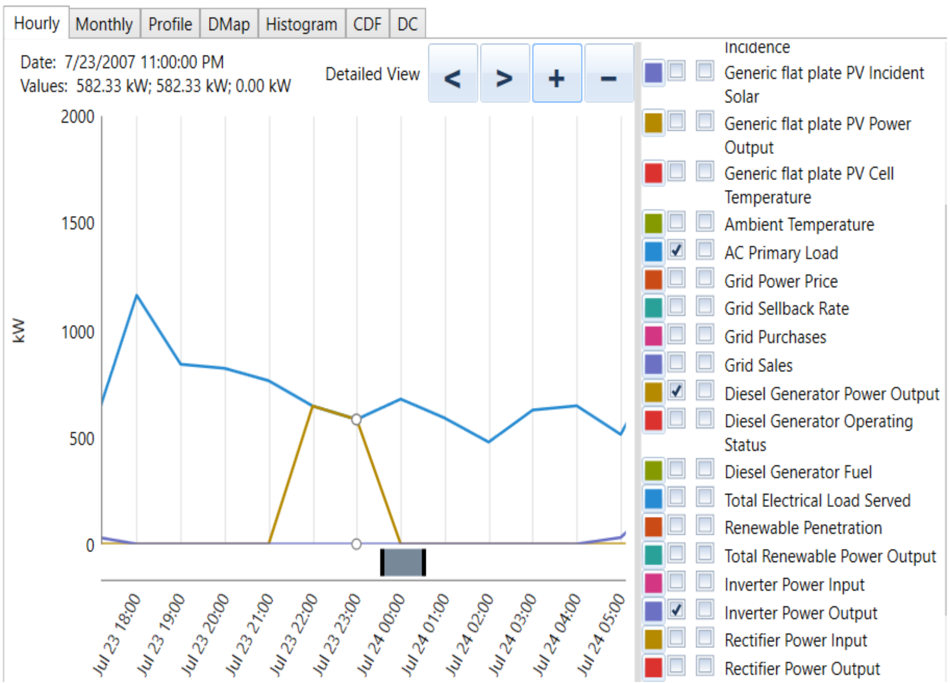
Diesel				
Hours	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)
3.00	1,871	730	202	73.0

Fig. 6-41. Diesel generator output and its costs

In this scenario, the only difference between scenario two and three is that the diesel is needed to run extra two hours at night where the PV cannot provide any output power to support the load required when power outage occurs. These extra hours are shown in Fig. 6-42a and Fig. 6-42b. The first hour that the diesel runs in this scenario is shown in Fig. 6-33a as mentioned in scenario two with power output of 643.93 kW. When the power outage happens again at night, the diesel runs with maximum and minimum power output of 645.22 kW and 582.33 kW respectively as provided in Fig. 6-42a and Fig. 6-42b.



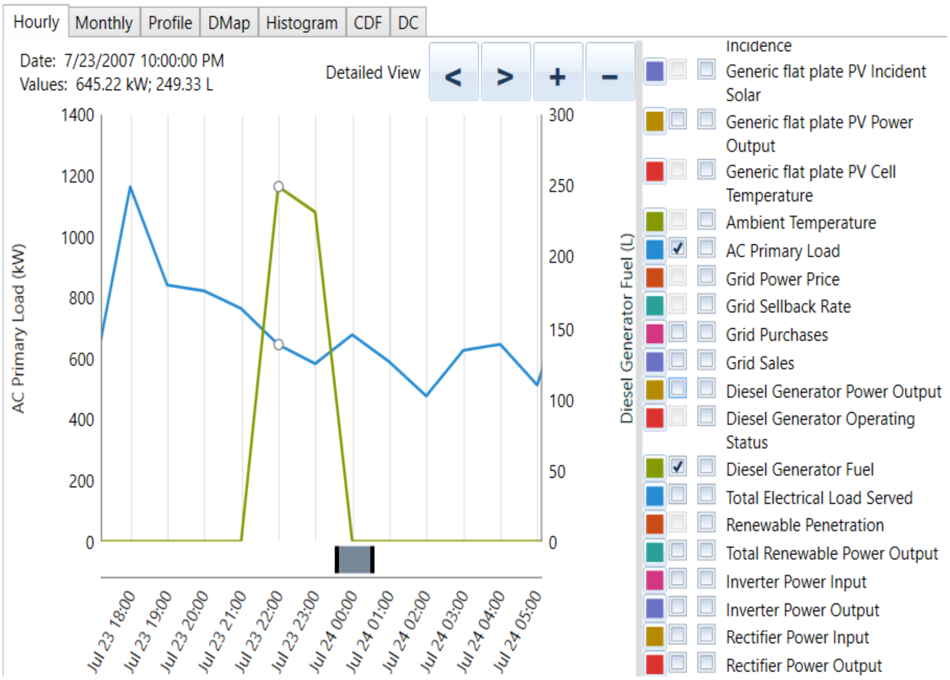
a)



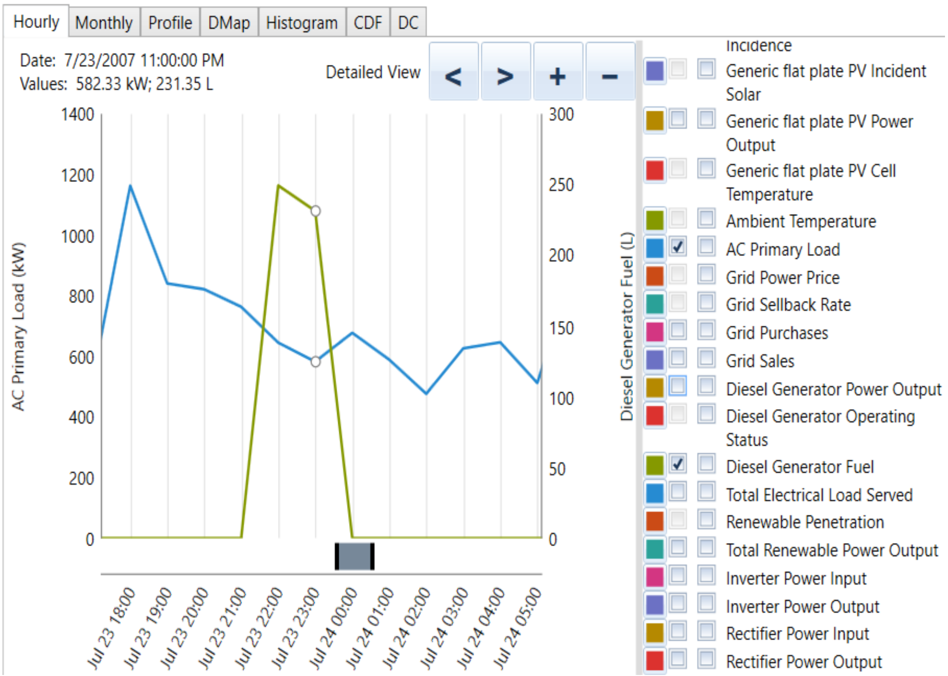
b)

Fig. 6-42. a) The second period of Diesel covering the power outage, b) the same period of diesel covering power outage

The fuel required to provide these power output of the diesel are shown in Fig. 6-43a and Fig. 6-43b. As illustrated in these figures, when the require power output is 643.93 kW, the fuel that is required is 249.33 L. Whereas, when the required power is at 582.33 kW, 231.35 L is needed to enable the diesel to support the load.



a)



b)

Fig. 6-43. a) The fuel consumption of second hour operation of generation and b) the fuel consumption of third hour operation

6.3.3.2. Sellback rate equal to the purchase price

In this sellback rate, HOMER chooses the optimum system to be the one that is produced by ML dispatch as shown in Fig. 6-22b. In this situation, the costs are lower than the first situation as COE, total NPC and operating costs with 0.0580 $/kWh (14.71%), $8.44M (14.66%) and 164,252 $/year (31.15%), respectively, as shown in Fig. 6-44, taking into account the components and renewable fraction are still the same.

Architecture					Cost				System
PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
2,772	1,350	999,999	2,000	ML	$0.0580	$8.44M	$164,252	$5.23M	54.1

Fig. 6-44. Optimum result of scenario three with sellback rate is equivalent to the grid energy price

The detailed costs of the system in this situation are displayed in Fig. 6-45. The costs of LCOE, total NPC and operating costs are 0.05803 $/kWh, $8,436,858.00, 164,251.50 $/year in this order. These are lower than the previous situation as mentioned above. Nevertheless, the initial capital costs and replacement are still the same.

The total O&M costs of the diesel, the inverter O&M and the other O&M are still the same with $3,952.96, $21,669.94 and $665,658.77 in respective. Notwithstanding, the total O&M costs become lower as the total grid O&M costs become $3,180,636.40 which is lower than the previous situation with 31.32% reduction, thus the total O&M costs ($3,871,918.07) are reduced by 27.25% from the previous situation.

The fuel cost is still the same as the previous situation with $1,424.32 in the system. To add, the salvage costs of the system are still the same for all the component as the diesel has the highest value with -$1,244,966.55 and the inverter has the lower value with -$311,658.55.

Total NPC:	$8,436,858.00
Levelized COE:	$0.05803
Operating Cost:	$164,251.50

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$3,952.96	$1,424.32	-$1,244,966.55	$813,760.72
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$3,180,636.40	$0.00	$0.00	$3,180,636.40
Other	$0.00	$0.00	$21,669.94	$0.00	$0.00	$21,669.94
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$3,871,918.07	$1,424.32	-$2,468,923.55	$8,436,858.37

Fig. 6-45. The costs of each component of the system in scenario three with the second sellback rate and the detailed values of total NPC, LCOE and operating cost

6.3.3.3. Sellback rate 5% higher than the purchase price

In this situation, the COE is 16.18% (0.0570 $/kWh) lower than the first situation of sellback rate, the total NPC drops by 16.09% as it becomes $8.29M and operating cost decreases with 34.21% (156,951 $/year) as in Fig. 6-46. This system is selected by HOMER to be the best system which is controlled by ML dispatch strategy as in Fig. 6-22c. In this system situation, the renewable fraction, the initial costs and the components are still the same.

Architecture										Cost				System
					PV (kW)	Diesel (kW)	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
					2,772	1,350	999,999	2,000	ML	$0.0570	$8.29M	$156,951	$5.23M	54.1

Fig. 6-46. Optimum result of scenario three with sellback rate is 5% higher than the grid energy price

The detailed costs of the system are given in Fig. 6-47 which includes all the components' costs and the economics of the system. As shown in the figure, the LCOE is 0.05705 $/kWh, the total NPC is $8,294,344.00 and the operating costs are 156,950.90 $/year. Additionally, the initial costs and the replacement are still with no change.

In this sellback rate, all the O&M costs do not change apart from the grid O&M costs which become lower than the first sellback rate with 34.40% ($3,038,122.47). Thus, this results in having overall lower total O&M costs with 29.93% ($3,729,404.13) as shown in Fig. 6-47. In regards with the salvage costs, the salvage costs for all the components are still without any change from the previous situation.

Total NPC:	$8,294,344.00
Levelized COE:	$0.05705
Operating Cost:	$156,950.90

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$2,053,350.00	$0.00	$3,952.96	$1,424.32	-$1,244,966.55	$813,760.72
Generic flat plate PV	$2,495,250.00	$1,343,078.35	$0.00	$0.00	-$912,298.45	$2,926,029.90
Grid	$0.00	$0.00	$3,038,122.47	$0.00	$0.00	$3,038,122.47
Other	$0.00	$0.00	$21,669.94	$0.00	$0.00	$21,669.94
System Converter	$681,940.00	$458,821.18	$665,658.77	$0.00	-$311,658.55	$1,494,761.40
System	$5,230,540.00	$1,801,899.53	$3,729,404.13	$1,424.32	-$2,468,923.55	$8,294,344.43

Fig. 6-47. The costs of each component of the system in scenario three with the third sellback rate and the detailed values of total NPC, LCOE and operating cost

Table 6-2 summarises the economics of the grid-connected PV system in all scenarios with the sellback rate is 5% higher than the grid energy price. This table shows that the second scenario provides the lowest costs in terms of total NPC, LCOE and operating costs. However, the first scenario gives the lowest total O&M costs due to the diesel generator is not being used.

In term of the other O&M costs, the more the diesel generator is utilised, the higher the other O&M costs become. This can be seen as the increase of the duration of the grid power outage and the longer the diesel is operated in the scenario as in the second and third scenarios. Thus, the second scenario with 5% sellback rate higher than the grid energy price results in the optimum solution for this system.

Table 6-2. The summary of the economics of the grid-connected PV system in all scenarios with the 5% sellback rate higher than grid energy price

Costs of each scenario	Scenario 1	Scenario 2	Scenario 3
Total NPC ($)	8,317,271.00	8,288,628.00	8,294,344.00
LCOE ($/kWh)	0.05721	0.05701	0.05705
Operating Costs ($/year)	158,125.40	156,658.00	156,950.90
Total O&M ($)	3,728,730.62	3,728,796.11	3,729,404.13
Grid O&M ($)	3,041,416.30	3,040,159.30	3,038,122.47
Diesel O&M ($)	0.00	1,317.65	3,952.96
Inverter O&M($)	665,658.77	665,658.77	665,658.77
Other O&M ($)	21,655.56	21,660.40	21,669.94

6.4. Comparison of optimum systems with regards of Economics

Based on the above analysis of grid diesel backup generator system and grid-connected PV with diesel backup generator, the proposed system, which is involving the PV system, is found to be feasible solution when the sellback rate of energy is higher than the grid energy price by 5%. Hence, based on that, a comparison between the results of the existing power generation system that is used in the building and the results of the optimum systems' situation that is given by the grid-connected PV system is done in terms of economic aspects. This comparison is based on three main economic factors which are the LCOE, total NPC and annual operating costs of both systems in each scenario. This is to figure out which system results in better cost-effective system and understanding the reason behind the selection of the techno-economic system.

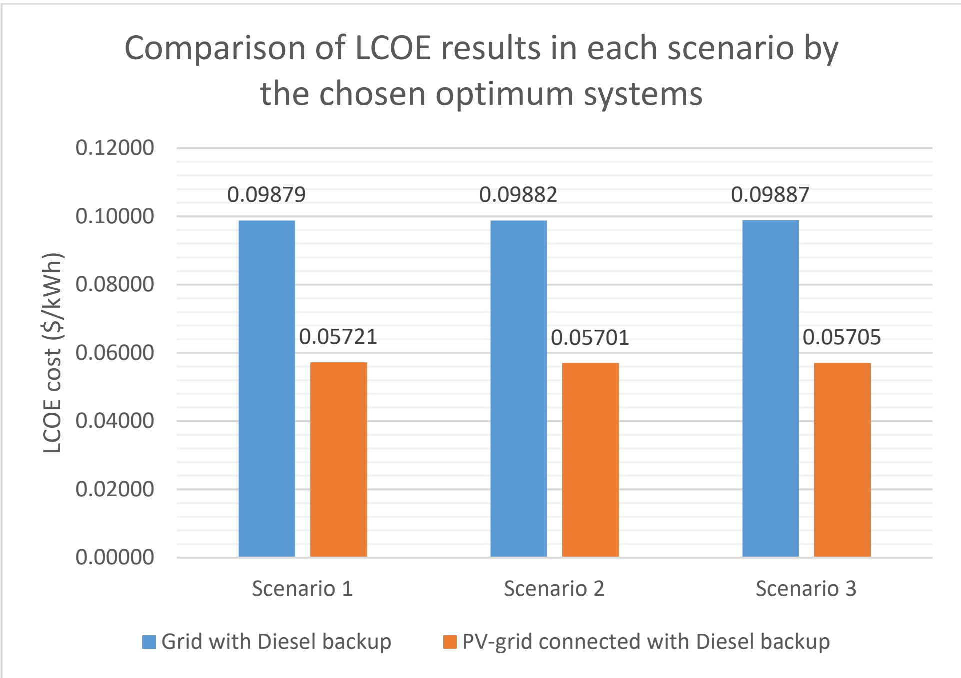


Fig. 6-48. Comparison of LCOE results in each scenario by the chosen optimum systems

Fig. 6-48 depicts the comparison of the LCOE, which is one of the significant economic factors of all systems in each scenario. This shows that PV system is a feasible solution for the building as the results in each scenario gives a reduction of the LCOE with 42.09% up to 42.31% compared with the existing system. In addition, in scenario two the PV system provides the best LCOE with 0.05701 $/kWh where the diesel is needed to operate once a year and for only one hour to cover the power outage. Plus, the PV covers one hour of the grid power outage.

It is noticeable that in the existing system, each time the operating of the diesel generator is increased, this consequently lifts the LCOE up. Therefore, it will limit the usage of the diesel and the grid is critical to have an economic system for this building. This is also shown in scenario three for the PV system, when the diesel generator runs for extra 2 hours more than the scenario two, the LCOE is increased from 0.05701 to 0.05705 $/kWh.

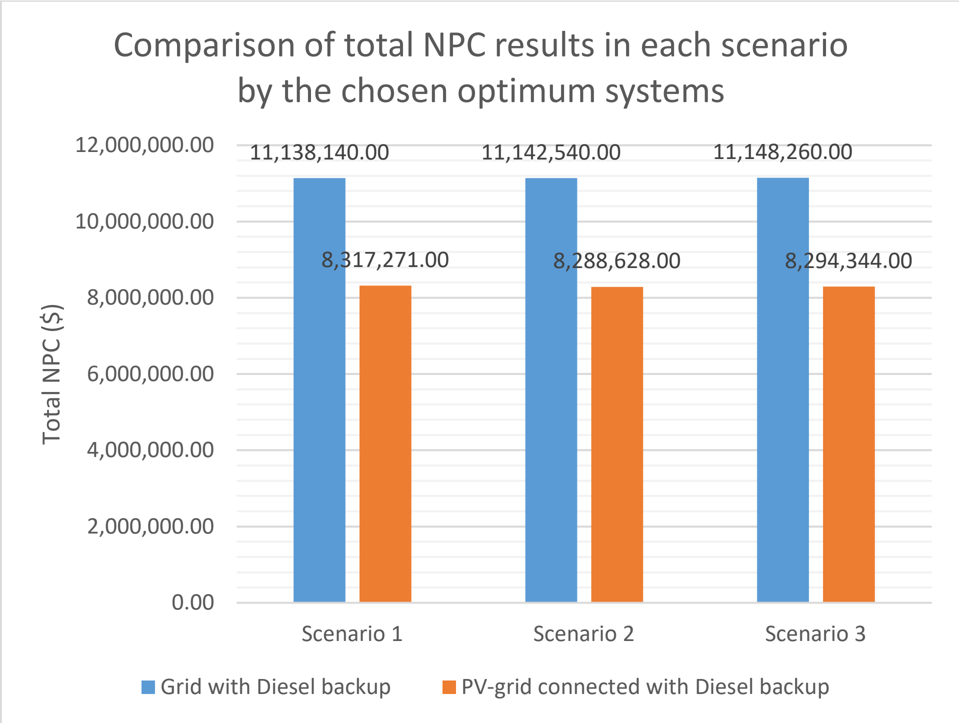


Fig. 6-49. Comparison of total NPC results in each scenario by the chosen optimum systems

The best total NPC for the grid-connected PV system and grid-diesel system in all scenarios are provided in Fig. 6-49. It is obvious that in all scenarios the PV system gives the lowest total NPC. The reduction in total NPC due to using the PV varies from 25.33% to 25.61% compared to the grid-diesel system. Also, the scenario two provides the best total NPC for the PV system among the other scenarios due to the same reason as mentioned above that the dependency on the diesel and the grid is less.

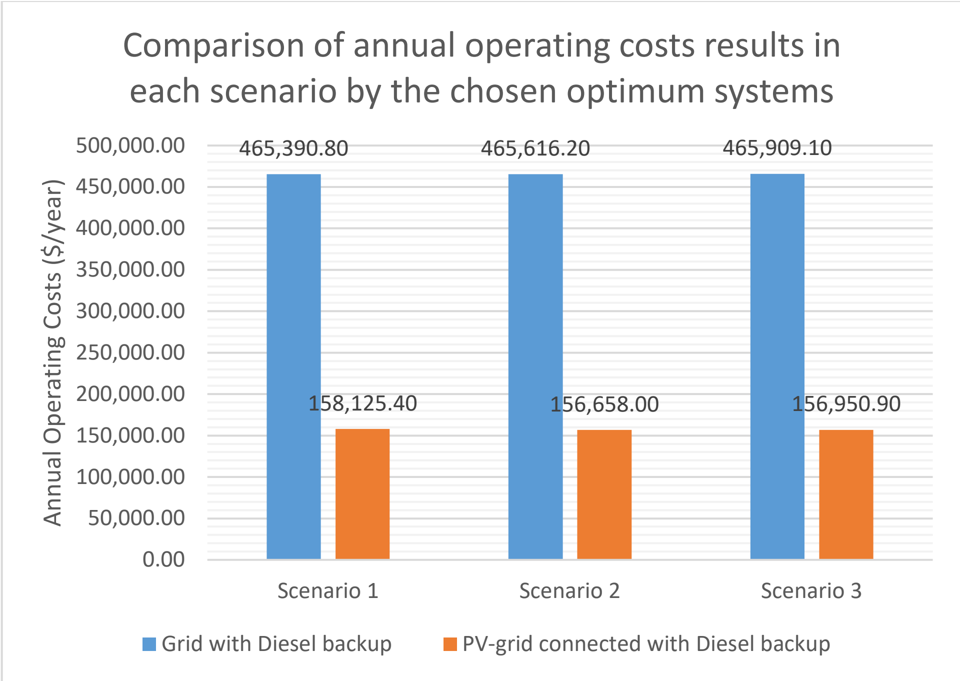


Fig. 6-50. Comparison of annual operating costs results in each scenario by the chosen optimum systems

Annual operating cost is another important economic factor in decision making for choosing the most economic system. Fig. 6-50 displays the comparison between the optimum systems chosen from the grid-connected PV with diesel backup and the existing system in the building of the hospital with regards of the annual operating costs. Noticeably, the grid-connected PV systems are outweighing the grid-diesel backup generator by percentage ranges from 66.02% to 66.36% of reduction in annual costs. This is a huge reduction in annual costs; and hence, this is a huge cost saving.

6.5. Comparison of optimum systems with regards of Environment

The same optimum systems, which are considered to be compared with regards to the three economic factors, are also taken into account for another comparison with respect of environmental aspects. In this comparison, three main emissions are taken into consideration to be used to identify the most environmentally friendly system which are Carbon dioxide (CO_2), Sulphur dioxide (SO_2), Nitrogen oxides (NO_x) as mentioned in Chapter 5. In addition, the total costs of these emissions is going to be analysed.

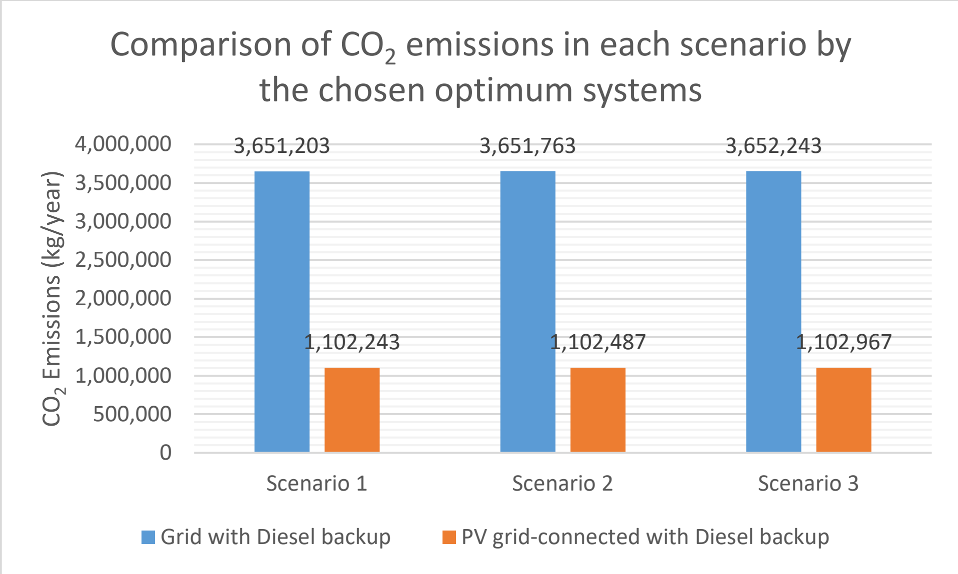


Fig. 6-51. Comparison of CO_2 emissions in each scenario by the chosen optimum systems

Fig. 6-51 illustrates the huge difference results of emitting the CO_2 from both systems as the system that does not involve PVs provides a huge amount of this gas. The difference in emitting CO_2 in both systems is varying from 2,548,960 kg/year to 2,549,276 kg/year. Surprisingly, in scenario two and three the difference in the amount of CO_2 emissions between both systems are the same (2,549,276 kg/year), this is due to the increase of the usage of the diesel generator to support the load during the power outage occurring in scenario three in the grid-connected PV system. As a result, this reduction of CO_2 emissions is providing a massive saving for the environment.

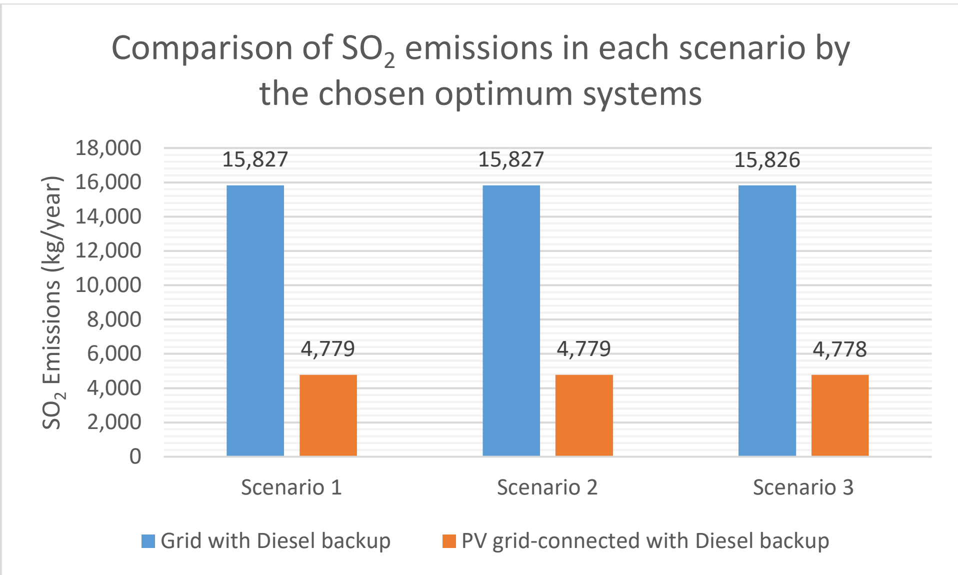


Fig. 6-52. Comparison of SO_2 emissions in each scenario by the chosen optimum systems

As can be seen in Fig. 6-52, the amount of SO_2 emission from both systems is much less than the CO_2 emission, but it is still considerably high and is affecting the environment. Comparing both systems with respects of this gas shows that the system involving the PV is a significantly saver for the environment. This is because the grid-connected PV system results in dropping the SO_2 emissions to 69.81% in all scenarios. It is quite surprising that this gas emission is decreasing as the grid is not operating even though the utilisation of the diesel generator increases. This indicates that this gas is more emitted from the grid which by including the PVs will be a great way to reduce it.

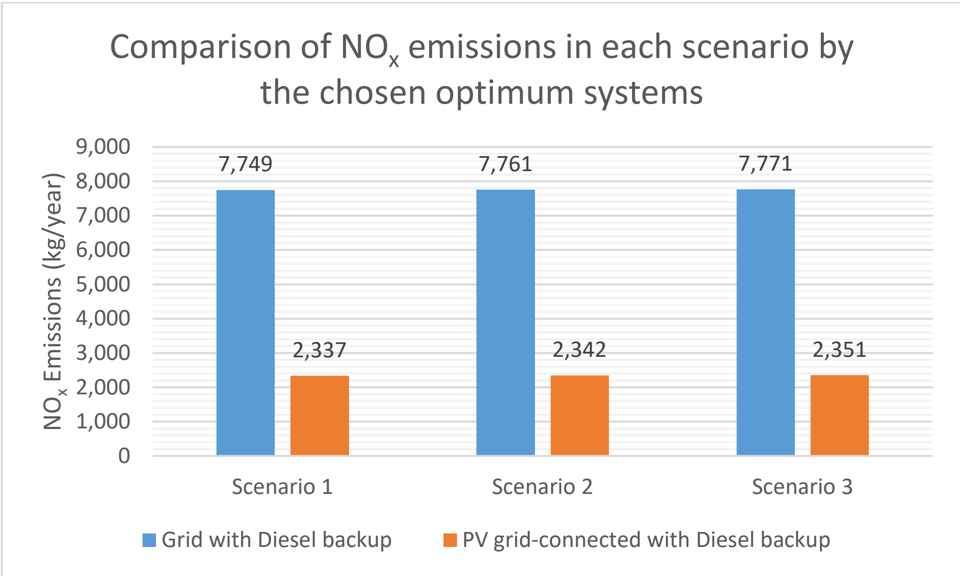


Fig. 6-53. Comparison of NO_x emissions in each scenario by the chosen optimum systems

In Fig. 6-53, a comparison of the emitted NO_x between the two systems in each scenario is demonstrated. It is very clear that the grid-connected PV system outweighs the grid-diesel system in the lower production of this gas in overall. Scenario one shows the lowest amount of NO_x for both systems as the operating of the diesel generator is very minimal in this scenario. Notwithstanding, as the dependency on the diesel rises for both systems, this gives more opportunity for this gas to be released more. This is displayed in the figure, Fig. 6-53, as for the grid-diesel system, it increases from 7,749 kg/year to 7,771 kg/year and for the grid-connected PV system, it arises from 2,337 to 2,351 kg/year, from scenario one to three. However, it is still that the inclusion of the PVs is evidently significant in the aim of reducing such gases like NO_x as shown in this figure.

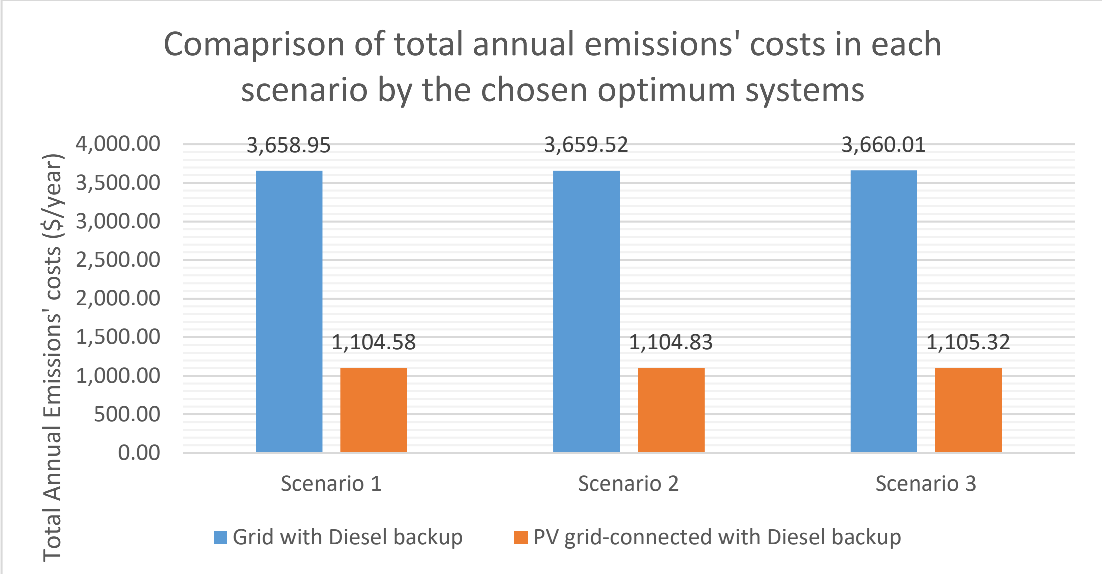


Fig. 6-54. Comparison of total annual emissions' costs in each scenario by the chosen optimum systems

These emissions are increasing the overall costs of both systems, and more specifically rising the other O&M costs of the systems. It is assumed in this study that each of these three emissions are costing the systems 1 $/tonne as mentioned in Chapter 5. The total costs of these emissions are calculated for all the scenarios to be compared as in Fig. 6-54. As illustrated in the figure, the difference between the existing system and the grid-connected PV system is 69.81% (2,565.42 $/year) in scenario one, 69.81% (2,565.74 $/year) in scenario two and 69.80% (2,565.74 $/year) in scenario three. The difference in costs between the systems are almost identical in all scenarios, due to the operations of the diesel generators in both systems. Not to forget that the assumption made is low in cost; hence, if the costs of these emissions was higher like just 10 $/tonne, the other O&M costs will rapidly increase which in overall will affect the systems costs.

6.6. Summary

To summarise, the existing power generation system is tested under three scenarios of grid power outages to better understand and evaluate the effect of these outages as well as to show how the PVs possibly assist in improving the system in terms of reducing the air pollutants and minimising the costs. To add, the same scenarios have been applied to the proposed grid-connected PV system, and an additional sensitive analysis of having three different sellback rates applied. From these analyses, in the grid with diesel backup generator system, the first scenario provides the most cost-effective system with LCOE of 0.09878 $/kWh, total NPC $11,138,140.00 and annual operating costs of 465,390.80 $/year.

Nevertheless, in the proposed grid-connected PV system, the second scenario contributes in having the optimum techno-economic system in this case. The LCOE, total NPC and annual operating costs are 0.05701 $/kWh, $8, 288, 628.00 and 156, 658.00 $/year, respectively for the grid-connected PV system. Besides, the ML strategy shows better results than the ones by the CC strategy. Consequently, the ML strategy provides optimised results compared with the CC strategy by HOMER. Furthermore, the two comparisons with regards economics and environment between the optimum systems of the existing system and the proposed system display that the grid-connected PV system is superior as it reduces the economic system costs and the emissions.

7. Conclusion and Future work

7.1. Conclusion

Utilising PVs in the building of the hospital for the selected location in Dammam is a feasible solution based on the carried-out analysis by HOMER with the customised ML strategy despite the grid power interruptions. This analysis shows that the grid-connected PV system provides lower system costs in all three scenarios of grid power interruptions considered in this thesis. Besides, the customised ML strategy provided the optimum results in all the simulations in HOMER for the grid-connected PV system and the exact same results as the cycle charging strategy by HOMER for the grid with diesel backup generator. Moreover, for the grid-connected PV system case, another three sensitive analyses are added which are three different sellback rates to the grid due to the fact that the PVs can produce energy that is more than the load required by the system. As a result, the sellback rate that is higher than the grid energy price by 5% yield the optimum solution for the system in all three scenarios.

The economics of the existing system (grid with backup diesel generator) for the building using both ML strategy and CC strategy are presented and discussed. The results show that as the frequency of grid power outage increases, the overall system costs increases proportionally. Therefore, the less power outage frequency, the more economical the system becomes. Based on that, the first scenario (once per year power interruption) for this system gives the most cost-effective situation with LCOE of 0.09878 $/kWh, total NPC of $11,138,140.00 and annual operating costs of 465,390.00 $/year. Nevertheless, the grid-connected PV system in all scenarios with the sellback rate of 5% higher than the grid energy price are more economical than the existing system. The economic results of the grid-connected PV system are attained by ML strategy as it produces the optimum results. Interestingly, the second scenario (twice per year power interruptions) among the other scenarios results in the optimum solution for this grid-connected PV system as the LCOE, total NPC and annual operating costs are 0.05701 $/kWh, $8,288,628.00, 156,658.00 $/year in this order.

A comparison between the existing system and the optimum situation for the grid-connected PV system in all three scenarios is conducted with regards to the main three economic aspects (LCOE, total NPC and annual operating costs). In regard to the economics, the grid-connected PV system outweighs the existing system as it reduces the LCOE with a percentage from 42.09% to 42.31%, and the scenario that results in the lowest LCOE is the second scenario. To add, the proposed system results in lowering the total NPC with minimum of 25.33% to a maximum reduction of 25.61% in the second scenario. Furthermore, the operating costs of the grid-connected PV system are 66.02% lower than the existing system at minimum and at maximum in the second scenario with 66.35% drop. In terms of the pollutants, the proposed system reduces all emissions with a minimum percentage of 69.75% and with maximum of 69.84%.

Another comparison between the existing system and the optimum situation for the grid-connected PV system in all three scenarios is conducted with regards to the considered three emissions (CO_2, SO_2 and NO_x). The scenarios one and two result in the highest reduction of CO_2 with 69.81%, and the scenario one results in the highest decrease of NO_x with 69.84%. However, for the SO_2, the grid-connected PV system results in an equal amount of percentage drop with 69.81% in all three scenarios. Even though the grid-connected PV system reduces the pollutants in general, the results display that each time the power interruptions increase, the CO_2 and NO_x emissions increase; while the SO_2 drops when the power outages become more frequent.

7.2. Future work

This thesis research is conducted to investigate the feasibility of the grid-connected PV system while optimising this system by customised ML strategy in HOMER. Also, it takes into consideration the impacts of the power interruption frequencies of the grid in Saudi Arabia which aids in more realistic estimations of the system costs as well as the diverse sellback rates to the grid. Nevertheless, based on this study, a future work can be carried-out considering different aspects that are not included in this thesis. Some of these aspects are listed below:

a. To obtain load profile data of one of the cities in South and West of Saudi Arabia due to more power interruption frequencies of the grid and longer duration of these outages in South and West of Saudi Arabia.
b. To consider analysing off-grid PV system for any chosen city with higher outages to assess the feasibility of supplying the load without the grid.
c. To consider adding another suitable renewable energy in addition to the solar energy to support load at night when there is no sun depending on the location of the chosen city.
d. To consider storage systems for backup other than diesel generator like batteries or fuel cells (FC).

e. To apply economic dispatch through MATLAB in order to minimise system costs if HOMER Pro can develop their software to enable users to use quadratic fuel curve with the ability of defining the variables of the quadratic equation for the curve.
f. To consider a recent software that is released by the same company called HOMER Grid if the system is grid-connected as this new software focuses on all systems that are connected to the grid.

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