APPLYING A PV GRID-TIED SYSTEM IN INDUSTRIAL SECTOR WITH PAYBACK REDUCTION: A CASE STUDY IN K.S.A.

by

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Dedicated

To my family & my parents

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ABSTRACT

The key to creating clean energy is to use renewable energy sources. Saudi Arabia has an abundance of solar radiation due to its geographical location; therefore, solar energy applications provide excellent opportunities for generating electricity in the region. Since 1960, Saudi Arabia has examined potential photovoltaic (PV) applications however, the progress towards implementing a solar energy program has not been sufficient. In Saudi Arabia, the industrial sector consumes a large portion of the power load demand. The biggest industrial cities in Saudi Arabia are Dammam, Al-Jubile, Jeddah, and Riyadh. This study examines the potential application of solar energy through a PV system in the Saudi Arabian industrial sector. The research seeks to examine whether a PV system combined with a grid system could be feasible to apply in the country. To examine this, a typical energy consumption daily profile is assumed. The study uses an existing factory in the city of Jeddah for simulation. HOMER and Microsoft Excel are used to carry out the study. Furthermore, the economic reliability and feasibility of the examined results will be included. Finally ways to reduce the payback time was investigated and a cost effective system is recommended.

*Index Term*s – *Industrial area, Saudi Arabia, Solar system, PV system, Renewable energy.*

LIST OF ABBREVIATIONS AND SYMBOLS USED

PV	Photovoltaic
a-Si	Amorphous Silicon
FIT	Feed-in-Tariff
GSR	Global Solar Radiation
GOIC	Gulf Organization for Industrial Consulting
KACST	King Abdulaziz City for Science and Technology
RETscreen	Renewable Energy Technology Screen
HOMER	Hybrid Optimization Model for Electric Renewable
i	The Discount Rate
CRF	The Capital Recovery Factor
NPC	Net Present Cost
COE	Cost of Energy
P	Present Worth
F	Future Worth
LCC	Life Cycle Cost
LEC	Levelized Energy Cost
E	The Annual Energy
IRR	Internal Rate of Return
PB	Payback Period

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CHAPTER 1 INTRODUCTION

1.1 General

The Kingdom of Saudi Arabia (KSA) is blessed with an abundance of energy resources. KSA currently holds the largest oil reserve in the world and is also rich in gas reserves, and has great potential for wind and solar energy. KSA is currently the world's 20th largest producer and consumer of electricity. The country's geographical location includes a photovoltaic (PV) area of 22 – 40 km^2 and can produce as much electricity as a 1000 MWe oil-fired power station. This advantage can potentially make electricity generated from PV systems more competitive than electricity generated from oil-fired power generation [1].

1.2 Motivation

The present peak electrical load in KSA is 120 times greater than it was 35 years ago, with an increase in utility consumers that is 15 times larger than it was in the 1970s [2]. Figure (1-1) shows the increase in peak load over the last few years in Saudi Arabia.

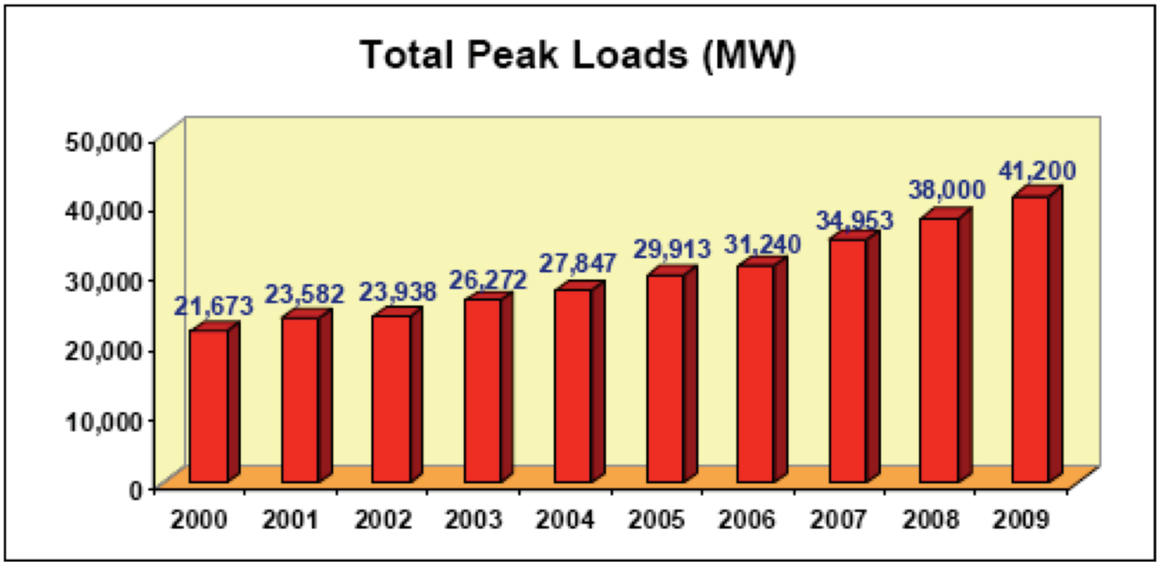


Figure (1-1): Peak load in Saudi Arabia [3]

The fast growing population, high economic growth, and low utility tariffs are some of the many factors playing a role in and fueling this increase in power demand. In addition to the increasing population and increase in the power utility consumers, KSA needs to expand its electronic power transmission network and generation capability to support its motivated industrialization plan [2].

Following residential load, the industrial sector is the highest consumption sector in Saudi Arabia. The industrial sector industries in Saudi Arabia consist of petrochemicals, oil refining, steel and iron, cement and other industries. The average growth rate in the industrial sector is 4.3%. In 2008 the energy consumption of the industrial sector in Saudi Arabia reached 150 TWh [1]. Present reports confirm the industrial sector is currently consuming 18% of the country's total energy consumption [4].

Jeddah is one of the cities facing a current overload in industrial power demands. The Saudi electricity utility recently informed industries that it might need to cut back on the amount of power supplied to the industrial sector during peak hours. The government has reported that this decrease will help avoid any massive power outages in the city. A power reduction in the industrial sector will not only affect business, but it could potentially cause damage to certain machinery used in the sector. This alarming issue has motivated the industrial sector to develop a solution [5].

1.3 Objective

The main goal of this thesis is to find a renewable energy solution by supplementing the grid source with a PV system and potentially selling any excess power generated by the PV system back to the grid during peak hours. An economic study of the cost and economic payback will determine if the application of this method is cost effective and efficient.

1.4 Thesis Outline

This thesis will begin with a brief discussion of the nature of solar energy and PV systems in Chapter 2. Some general definitions and terms will also be discussed in this chapter.

Chapter three will deal with weather conditions in Saudi Arabia and present the climatic reasons that make Saudi Arabia's geographic location optimal for the application of solar energy.

Chapter four will present the methodology used to generate the optimal application methods and will discuss the use of HOMER, Excel, and economic calculations used to support the results.

Chapter five will present the results and a brief discussion of the optimal solution. Chapter six will offer a brief conclusion and will suggest some future work that could be applied to further develop the application of solar energy in KSA.

CHAPTER 2: SOLAR ENERGY

This chapter presents a literature review intended to provide a background understanding of the concepts of PV systems and PV system types. A short background to solar energy and the types of solar systems is also provided.

2.1 Solar Energy

The history of solar energy technology dates back to more than one hundred and fifty years ago. The term solar energy refers to any source of energy that is directly obtained from sunlight or the heat that the sunlight generates. Solar energy is a renewable source of energy.

Technology to exploit solar energy has been developed since 1860. At that time, solar energy was used to capture the sun's heat and generate steam, which would enable activities like running engines and irrigation pumps. This technology has recently undergone a drastic growth. The direct consequence has been relevant cost reductions for the use of solar energy. There has also been an increase in government support to implement solar energy due to its renewable nature and the fact that it is environmentally-friendly [6].

Reaching up to 0.06W/m^2 of irradiance on the earth's surface at the highest latitudes and 0.25kW/m^2 at the lowest, solar energy represents by far the largest source of renewable energy known today [6].

The following subsections explain a classification of the various solar energy technologies.

2.1.1 Solar Thermal System

To generate solar thermal power, the sun is exploited as a source of heat. The heat is concentrated and used to generate power by means of a heat engine. This method reflects the traditional forms of power generation, which are based on fossil-fuel combustion and which also generate electrical energy from the heat produced by the heat engine. Currently, the technologies employed to produce solar thermal power are categorized in a) parabolic trough systems, b) solar tower systems, and c) solar dish systems. The distinction is based on the way these systems concentrate solar radiation [7].

2.1.2 Solar Photovoltaic Technology (PV)

The term “photovoltaic” is composed of the words “photo”, which stems from the Greek “light”, and “voltaic”, which indicates electricity. The purpose of PV is to convert sunlight directly into electricity, with an efficiency that currently reaches to 12-19% when the conditions are best [8, 9]. PV use is very common in houses, residential or commercial buildings, telecommunication industries, work in rural areas, etc. This source of electrical power was considered after the 1973 fuel crisis [10].

Current predictions indicating an upcoming shortage in gasoline and petroleum has increased interest in PV technology. Consequently, this alternative form of energy conversion has become a crucial element in most renewable energy programs [10]. PV modules are becoming more present on roofs and facades [11] in developed countries.

The following section will discuss the ways that solar PV technology has recently begun to grow and has attracted international government support, turning it into a non-renounceable component of the 21st century energy mix.

2.2 Solar Photovoltaic Technology (PV)

The term photovoltaic applies to all devices or materials that, through the smallest complete and environmentally protected assembly of connected solar cells, are able to convert the energy contained in photons of light into electrical voltage [12]. As a future energy technology, PV has the advantage of producing electricity silently without producing harmful waste products [10]. Their convenience also lies in the fact that they require very little maintenance, given the absence of moving parts wearing down the device. This enables them to operate for many years on end. Their modularity allows producers to obtain generators of any size or voltage by assembling varying numbers of standard modules. This assembly is built to convert solar energy into electricity for some specific purposes. The latter are met either alone or in combination with further energy suppliers. Solar cells play a critical role in the conversion of solar energy into electrical energy [13].

2.2.1 Solar Cells

Solar cells are semiconductor devices generating electricity exactly the moment light falls on them [8]. Solar cells can also be called photovoltaic cells. Currently, PV devices are generated starting from pure crystalline silicon, although their main technology is closely related to the technology used to produce transistors, diodes, and all the semiconductor devices widely used nowadays in the world [12]. As shown in Figure (2-1), the atomic number for silicon is 14, with each atom having 14 negatively charged electrons orbiting around a positively charged nucleus. Only ten of these electrons revolve tightly against the nucleus, whereas the remaining four, which are not tightly bound to it, are the ones playing the crucial role in PV systems. This bond can in fact be broken if sufficiently jolted by an external source of heat or light [14]. Silicon is not an insulator (like glass) or a conductor (like copper); silicon stands in the middle between the two.

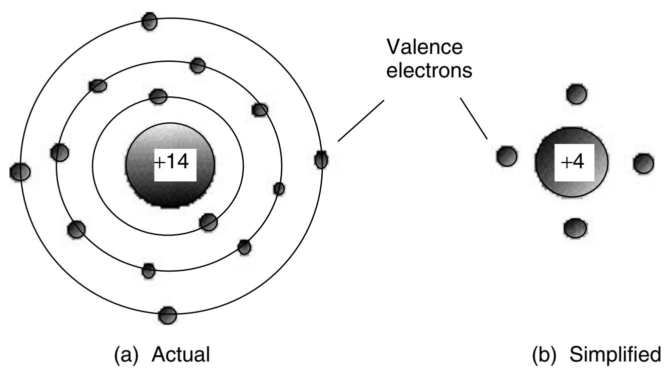


Figure (2-1) Silicon atoms [12]

However, a single and pure silicon wafer will never produce electricity, even if placed in strong and direct sunlight. It is necessary for it to be connected to a mechanism propelling electrons and holes in opposing directions in the crystal lattice. The current therefore produces power by being forced through an external circuit. The mechanism mentioned above is provided by the semiconductor p-n junction [14]. In order to make the latter, the cell, which has two layers of silicon, has its layers doped with impure atoms. Phosphorus is often added since, when doped with silicon, it generates a large number of free atoms. These are known as majority carriers. Minority carriers are also present in the shape of thermal-generated electron-hole pairs. This material makes an excellent conductor and is mentioned as negative type, or n-type. If the silicon is doped with boron, then other holes are created from broken bonds into the crystal; the situation is reversed with respect to phosphorus, and the holes become the majority carriers while the electrons are the minority carriers. This type of conductor is referred to as n–type, or p-type [15].

While the doped material gathers to form a p-n junction and the free electrons that are in the n-type material diffuse into the p-side, the hole in p-type diffuses in the n-side. By doing this, they respectively leave behind two layers that are positively and negatively charged. This diffusion of the materials in opposite directions across the interface is what creates a strong electric field representing a potential barrier to further flow. The diffusion continues until the electrons and holes come to a condition of balance; when this occurs, charge carriers are no longer close to the junction, but they form what is called "depletion region" as shown in Figure (2-2) [15].

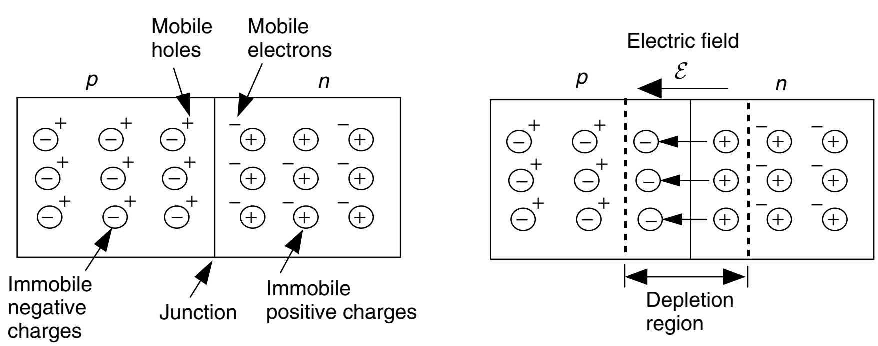


Figure (2-2): The depletion region [12]

At this point, the current flows in one direction because the p-n junction in the depletion region acts like a diode. The electrons use the energy coming from the sun, in the form of packets of energy termed *photons*, to free themselves from their nucleus. Hitting the solar cell, the photons are powerful enough to create hole-electron pairs and the resulting voltage will deliver the current to the load as shown in Figure (2-3) [12].

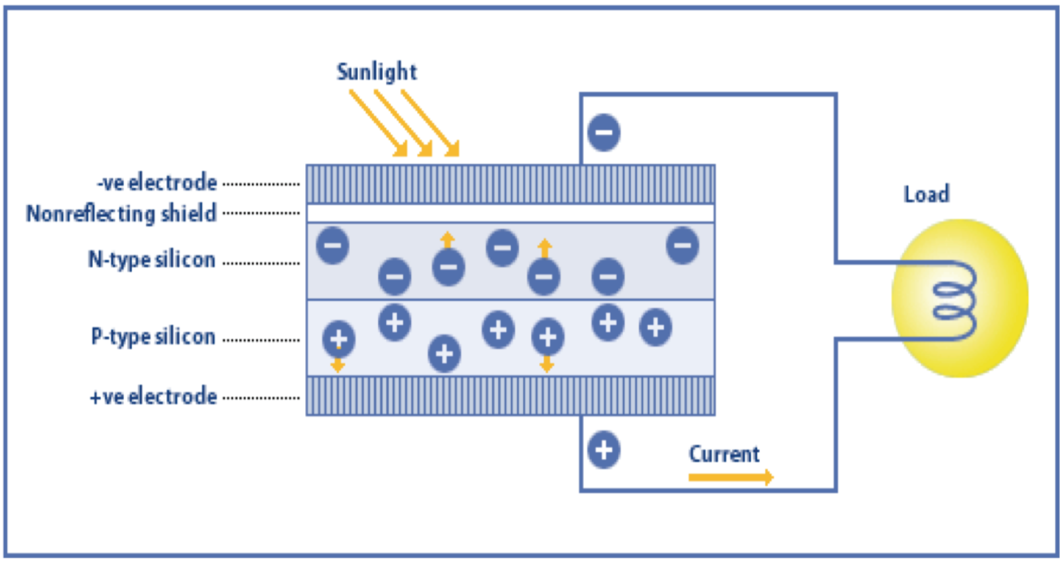


Figure (2-3): Photovoltaic system [16]

The former amounts to the percentage of solar radiation converting into electric energy; the latter, instead, is usually lower than the cell efficiency because the module also includes the frame and its surface cannot be fully covered with solar cells. The highest efficiency for crystalline silicon cells is obtained when they operate in strong sunlight [15].

Crystal silicon solar cells in the current high volume production can be divided into three types:

2.2.1.1 Monocrystalline Silicon

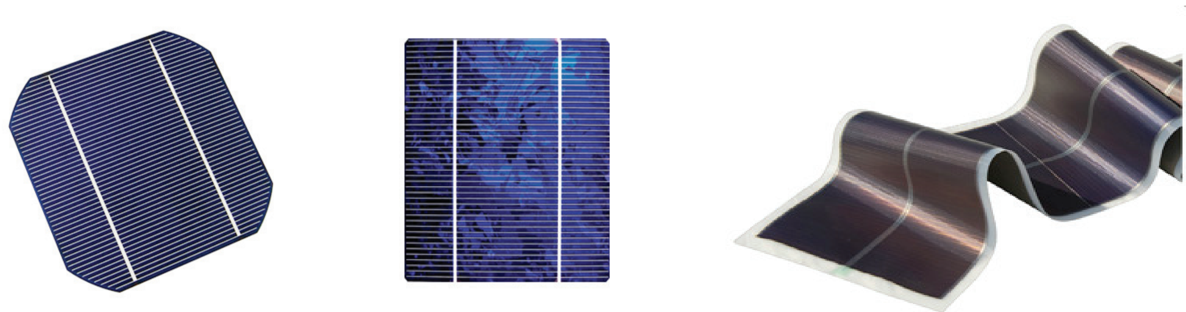
Monocrystalline silicon, also known as single-crystal silicon, is the most common solar cell semiconductor and the most promising in terms of high efficiency performance, as shown in Figure (2-4 a). The highly efficient performance is a result of the abundance of the material itself. The superior optical absorption coefficient makes it optimal for thin film solar cells, with a cell thickness of < 1/xm. Its low costs are also widely advantageous. Its low raw material requirements and low production energy requirements provide cost-effective fabrication. Particularly, cost efficiency is what modeled solar cells research toward developing single crystal ribbon silicon, which is also higher in quality. Today in fact, the best single crystal Si solar cells can provide 24.7% efficiency in the laboratory, while the conversion efficiency of commercial solar cell modules only reaches up to 18% [8].

2.2.1.2 Polycrystalline Silicon

Unlike Monocrystalline silicon, polycrystalline cells consist of small particles of single-crystal silicon as shown in Figure (2-4b). Polycrystalline PV cells are less efficient than monocrystalline silicon with a lower (10-14%) energy conversion efficiency. This occurs due to the flow of electrons being huddled by the grain boundaries; thus the cell power output is inevitably reduced. Differing approaches are nowadays commonly employed to produce polycrystalline silicon PV cells. One is to cut thin slices off blocks of cast polycrystalline silicon, or to directly grow silicon as ribbons ("ribbon growth" method) that are thick enough to make PV cells. EFG (the edge-defined film-fed growth) is the most common and best developed "ribbon growth" approach. Polycrystalline silicon has the advantage, unlike single-crystalline silicon, of being strong enough to be sliced into one-third the thickness of single-crystalline silicon, with lower costs and fewer growth requirements than single-crystal modules [8].

2.2.1.3 Amorphous Silicon (a-Si)

Amorphous silicon was discovered in 1974. The main characteristic of this non-crystalline form of silicon is the disorderly structure of its atoms. PV modules produced with this type of silicon were the first with a thin film produced at a commercial level as shown in Figure (2-4 c). Currently, amorphous silicon provides the only thin film technology casting a solid influence on PV markets. Its high sunlight absorbability being 40 times higher than that of single-crystal silicon represents its primary advantage. In other words, using one thin layer of amorphous silicon it is possible to produce PV cells that are 200 times thinner than those obtained with crystalline silicon (1μm compared with 200 μm). Another remarkable advantage is the possibility of placing a-Si on low-cost substrates made of steel, glass, and plastic due to the much lower temperatures necessary for the manufacturing process. As a result, lower costs per unit area make a-Si significantly more convenient than producing crystalline silicon cells [8].



a: Moncrystalline silicon[17]. b:Polycrystalline silicon [18]. c:Amorphous silicon[19].

Figure (2-4): Types of crystalline silicon solar cells

2.3 Classification of PV Systems

Photovoltaic systems can be generally classified into two main categories:

2.3.1 Stand-Alone or Off-Grid System

In this self-contained and cost-effective system, PV energy is converted to AC power without being connected to a utility grid. This is a characteristic of all off-grid systems. Off-grid systems have an inverter that regulates the AC voltage to all the loads. Most stand-alone PV systems also require batteries to store the produced energy. This is necessary since PVs can provide power during the daylight hours only. Energy storage is thus required when the sun is not shining [12]. A charge controller prevents battery overcharging and excess discharging, regulating the current that flows into the battery bank from the PV array and then into the various electrical loads. While overcharging is prevented by disconnecting the PV input whenever the battery voltage comes to an upper set point, excess discharge can be avoided by simply disconnecting the load. It is also possible to give a warning when the voltage falls to a lower set level [20]. In Figure (2-5) the constituent elements of the system are a PV module, a controller, an inverter, and a battery [21].

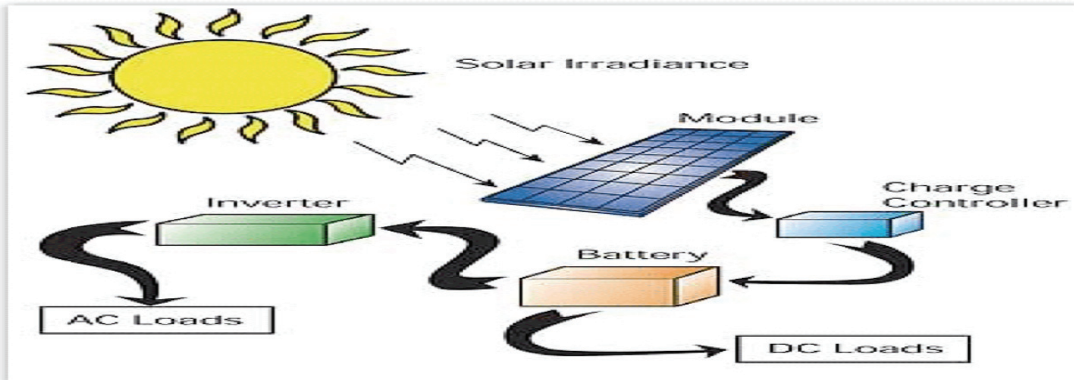


Figure (2-5): Stand-alone system [22]

2.3.2 Grid-Connected or Grid-Tied System

Unlike off-grid systems, grid-tied systems have the power sent directly into the utility grid if the system does not require power. The electricity automatically flows back and forth according to electricity demands and sunlight conductions. In this system, the PV array can be mounted on a pole or attached to the roof; it can also become an integral part of the skin used in the bulling structure [20]. By the beginning of 2000, grid-tied systems were substituted for stand-alone systems while 95% of solar cell production was being arranged in grid-tied systems by 2009. The size is measured in Kilowatts for residential systems, hundreds of Kilowatts for industrial systems (with an average size of 500KW, which grew after 2008), and Megawatts for utility power [21]. Figure (2-6) shows a diagram of a grid-tied system used in industrial system.

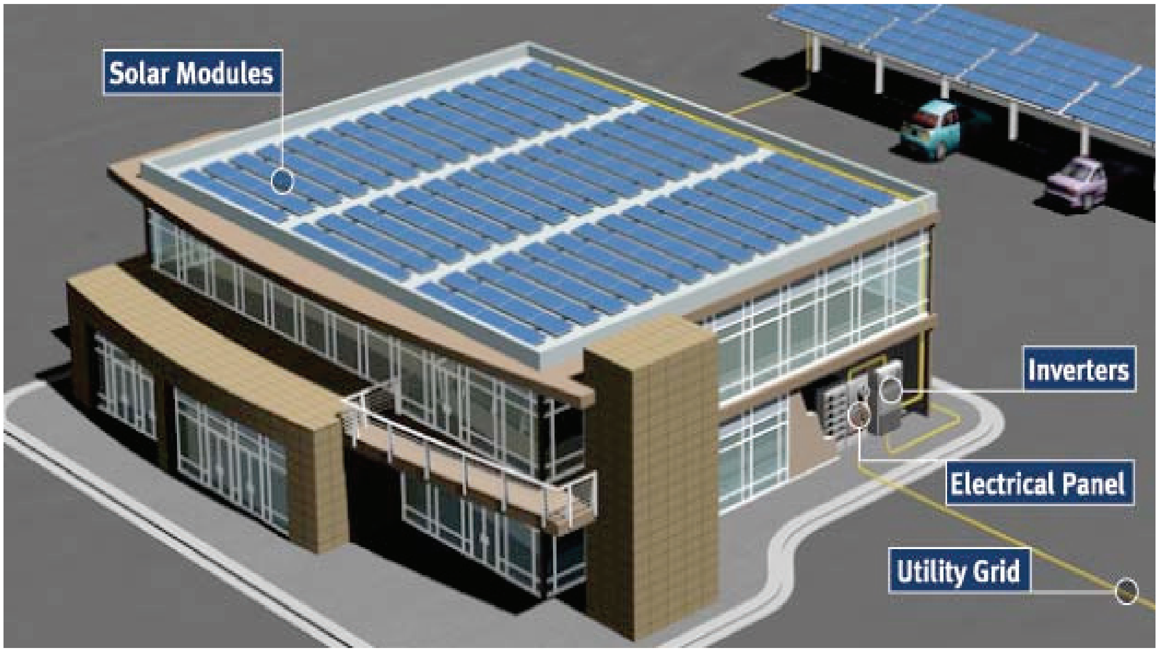


Figure (2-6): Grid-tied system [23]

2.3.3 Typical System Components

2.3.3.1 PV Array

As shown in Figure (2-7) a PV array is a series of modules, or an environmentally sealed series of PV cells, that are often attached in sets of four or smaller modules to form what is called a panel. While a PV array commonly weighs about 10-20 kg/m2 and measures 1-3 m2 in size, a panel usually has an area of 2-4 m2. This makes it easier to handle on a roof, while other installations and wiring can be done on the ground, if required [20].

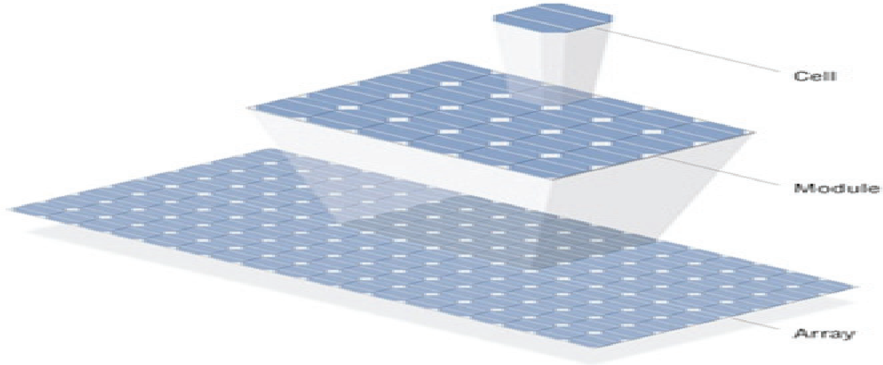


Figure (2-7): Components of PV array [24]

2.3.3.2 PV Combiner Unit

A PV combiner unit is a junction box that connects all the modules according to any desired order or configuration [20].

2.3.3.3 Protection Unit

A DC switch is included in the protection unit; it isolates the PV array and the anti-surge devices in order to guarantee protection against lightning surges [20].

2.3.3.4 Fuse Box

The fuse box used is of the common type that is usually provided with a domestic electricity supply [20].

2.3.3.4 Inverter

This element is essential in converting the DC electricity obtained through a PV array into AC electricity. The inverter is one of the most important components in the grid-tied system; its advanced electronics enable it to produce AC power at the right frequency and voltage. In this way, the AC power matches the grid in all grid-tied systems. There are four types of converter, and they are generally classified according to their use: central, string, multi-string, and individual. The central inverter can go well beyond 1MWp capacity, weighing over 20 tons [20].

2.3.3.5 Junction Box

The junction box is used to connect the building to the utility supply cable [20].

2.3.3.6 Energy-Flow Metering

This system employs KWh meters to record and measure the flow of electricity travelling to and from the grid. Some of these meters can also indicate industry energy usage [20].

2.3.3.7 Balance of System Equipment (BOS)

BOS connects the PV modules to the structural and electrical systems of a house or building through a series of wires and mounting equipment [20].

Chapter 3 USING SOLAR ENERGY IN SAUDI ARABIA

This chapter provides a summary about the potential use and application of solar energy in Saudi Arabia.

3.1 Saudi Arabia's Location

Due to its geographical and climatic conditions, Saudi Arabia is one of the countries where solar energy can be most satisfactorily employed.

Located in the Middle East, between the Persian Gulf and the Red Sea, Saudi Arabia is the largest country in the Arabian Peninsula [25]. Its total area measures 1,960,582 Km2 (one-fifth of the United States), going from 31°N and 17.5°N latitude, and 50°E and 36.6°E longitude. Also its broad span of elevations, ranging from 0 to 2,600 m above sea level, makes it one of the world's most productive solar regions [26]. Saudi Arabia receives powerful and direct sunlight, with an average annual solar radiation of about 2,200 kWh/m^2 as shown in Figure (3-1). Moreover, the country's large swaths of land (1.4% of the total land) make it perfectly suitable to host thousands of Km^2 of solar panels. Sun harvesting thus becomes a profitable and potentially efficient source of energy [27].

During the year, Saud Arabia mainly alternates between two seasons, summer and winter. Saudi Arabia has a dry desert climate with wide temperature extremes and a scarcity of clouds. This provides Saudi Arabia with high insulation rates, intense solar radiation and long hours of sunshine exposure [25].

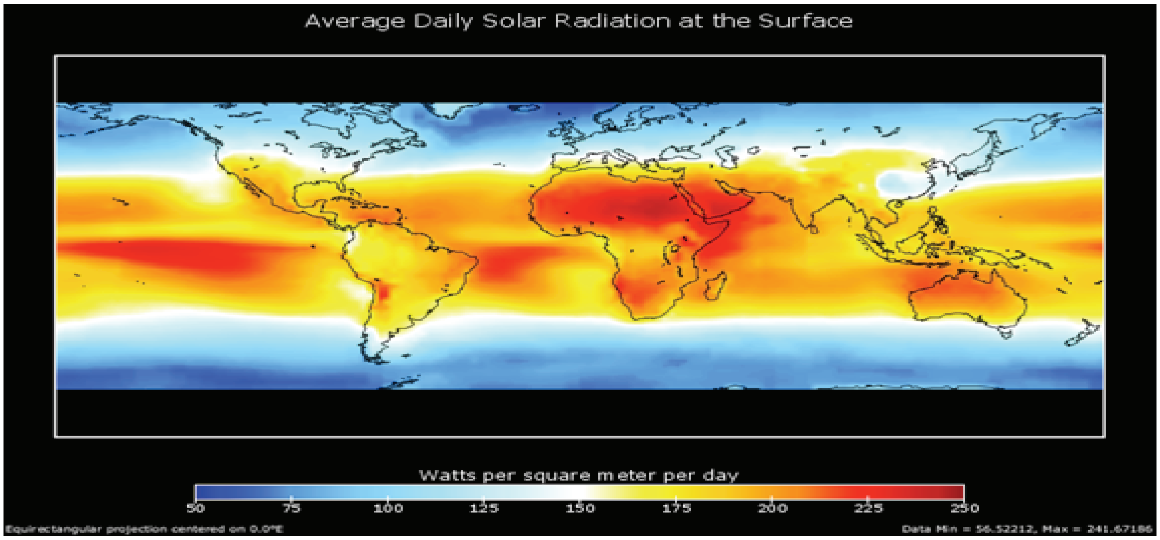


Figure (3-1): Average daily solar radiation [28]

3.2 Saudi Arabia and Solar Energy

Saudi Arabia holds many worldwide records in terms of natural resources: the world's largest oil reserves, the fourth largest gas reserves, and it is the 20^{th} largest producer and consumer of electricity. Wind and solar power are just two of the many resources with which this country has been endowed [29].

Another record held by KSA is the highest summer temperatures ever recorded on earth, due to its vicinity to the equator. The massive and powerful quantities of sunlight that fall on the Arabian Peninsula, where KAC is located produce up to 12,425 TWh; this amount of electricity would be adequate to power the whole country for 72 years [30].

3.3 Power Consumption in Saudi Arabia

Saudi Arabia has one of the highest growing populations in the world, with growth rates of 2.5-3%. Consequently, the growing need for electricity has become a crucial reality.

Power project developments have been increasing and almost 50% of all the ongoing power projects of the Gulf States are being implemented in the country. Due to the population growth rate and a growing industrial base, it is estimated that by 2020 Saudi Arabia will need up to 55,052 MW of power capacity. This amount is approximately twice the current production amount [31]. The residential sector consumes 53% of the country's produced power, the industrial sector consumes the second largest amount of power at 18%,, and the commercial sector consumes 12% [4].

According to Obaid and Mufti (2008) this rapid growth, which is expected to reach up to 60,000 MW within the next fifteen years, requires that power demand be met in new and innovative ways, with major steps being taken to meet the ever-growing demand [2].

3.4 Electricity Price (Tariff and Feed-in Tariff):

3.4.1 The Tariff

The electricity utility in Saudi Arabia has a new tariff depending on the consumer's sector (residential, commercial and industrial) as well as time of day and year.

In the industrial sector, the electric utility divided the factories into two groups depending on the value of load. First, factories whose load totaled less than 1000 KVA and then factories whose load totalled more than 1000KVA. However, each group was subjected to a different tariff depending on the time of the day and season. Table (3-1) shows the tariff for the factories that consume more than 1,000 KVA [32].

Table (3-1): Industrial sector tariff [32].

<table>
<tr><th colspan="2">Seasonal Tariff (EM Meter)</th><th colspan="5">TOU Tariff (digital meter)</th><th rowspan="2">Consumption Period</th></tr>
<tr><td>Tariff (halalah /kwh)</td><td>Consumption Hours</td><td>Tariff (halalah /kwh)</td><td colspan="4">Consumption Hours</td></tr>
<tr><td>14</td><td>All time</td><td>14</td><td colspan="4">All Time</td><td>OCT-APR</td></tr>
<tr><td rowspan="11">15</td><td rowspan="11">All</td><td rowspan="7">10</td><td colspan="4">Off peak Houre</td><td rowspan="11">MAY-SEP</td></tr>
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<tr><td colspan="4">Peak Hours</td></tr>
<tr><td>26</td><td colspan="2">Hours</td><td colspan="2">Day</td></tr>
<tr><td rowspan="2"></td><td>To</td><td>from</td><td>to</td><td>from</td></tr>
<tr><td>17:00</td><td>12:0 0</td><td>THU</td><td>SAT</td></tr>
<tr><td>15</td><td colspan="4">Other Hours</td></tr>
</table>

3.4.2 Feed-in-Tariff:

Feed-in-Tariff (FiT) refers to the top payment paid for new and renewable energy technologies and in turn is not cost effective when compared to current electrical technology generation. The FiT has allowed the potential growth and recognition for grid connected solar power. The logic behind this tariff is based not only on the cost of electricity produced, but also takes a return on investment for the organization producing it, in turn reducing the potential risks associated with investing in this new technology. This new FiT has already been implemented in many countries including Canada, Australia, Germany, Italy, and China. The application of FiT has exhibited particular success in Germany and Italy, where solar energy is more commonly applied. A currently published study evaluating renewable energy policies in EU countries reported the FiT to be the most successful way to promote the application of renewable energy sources [6].

3.5 The Industrial Sector in Saudi Arabia

As confirmed by the Secretary General of the Gulf Organization for Industrial Consulting (GOIC), the number of factories operating in Saudi Arabia has increased by 50%, from 3,118 factories in 2000 to 4,663 in 2010. This rise was followed by a proportional increase in the need for electric energy, demand for which passed from 114.2 million megawatt hours (2000) to 193.5 million megawatt hours (2009), which amounts to a 69% increase (6% annual growth rate). The authority in charge of the development of industrial cities, including their infrastructure and services, is MODON (Saudi Industrial Property Authority) which was created in 2001. After establishing a number of industrial cities throughout Saudi Arabian territory, MONDON is currently overseeing underdeveloped cities such as Riyadh (1, 2 and 3), Dammam (1, 2 and 3), Jeddah (1, 2 and 3), Makkah, Al-Ahssa', Najran, Qassim (1 and 2), Madinah, Al-Kharj, Hail, Tabuk, Ar'ar, Al-Jouf, Assir, Jazan, Al-Baha, Al-Zulfi, Sudair, Taif, Shaqraa, and Hafr Al-Baten. Other prospective industrial cities are Salwa, Dhuba, Nawan, military industries, and Jeddah (4). According to current estimates, 40 more cities with 160 million square meters of high industrial power demand will increase within the next five years, as illustrated in Figure (3-2). It is clear why Saudi Arabia can no longer postpone renovating a system to perfectly meet the new load demands. These are not only dictated by new and vast industrial areas scattered all across the Kingdom, but also by the rising population. It is extremely necessary to rely on independent and environmentally friendly sources of energy and Saudi Arabia is a country in which solar energy can be used extensively [33].

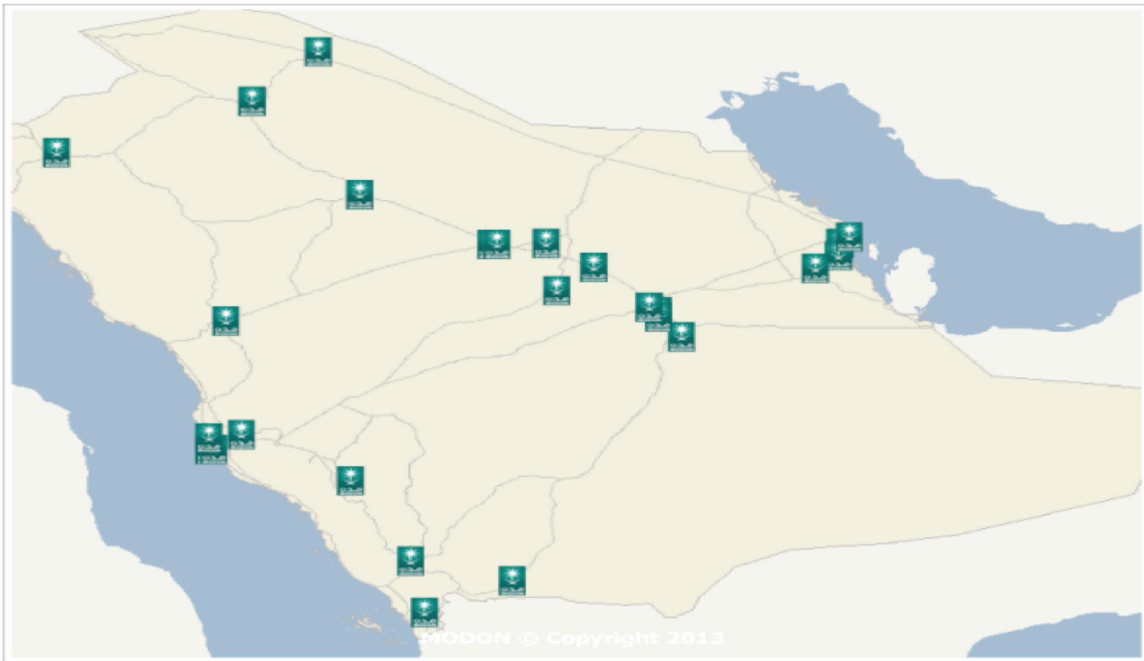


Figure (3-2): The industrial cities in Saudi Arabia [33]

3.6 PV System Applications in Saudi Arabia

The first PV beacon in Saudi Arabia was installed in the 1960s at the airport of Al-Madinah Al-Munnawara. Since then demand for renewable energy and solar energy applications have been increasing. It was at the end of the 1960s that research started to be conducted at the university level through small-scale projects. More systematic and major research targeting the development of solar energy began much later, in 1977, and was initiated by the King Abdulaziz City for Science and Technology (KACST). In 1977 Saudi Arabia and the United States signed an agreement for project cooperation in the solar energy domain. The agreement was named SOLERAS (Saudi Arabian-United States Program for Cooperation in the Field of Solar Energy) [26].

In January 1985, PV power systems began being part of the Saudi electricity network [26]. As reported by Kettani [34], the Arab world has shown a growing interest in PV conversion, running and funding university research programs and applications in the field. Kettani explained the factors that contributed to such a strong interest in PV, at the same time offering an overview of the research activity. Kettani also mentioned factors such as the "insulation factor" and the "remoteness factor" as having great importance in terms of economic attractiveness. These factors can determine whether a specific geographical location is suited to host PV applications [34].

Sayigh [35], on the other hand, mentioned the Saudi-American $100 million PV agreement (the SOLERAS) to point out the willingness of both countries to cooperate over a future of renewable energy production. In particular, he reported the objective of the five-year agreement was to improve the quality of rural life in Saudi Arabia. Solar systems represent the most important step in this direction. Sayigh deems the solar village in Saudi Arabia the biggest project of this kind in 1980 and its specific purpose was to increase the efficiency and environmental sustainability of electric power production in isolated communities, agriculture, and local industries. The availability of five PV villages in the Arab world also represented a relevant and meaningful project according to Sayigh [35].

Salim and Eugenio [36] reported the details of what in 1981 was the largest solar PV power system concentrator in the world with a performance of 350 kW. They provided information about its design, the fabrication and installation phases, including, in terms of performance, the glitches and failures that took place over a seven-year period. When installed in September 1981, the concentrator was the only one in operation in the world. Moreover, the system gave extremely satisfactory performances, meeting all of its design objectives. After many long-term applications, it was observed that large PV systems are also advantageous due to their minimum operation and maintenance requirements. Stand-alone and co-generation with diesel generators are two of the different modalities this system has been operated in. After being connected to the utility grid, the system was operated in peak power-tracking mode. Expectations for the near future include the capacity of the system to be directly coupled with a 350 kW electrolyze for the production of oxygen [36].

Alawaji *et al* [37] discussed the equipment of PV systems, analyzing their performance values and primary uses. They came to the conclusion that solar energy is the best way to power certain specific activities; and that solar energy is a good option to supply desalination plants and their equipment: submersible pumps, reverse osmosis unit, storage batteries, etc. Alawaji *et al.* consider this approach the most efficient due to the high insulation rate in Saudi Arabia [37].

Likewise, Alajlan and Smiai [38] discussed the design and development of the first PV plant in Saudi Arabia for desalination and water pumping practices in rural and remote areas of the country. The PV plant included two separate systems. The first pumped the water into two storage tanks, but without electricity storage. The second system dealt with the operations of reverse osmosis, or water desalination, which, along with the storage of electric energy, took place through batteries. The plant had a total installed PV capacity of 980 Wp and 10.89kWp for pumping and desalination respectively. The reverse osmosis unit produced a total amount of 600L/h. The submersible pump had its head 50m from the surface level [38].

Al-Harbi *et al*. [39] proposed and discussed two methods to turn solar energy into power. The first is the PV method, where a beam of sunlight is directly converted into electrical energy; the second is the thermal method, where the sun's dissipated heat is conveniently applied to a single hybrid system called PV-thermal system. This system was assessed under Saudi Arabian environmental conditions [39].

Hasnain and Alajlan's [40, 41] idea was also innovative. They proposed to couple the existing PV-RO plant with a solar still plant. The latter has a distillate capacity of $5.8m^3$. The two systems together use most of the reject brine that otherwise would be thrown on the ground. The cost of product water was estimated at $0.50/m3. Hasnain and Alajlan also came to the conclusion that such a system would produce the finest benefits in remote areas with negligible land values. The low investments required for land acquisition and the maintenance of the solar stills, together with the ease of installation and the materials being locally available, make the project a convenient and beneficial one [40, 41].

Elhadidy and Shaahid [42] analyzed key parameters like PV array area, battery storage capacity, and number of wind machines in hybrid conversion systems. Hybrid systems utilize solar energy, wind, and diesel. In particular, the analysis was done for systems that satisfy an annual load of 41,500 kWh, by using hourly wind-speed and solar radiation measurements [42]. These were obtained at the solar radiation and meteorological monitoring station of Dharan, in Saudi Arabia. The measurements gave the following values: monthly average solar radiation for Dhahran: 3.6-7.96 kWh/m2, 23% of load demand provided by the diesel back-up unit (with three 10 kW wind machines together, three days of battery storage, and PV deployment of 30 m2) and 48% of load demand provided by the diesel back-up unit (without battery storage) [42].

Rehman *et al.* [43] investigated the economic feasibility of PV technology using GSR (Global Solar Radiation) data as a basis for their research. In particular, the data regarded the horizontal surface for a campus site in Abha, Saudi Arabia, and included annual and seasonal GSR variations on the horizontal surface, temperature, and relative humidity. The obtained data made it possible for them to understand the climatic conditions and the solar availability for Abha City. Three main scenarios were covered: daily average energy demands of full load with annual peak load of 3.84 kW; 75% load with annual peak load of 3.06 kW; and half load with annual peak load of 2.27 kW [43].

The short-run (1-5 days) effects of the battery storage were also investigated through further studies on each of these loads. Rehman *et al*. [43] concluded that the battery storage capacity was the key variable to reduce the system's overall costs; thus, using battery storage for smaller periods of time is a possible alternative. Also, they recommended the use of a larger PV system over a smaller one. The cost of PV energy in the full load scenario was 29% cheaper than the diesel generating cost. The PV system cost was again 56% and 116% lower for the 75% and 50% load respectively [43].

Shaahid and El-Amin [44] also analyzed solar radiation data with the objective of understanding how economically feasible a hybrid system can be. The hybrid was, this time, a PV-diesel-battery power system [44]. Shaahid and El-Amin's (2009) investigation also covered the technological aspects of the issue, not just the economical ones, in order to verify whether this type of hybrid system can meet certain load requirements. The analysis was performed on radiation data for the city of Rafha, in Saudi Arabia, particularly in the remote village of Rawdhat Bin Habbas (a village locate near Rafha). The village's annual electrical energy demand is 15,943 MWh. The assessment was performed using the software HOMER (NREL's Hybrid Optimization Model for Electric Renewable). The GSR daily intensity for the location was high, with a monthly average of 3.04-7.3 kWh/m2, which made this location an ideal candidate for the deployment of PV power systems. The following results followed the simulation: for a hybrid consisting of a 2.5 MWp PV system, a 4.5 MW diesel system, and a battery storage autonomy of 60 minutes, or 1 hour of average load, the PV penetration was 27% with a resulting cost of 0.170 USD/kWh (fuel price set at 0.1$/L). 1005 tons of carbon per year could be prevented from being released in the atmosphere if using a PV-diesel-battery hybrid system. In addition, this study was recommended for the creation and utilization of equal or similar hybrid systems in locations with similar terrain, climatic, and load conditions as the area around Rafha [44].

Rehman *et al.* [45] analyzed the distribution of radiation and sunlight duration in Saudi Arabia. To do so, they calculated the monthly average of daily GSR and sunshine duration data [45]. Rehman *et al.* [45] used the RetScreen software, a tool to assess the economics of energy production, to do an economic analysis of a 5MW installed capacity PV-based grid. The latter generated electricity by being connected to a power plant. The minimum and maximum GSR values, obtained at Tabuk and Bishah, were respectively: 1.63 MWh/m^2 yr and 2.56 MWh/m^2 yr; the average value was of 2.06 MWh/m^2 yr, whereas the average sunshine duration was of 8.89h, with minimum and maximum values at 7.4h and 9.4h. Other data obtained regard the specific yield: 211.5 to 319.0 kWh/m^2, with a mean value of 260.83 kWh/m^2; each year, the 5MWp installed capacity plant produced an amount of energy ranging between 8,196 and 12,360 MWh, with an average of 10,077 MWh/yr. Moreover, the results indicated that from an environmental perspective, the 5MW capacity power plant could prevent up to 8182 tons of greenhouse gases from entering the atmosphere, and Bishah proved to be the best site for the utilization of this type of power plant, while Tabuk was the worst. The results were obtained in consideration of a number of factors and variables, namely: the simple payback period, the net present value, the internal rate of return, the profitability index, the cost of renewable energy production, the years to positive cash flows, and the life cycle savings [45]. Rehman *et al.* [45] also suggested that a pilot plant be installed in Bishah, in order to acquire more data over the techno-economic aspects of the project. A pilot plant in the territory would allow for constant monitoring, with the chance to overcome the numerous aspects of technology transfer and use in Saudi Arabia [45].

The HOMER software was also used by Shaahid and Elhadidy [46]. They carried out a techno-economic feasibility assessment based on the utilization of hybrid power systems, composed of a 4-kWp PV system, a 10 kW diesel system and a battery storage with a 3-hour autonomy. The study was based on long-term solar radiation data in the East Coast of Saudi Arabia and, particularly, in Dharan. Here, the daily solar global radiation oscillated between 3.61 and 7.96 kWh/m2. The study made it possible to simulate the load of an average residential building that has an annual electric demand of 35,120 kWh, showing that for a hybrid system with the characteristics mentioned above, there was a 22% PV penetration. 0.179$/kWh was the COE (Cost of Energy) of this hybrid system, calculating the fuel price at 0.1$/L. Shaahid and El-Hadidy [46] concluded that the potential of solar energy in Saudi Arabia has to be taken in serious consideration, since a broad fraction of Saudi Arabia's energy demand could be met through the use of PV systems. The hybrid system that they designed, which is perfect for the climatic characteristics of Saudi Arabia, can be used for other areas of the planet with similar climatic features. Shahiid and Elhadidy [46] encouraged the use and reference of their system for similar contexts to that of Saudi Arabia [46].

Another study conducted by Shaahid *et al.* [47] assessed, through the NREL's HOMER software, the economic potentiality of wind-PV-diesel hybrid power systems through specific conditions of wind speed and solar radiation. The hybrid system featured various combinations of 600 kW wind machines, PV panels, and was supplemented by diesel generators. The simulation was conducted in the remote village of Rawdhat Bin Habbas. Here, the annual electrical energy demand is of 15,943 MWh, with a monthly average daily GSR going from 3.04 to 7.3 kWh/m^2. The following results were obtained: a 24% (10% wind and 14% PV) renewable energy fraction with a 0% annual capacity shortage, which was obtained with a 1.2 MW wind farm capacity, a 1.2 MW PV capacity and a 4.5 MW diesel system. The COE of this hybrid system was 0.118$/kWh at a fuel price of 0.1$/L [47].

Rhman and Al-Hadhrami [48] conducted an experiment also aimed at assessing the potentials of solar power as a substitute for fossil fuel. The experiment was adapted to the variables of Rowdat Ben Habbas, a small village in a northeastern area of Saudi Arabia. Their method of assessment was different than the ones described above, as Rhman and Al-Hadhrami [48] compared different power systems. They first used the hourly solar radiation data measured in Rowdat Ben Habbas through PV modules installed on fixed foundations. They utilized four generators with different rated powers with diesel prices oscillating between 0-2 and 1.2 US$/L. Also batteries and converters were compared at different sizes in an attempt to find the best power system for that specific location. A first analysis of the existing diesel power system revealed that the current one was the most economical; it featured four diesel generating units, each of 1500, 1000, 1750, and 250 kW, with a diesel price at 0.2$/L, its COE was 0.19$/kWh. Following in terms of lower costs, was a four generator diesel system (1250, 750, 2250, and 250 kW) with a battery bank of 300, a power converter of 3000 kW, with a diesel price of 0.2$/L and a total COE of 0.219$/kWh. The diesel system started to become not the best option as the diesel price increased, becoming fully uneconomical when the price reached 0.60$/L and more. At this point the hybrid system became the best option. Rhman and Al-Hadhrami [48] thus, also concluded recommending the development of a hybrid system with a 20% solar PV penetration, highly encouraging precise assessments and studies over the operations of development, installation, maintenance, and improvement of such a system [48].

CHAPTER 4 METHODOLOGY

In order to assess whether or not using a PV system would be beneficial and cost effective in the city of Jeddah, two potential scenarios were simulated and the results were analyzed. The first scenario considered a connected grid combined with a PV system. . Both options were studied at different load fractions (25%, 50% and 75%) generated from the PV system. In scenario 1, the potential sellback price (FiT) of any excess energy that could be generated from the PV system sold back to the grid was equal to the current cost of power charged by the utility. In scenario 2, the potential sellback price of any excess power generated by the PV system was assumed to be sold back to the grid at a higher price than the current price charged by the utility. In addition, the payback of the chosen system was investigated to make the system more efficient.

To asses these options, HOMER was used in the simulation.

4.1 HOMER Software

HOMER software was used to evaluate the efficiency of alternative power systems. HOMER simulated the performance of the energy balance calculation for 8,760 hours a year for the alternative power system in question. It also calculated the achievable configuration and predicts the cost under the specified conditions within the specified time period. The capital, operating, maintenance, and replacement costs were also included in the calculation of the alternative system's cost. HOMER software presented optimal results based on the net present cost. These results were presented by the software after all possible system configurations were simulated and displayed. The optimal configuration results are referred to as a state of optimization [49].

4.2 How the Software Works

Designing a power system by HOMER gives the researcher a chance to compare the various configuration options of the alternative technology. HOMER simulated all potential configuration options including loads, renewable components, and whether the system was connected to the grid or stand alone; as shown in Figure [4-1] [49].

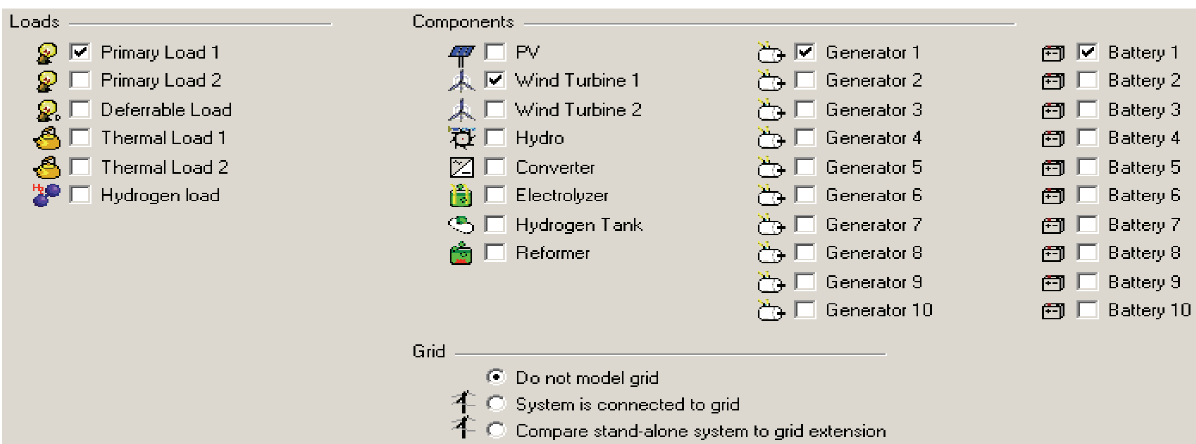


Figure (4-1): HOMER configuration [49].

After choosing the optimal configuration options, the optimization result was displayed in the main window as shown in Figure (4-2).

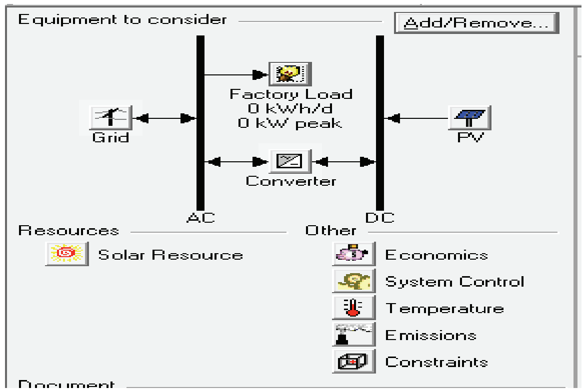


Figure (4-2): HOMER main window.

The information regarding the alternative power in question was entered into HOMER by the user.

4.2.1 The Load

The electric demand and type was entered by entering or uploading the load file. HOMER also needs information regarding the electricity load depicted per hour for one full year (this is a total of 8,760 values) [49].

After entering the load information, the information is displayed in both diagram and table formats. The load data collected from a sample factory in Saudi Arabia was used as a base for calculating potential results. The solar radiation and temperature of the region was also obtained for the calculations [49]. Both cost and features of the PV systems were as shown in Appendix (A).

4.2.2 System Components

Each component of the system in the simulation needs to have a corresponding cost, range, and lifetime. The costs of the component was divided into three parts, capital cost, replacement cost, and operating and maintenance cost as shown in Figure (4-3). In addition to the aforementioned costs, the size of the generator being considered is also necessary for accurate calculations and simulation [49].

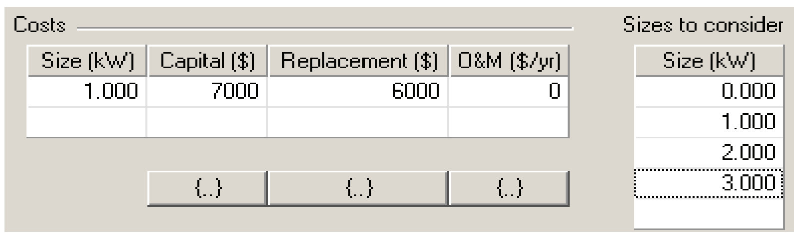


Figure (4-3): The components cost and range [49].

4.2.3 Grid Input

If the system is grid connected, the required data includes the tariff and FiT set by the utility to buy and sell electricity. The price of electricity in Saudi Arabia depends on the sector, time of day consumption and time of year consumption Figure (4-4).

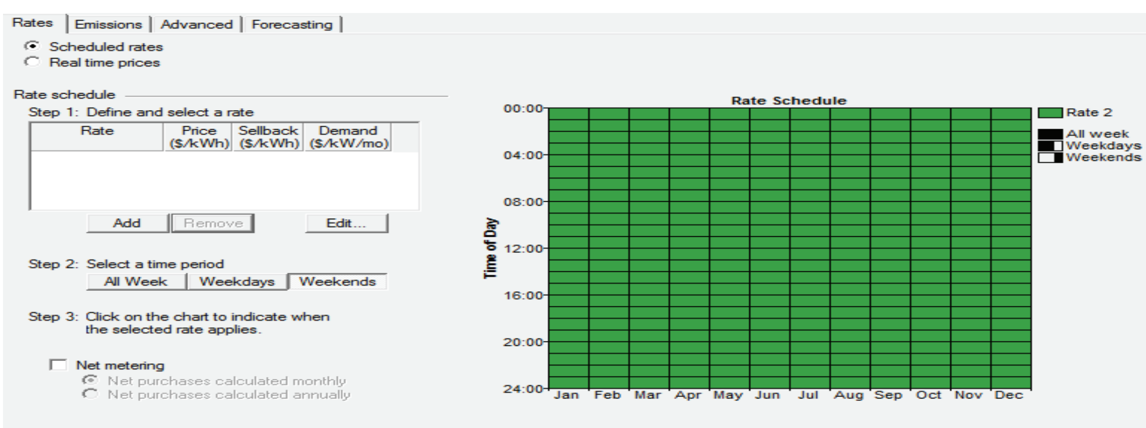


Figure (4-4): HOMER grid window.

HOMER simulates these options by using the scheduled rate entered by the user.

4.2.4 Solar Resource Input

The inputs described the availability of solar radiation for each hour of the year. These values are either attained by an uploaded file of a calculation option available in HOMER to synthesize hourly data and or average monthly values as shown in Figure (4-5) [49].

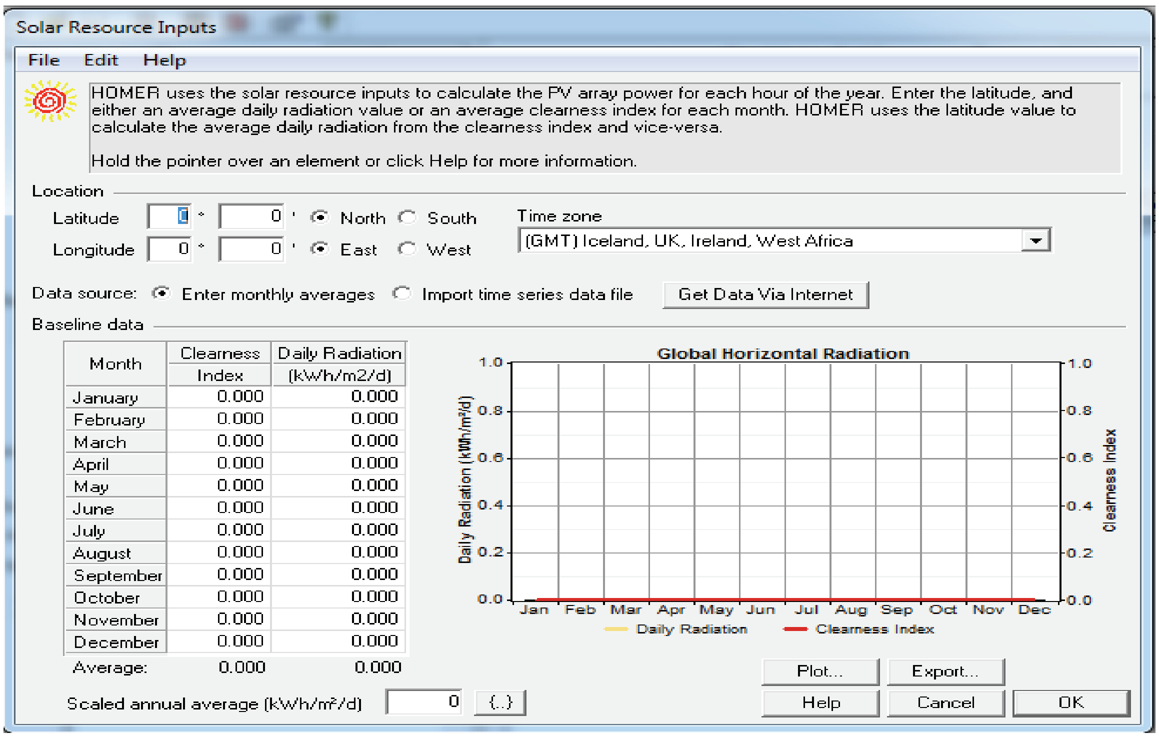


Figure (4-5): HOMER solar resource window.

4.2.5 Temperature Input

Temperature has a direct effect on the efficiency of PV panels. Inputting the temperature is a crucial step in calculating the amount of potential power produced by the PV array at any given time during the year. Therefore, an hourly average temperature needs to be entered (this also comes to a total of 8,760 values) as show in Figure (4-6) [49].

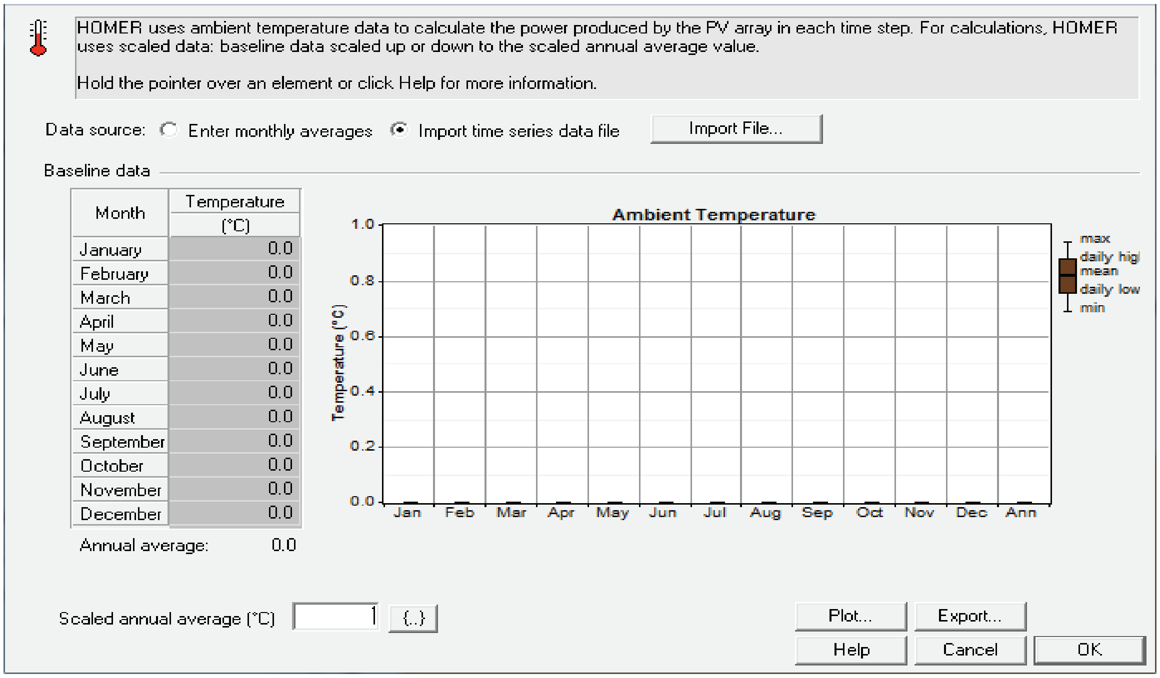


Figure (4-6): HOMER temperature window.

4.2.6 The Economic Input

Figure (4-7) illustrates the economic information that HOMER needs for the simulation. In order to calculate the economic input, the annual real interest rate and project lifetime need to be entered by the researcher [49].

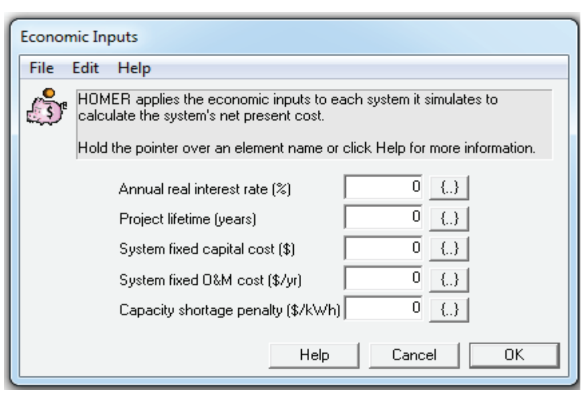


Figure (4-7): HOMER economic window.

4.2.5 Constraints

Constraints are the conditions and configuration limits, which the HOMER software system must satisfy. Any values that do not meet the required conditions will not appear in the results Figure (4-8).

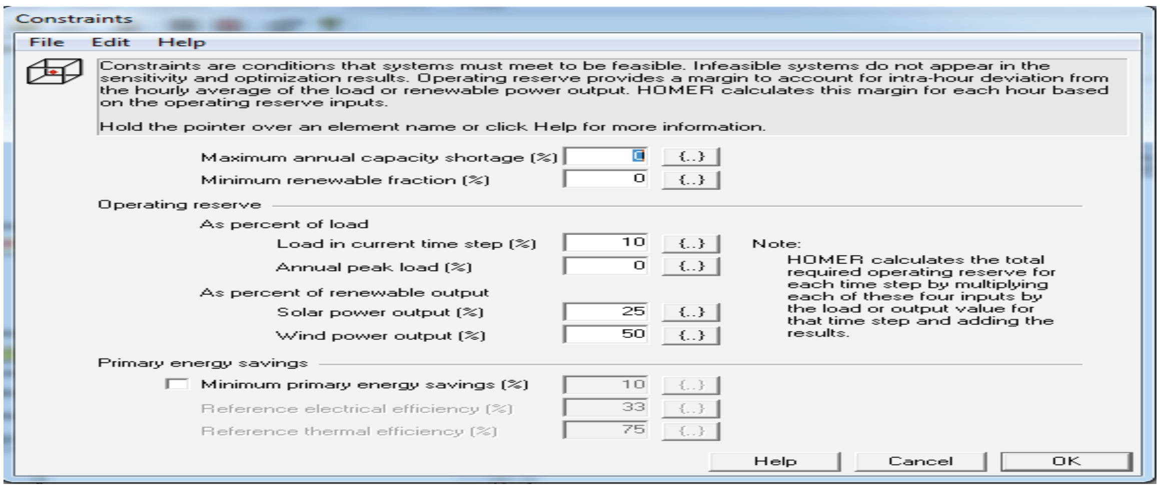


Figure (4-8): HOMER constraints window.

4.2.6 Simulation and Results

HOMER uses the combination of values entered in the various component inputs to simulate the power system. Any results that do not meet the load demands are labeled inefficient or infeasible and are then disregarded by HOMER [49].

A list of system configurations that HOMER has deemed feasible is labeled optimization results and is displayed in a table as shown in Figure (4-9). Optimization results are listed in order of cost effectiveness. Cost effectiveness is calculated by the net present cost which is labeled "Total NPC" in the results Table [49].

				PV (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Ren. Frac.
						16000...	$ 0	36,276	$ 708,234	0.040	904,458	0.00
				100	100	16000...	$ 230,100	29,468	$ 805,426	0.044	739,408	0.18
				150	100	16000...	$ 323,050	25,885	$ 828,417	0.045	662,607	0.26
				100	150	16000...	$ 252,200	29,718	$ 832,407	0.046	739,408	0.18
				100	160	16000...	$ 256,620	29,768	$ 837,803	0.046	739,408	0.18
				170	100	16000...	$ 360,230	24,899	$ 846,342	0.045	641,568	0.28
				150	150	16000...	$ 345,150	25,873	$ 850,279	0.046	656,883	0.26
				150	160	16000...	$ 349,570	25,923	$ 855,675	0.046	656,883	0.26
				170	150	16000...	$ 382,330	24,312	$ 856,979	0.046	623,873	0.29
				170	160	16000...	$ 386,750	24,362	$ 862,376	0.046	623,873	0.29
				100	250	16000...	$ 296,400	30,218	$ 886,369	0.049	739,408	0.18
				100	260	16000...	$ 300,820	30,268	$ 891,765	0.049	739,408	0.18

Figure (4-9): HOMER results window.

4.2.6.1 The Optimization Result

Optimization results can also be filtered to display only the most cost effective configuration of each system. This is simply done by choosing the categorized optimization option in HOMER Figure (4-10) [49].

Sensitivity Results | Optimization Results

Sensitivity variables

Max. Net Grid Purchases (kWh/yr) 1,000,0 Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

				PV (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Ren. Frac.
						16000...	$ 0	36,276	$ 708,234	0.040	904,458	0.00
				100	100	16000...	$ 230,100	29,468	$ 805,426	0.044	739,408	0.18

Figure (4-10): HOMER optimization results.

All information regarding the economic or technical details of the simulated configuration systems (example: cash flow, cost summary, and electrical output) are displayed in simulation results windows. Hourly performance, and performance of each component (example: the PV value, grid converter, etc.) are also displayed in the simulation results window [49].

HOMER was used to simulate the optimal results with considerations of cost effectiveness and a potential sellback revenue [49].

4.3 Input Data

4.3.1 The Factory Load

The following is the input data used in HOMER. The factory load was obtained from the electricity bills of a sample factory in Saudi Arabia. The load is presented per month over the course of year as shown in Table (4-1).

Table (4-1): The monthly factory load.

Month	KWh/month
January	28,001.40
February	30,800.00
March	44,000.00
April	74,000.00
May	103,600.00
June	123,200.00
July	123,200.00
August	135,200.00
September	123,200.00
October	44,000.00
November	42,400.00
December	32,800.00

The monthly load data was analyzed and converted to a daily and hourly load. The typical operating hours for most factories in Saudi Arabia is from 8:00am to 5:00pm for five days a week with two days off. During working hours, it was assumed that the factory used the highest load with only a minimum load used during the evenings and nights.

The load was assumed to be 90% during operating hours and 10% during the evenings and nights in the winter seasons. During the summer season, the load was assumed to be 80% during the operating hours and 20% during the evenings and nights. Figure (4-10) shows an example of the daily and monthly load for the factory.

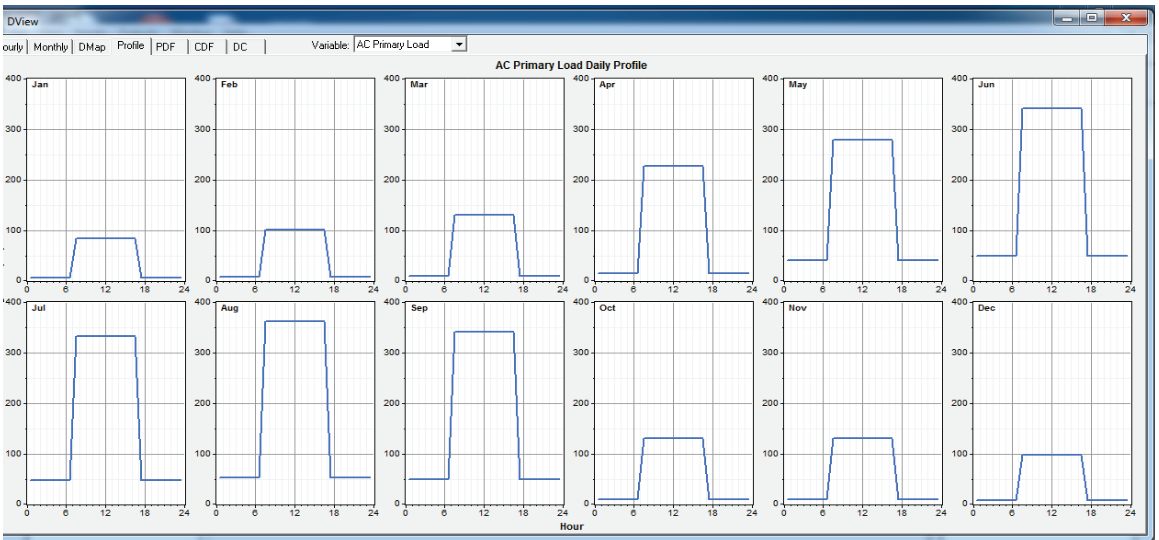


Figure (4-11): The factory load.

Since the HOMER program needs the hourly data entries over the course of a year, this required 7,860 different entries [49]. Figure (4-12) shows the load information after being entered in HOMER.

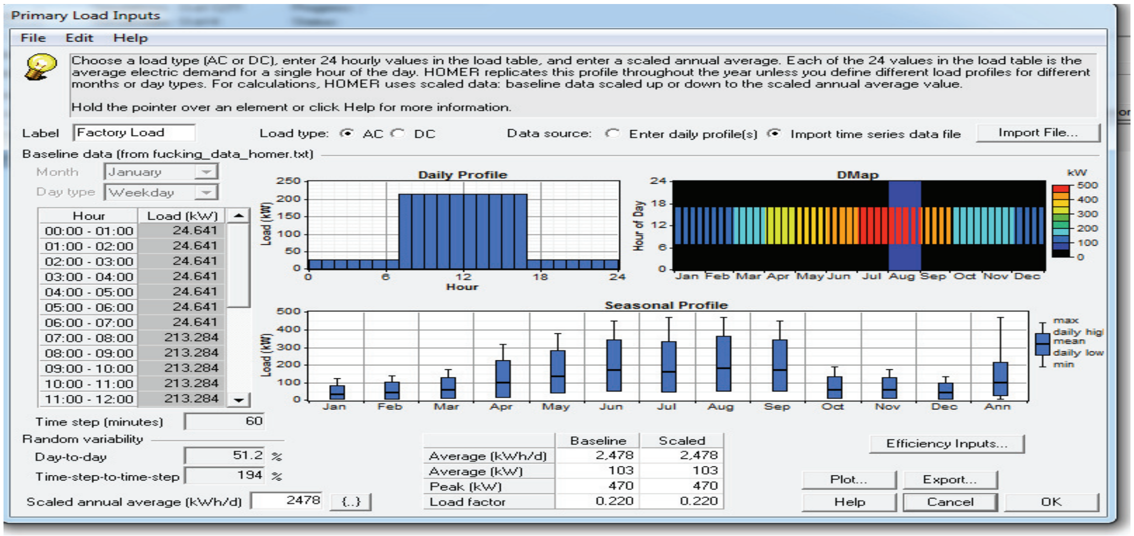


Figure (4-12): The factory load in HOMER.

4.3.2 The Temperature of the City

Temperature affects the efficiency of the solar cell. To obtain accurate results, the hourly temperature was gathered from the electricity utility that records the temperature each hour for the city. Entering the hourly temperature for one year entered required 8,760 entries [49]. Figure (4-13) shows the Jeddah temperature applied in HOMER.

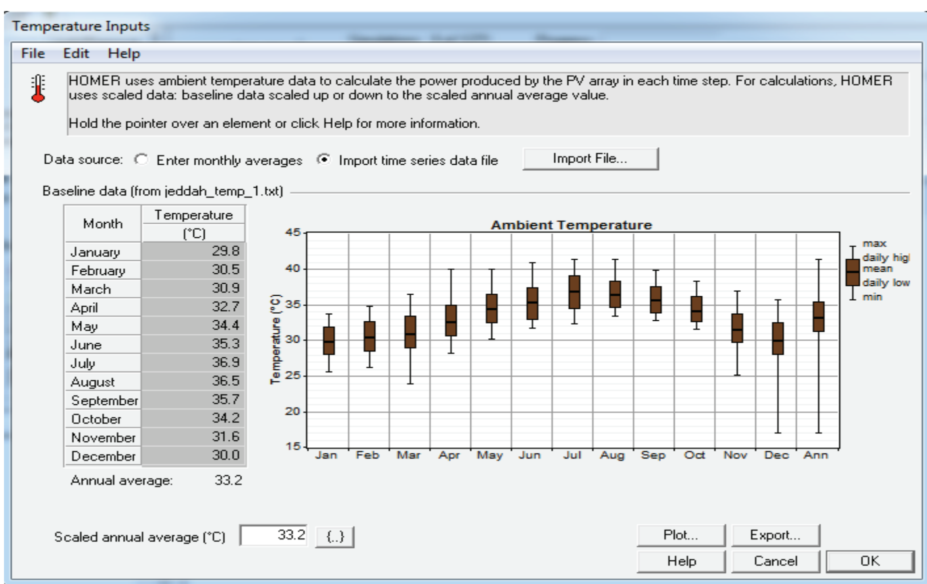


Figure (4-13): Jeddah temperature detail in HOMER.

4.3.3 Solar Equipment Specifications

1- The PV kit: The kit price includes all the equipment needed to connect to the panel. The extra costs such as costs for installation, shipping and engineering was added to the price before the cost was calculated per KW. The replacement price needed at the end of the kit's life cycle is assumed to be the same as the starting price. The PV panel does not require any maintenance after installation.

Table (4-2): The PV kit price.

PV (300W)	Solar Kit type	639
	Charger price	210
	Price	429
	Installation (10%)	43
	Shipping & Eng. (20%)	86
	Total for 300w	558
	1KW price	1,859
	O&M (0%)	0.00
	Replacement	1859
	Lifetime	25
	Module cost /w	1.859043333

For the panel specification used in the data sheet in appendix B, the price was obtained from the internet, as shown in appendix A. The price used may be decreased if more than one kit is ordered. In addition, increasing the size of the PV system will decrease the price therefore, the price of the kit was assumed at its highest possible price.

The size was entered with a wide range to give HOMER a chance to find the optimal size for the system. All of the aforementioned specifications for the panel were entered in HOMER such as the costs, the size, the properties and taking into consideration the effect of the temperature Figure (4-14).

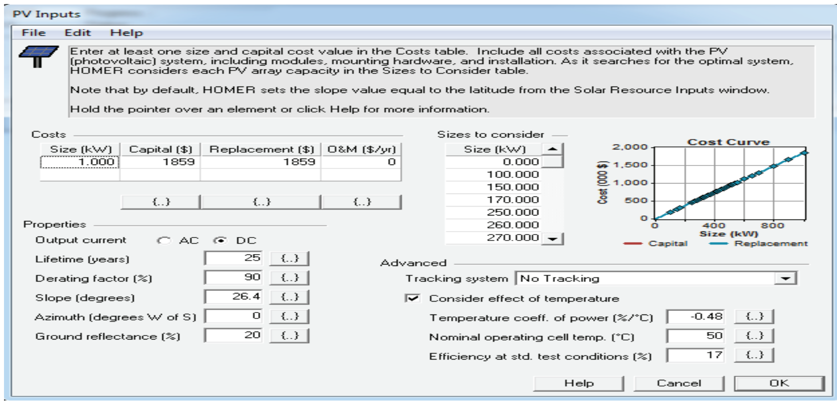


Figure (4-14): The PV detail and cost entered in HOMER.

2- The Center Inverter: The center converted size is assumed to be 500 KW. The cost of installation and shipping was added to this price. Calculations were computed to obtain the cost per KW. Since the inverter needs regular maintenance, the maintenance cost was assumed to be 1% of the cost of the inverter as shown in Table (4-3). All information entered to HOMER is presented in Figure (4-15) and appendix (A, B).

Table (4-3): The inverter price.

Inverter (500KW)	Price	169920
	Installation (10%)	16992
	Shipping &Eng. (20%)	33984
	Total	220896
	1KW	441
	O&M (1%)	5.00
	Replacement	441
	Lifetime/y	25
	Inverter cost/w	0.441792

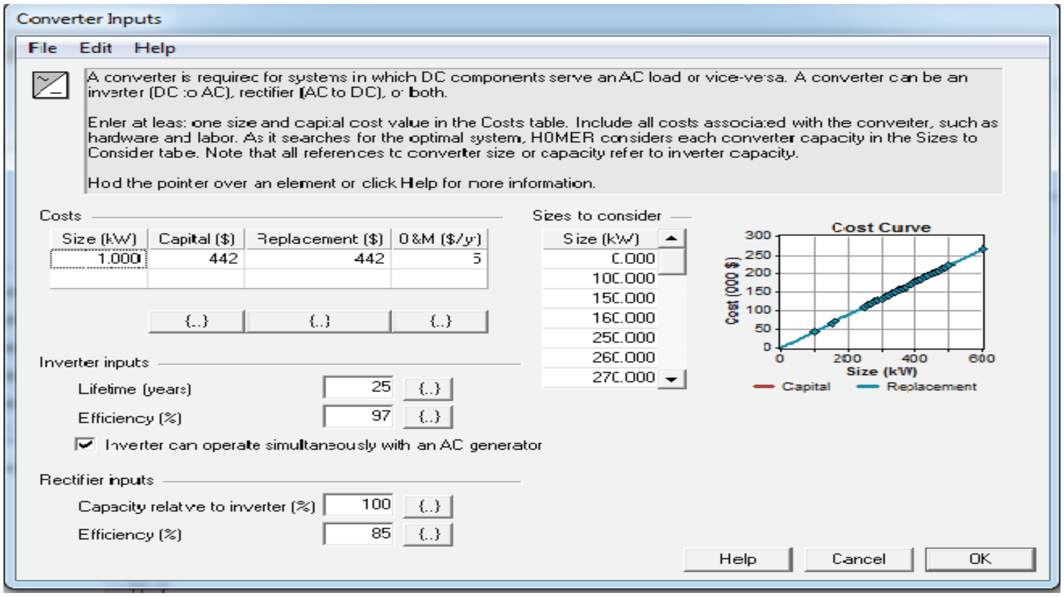


Figure (4-15): The PV detail and cost entered in HOMER.

4.3.4 The Grid Information

The rate used is the current price of electricity in Saudi Arabia. The exact cost was used because the Saudi Arabia electricity company has different electricity tariffs depending on the sector, season, and time. The Saudi Arabian tariff for the industrial sector was obtained from the electricity utility then converted to dollars and entered intoHOMER [32].

Up to now there has been no regulation for the FiT in Saudi Arabia. For this study therefore two scenarios will be assumed. In the first scenario the sellback price will be equal to the FiT price of the utility. Figure (4-16) shows the rate schedule for the tariff and FiT used in the first scenario.

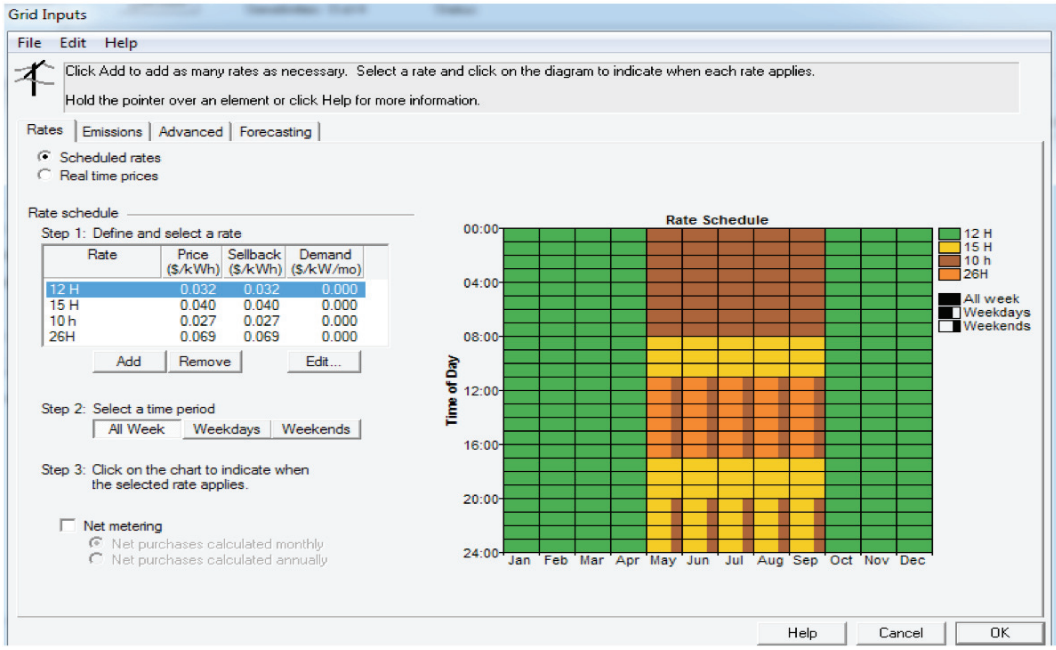


Figure (4-16): First scenario grid rate schedule.

In the second scenario, the sellback price is assumed to be the highest tariff price. The reason for this assumption is that the PV system will be providing power during peak hours; therefore, it is fair to assume a peak hour price. Figure (4-17) shows the rate schedule for the second scenario.

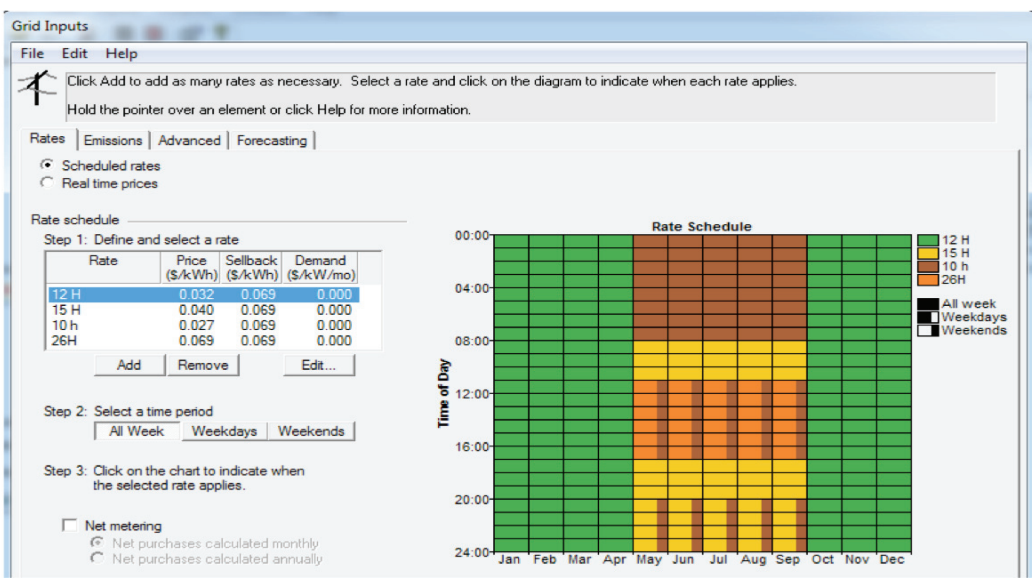


Figure (4-17): Second scenario grid rate schedule.

4.3.5 Solar Resource

The solar radiation was generated automatically by HOMER. This can be done by inserting the required coordinates of the selected area. Figure (4-18) shows the daily radiation and clearness index for every month of the year generated by HOMER. The maximum radiation is about 5.6 kWh/m^3/d, which is enough to generate the required power for the area.

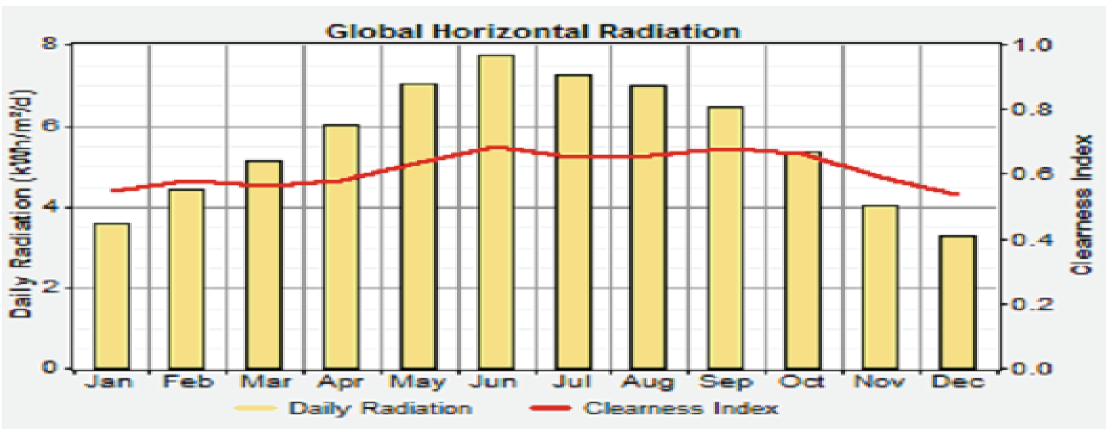


Figure (4-18): Solar radiation and clearness index.

4.3.6 Economic Entries

The most important economic factors for HOMER are the real interest rate and the project lifetime. For the real interest rate (discount rate) in Saudi Arabia 2% was added. The normal project lifetime for any PV system is between 25-30 years. A 25-year lifetime was chosen and was added to HOMER Figure (4-19).

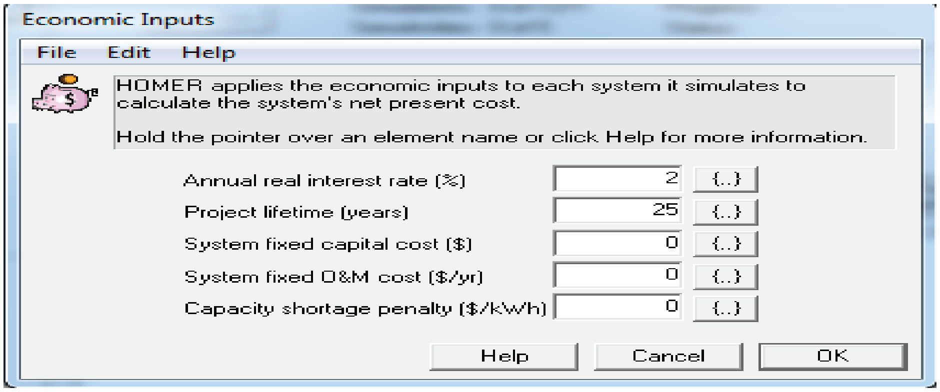


Figure (4-19): The economic information.

4.3.7 Constraints

HOMER was forced to follow the assumption that chose the fraction covered by the PV system. The fraction chosen is shown in Figure (4-20).

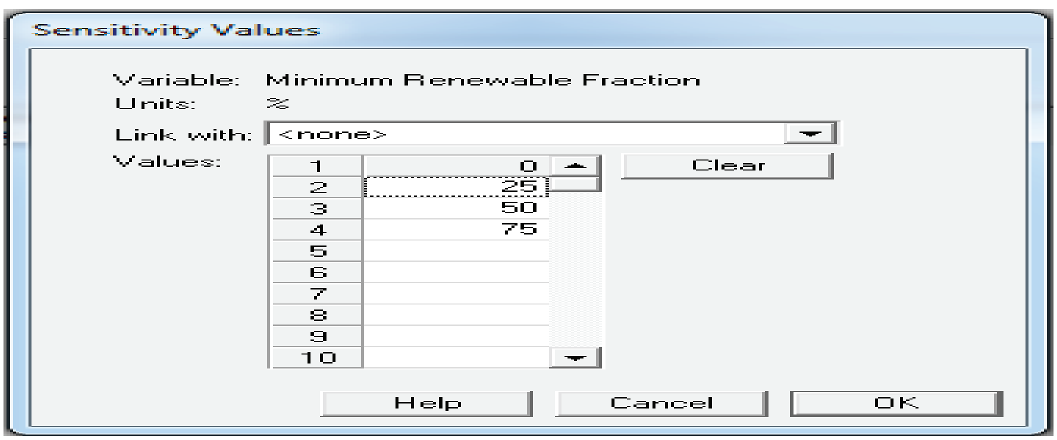


Figure (4-20): The fraction covered by PV system.

All data was entered into HOMER for simulation. Figure (4-21) shows the final system configuration after all the data needed for the simulation was entered.

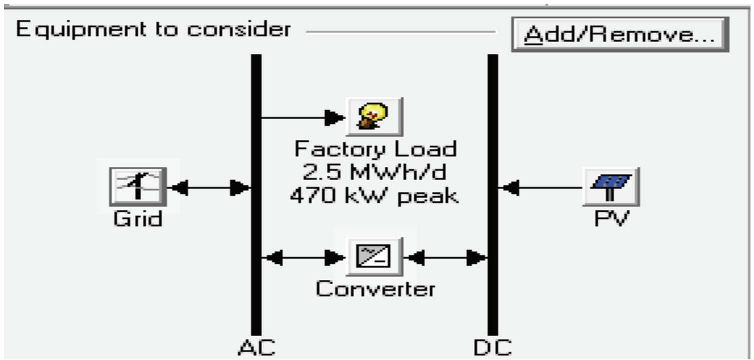


Figure (4-21): System configuration.

4.6 The Economic Calculation

4.6.1 Introduction

After completing the technical requirements and design of a PV system, an economic analysis that breaks down the costs and benefits of the system is necessary [50].

The costs of a PV system are broken down into various sub-costs. These sub-costs include the cost required to acquire the system, initial operating costs, maintenance costs and replacement costs [51].

At the end of the life of a system, a projected salvage and or decommissioning cost is needed. Life cycle costing is a method often used to project costs of the PV system. Life cycle costing refers to an evaluation of all purchase choices. [51]. In order to evaluate this, the Net Present Value (NPV), payback period, and Internal Rate of Return (IRR) methods are used [52].

4.6.2 Economic Factors

Before we start there are some factors that need to be defined:

4.6.2.1 The Discount Rate (i)

The discount rate (also referred to as the opportunity cost) refers to the value the owner contributes towards the capital invested in the system [50]. This factor is determined by the bank. When an investment is made on a renewable energy system, the rate is referred to as the discount rate. In other words, the amount of interest determined by the bank is an amount that can be earned on the principal saved. Therefore, the principal may increase yearly if the account is determined to have a positive rate. This can be problematic if the amount determined is greater than the rate of inflation [51].

The real challenge in investing money is to invest at a discount rate that is greater than the inflation rate [51].

4.6.2.2 The Capital Recovery Factor (CRF)

"A capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time" [50].

The CRF can be calculated by:

$$CRF = \frac{m(1+m)^n}{(1+m)^n - 1} \tag{4-1}$$

[50]

m in the aforementioned equation is equal to the discount rate.

4.6.3 Net Present Value and Future Worth

In the equation below, P refers to a sum received at a current time and has a determined present value. F refers to a sum spent in the future and has a determined future value. Therefore, if P is invested considering the discount rate (i), the future value is calculated using the following equation [50]:

$$F = P(1+i)^n \tag{4-2}$$

[50]

For the inverse relation, a present value of a future sum is calculated using the following equation:

$$P = F(1+i)^{-n} \tag{4-3}$$

[50]

4.6.4 Life Cycle Cost (LCC)

4.6.2.1 Definition

The life cycle cost (LCC) analysis is an analysis used to asses all costs pertaining to the life of the project. This is done with consideration for all costs (capital investment costs, purchasing costs, installations costs, operating costs, maintenance costs, and future salvage costs) [53].

4.6.2.2 Life-Cycle Cost Formula

To calculate and find the total LCC of a project, a sum of all costs is generated then a present cash value (example: resale worth) is deducted.

$$\text{LCC} = \text{Initial cost} + \text{electricity cost} + \text{O\& M cost} + \text{replacement cost} - \text{salvage} \quad (4\text{-}4)$$

[54]

1- Initial cost: is the price of all components in the PV system such as the PV panel, inverter and cables [54].

In addition, there are other parameters that will be added to the initial cost including installation cost, shipping costs and engineering costs.

$$\textit{Initial cost} = \textit{equipment cost} + \textit{shipping cost} + \textit{Eng. Cost} + \textit{installation cost} \quad (4\text{-}5)$$

2- Maintenance cost: System maintenance is a recurring cost over the project lifetime. This includes all equipment maintenance, site maintenance, and all required system supervision. PV systems require very little maintenance.

$$P = aunnual.main. * \frac{[(1+i)^n - 1]}{[i(1+i)^n]} \quad (4\text{-}6)$$

[50]

3- Replacement cost:

$$P = aunnual.rep * \frac{[(1+i)^n - 1]}{[i(1+i)^n]} \quad (4\text{-}7)$$

[50]

4- Electricity cost: "The monetary value of all electricity used over the total life cycle of the system" [55].

5 -Salvage cost: The salvage cost of a system refers to any remaining value at the end of the life cycle or at the time of replacement [53].

4.6.2.3 Annualized life cycle cost (ALCC):

The levelized energy cost (LEC) is often generated by energy providers such as utilities. This number provides a unit cost of electricity in $/kWh that remains invariable. This method uses the present worth of a cost and the capital recovery factor divided by the annual energy produced by the system, to generate an annual cost of electricity [50].

$$LEC = \frac{(NPW_c)(CRF)}{E} \quad (4\text{-}8)$$

[50]

NPWC refers to the present value .The term E refers to the annual energy in kilowatts per hour that is generated by the system.

4.6.5 Internal Rate of Return (IRR)

An internal rate of return (IRR) refers to a calculation method where the NPV equals zero. The discount rate is then assumed to be equal to the IRR. This assumption is often recommended when comparing projects of equal survival and possible risks. The project with the highest IRR is the optimal choice [56].

$$0 = \sum_{n=0}^{L} \frac{P_s}{(1+IRR)^n} \tag{4-9}$$

[50]

The assessment figure of IRR that satisfies the aforesaid equation is the assessment that should be accepted.

4.6.6 Payback Period (PB)

One of the great advantages of PV systems is that they are able to function for a long time. Solar panels are often guaranteed for 25 years and it is suggested that they will most likely perform successfully beyond 25 years with the proper maintenance. Therefore, a payback calculation needs to consider the savings that come with a solar system across a 25-year period. In addition, the parameters that effect the payback to make PV grid connected system more efficient must also be studied [57].

In order to determine the payback period, the following steps were used:

Step 1: The initial yearly savings as a result of using a PV system are determined. This is done by computing the output of the proposed system in kilowatt hours [57].

Step 2: Future increases in electrical costs were considered and included [57].

Step 3: The yearly savings were then multiplied by the future inflation rate [57].

Step 4: The aforementioned savings are then accumulated by year: This is done by adding the prior year's savings (whether adjusted for inflation) to the current year savings [57].

Step 5: The initial cost is then deducted from the potential accumulated savings. This will initially generate a positive number for the initial cost. However, over time the savings will surpass the initial cost. The point at which the savings surpass the initial cost is referred to as the payback period [57].

CHAPTER 5 RESULTS AND DISCUSSION

5.1 The Output Result

HOMER generated a simulated option with an optimal system being one without an alternative source, which means the factory load supplied electricity 100% from the grid as shown in Figure (5-1). The total NPC of this grid-only method came solely from the grid since the grid was the only supply. The output shows that a total energy of 904,458 kWh/year was purchased from the grid and no power supply came from the PV system as illustrated in Table (5-1). It can be noted there is no capital cost because no alternative system needed to be purchased or installed in this phase of the analysis.

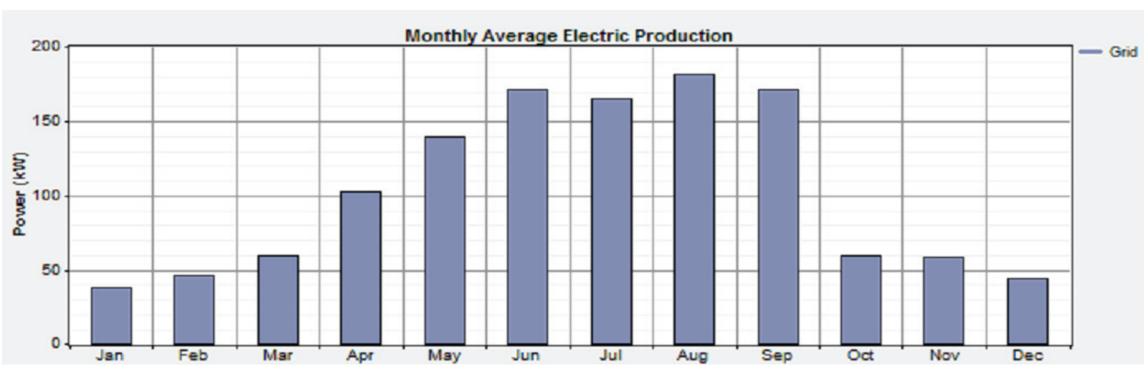


Figure (5-1): The monthly average electricity.

Table (5-1): Grid only system electricity consumption.

		Production (KWh/yr.)	Fraction %
Production	Grid purchase	904,487	100
Consumption	AC primary load	904,487	100

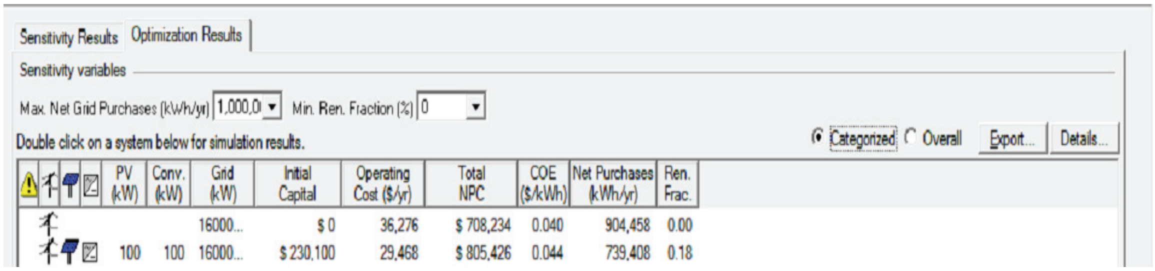
Figure (5-2) shows the HOMER output results ordered from lowest NPC for adding the alternative system to the simulation. The optimal result for HOMER depending on the NPC is to use a grid-only method as the first choice. This means that any alternative system will not be considered an optimal solution. The reason for this is the grid-only system is assumed to carry no capital or maintenance cost.

It can then be deduced that the most cost effective option is to use the supply from the grid only system without a PV generator. This option has a total net present cost (NPC) of $708,234 and the lowest cost of energy (COE) of $0.04/kWh. This option also results in an operating cost of $36,276/year. The operating cost was generated by multiplying the total energy purchased by the purchase prices. The initial capital cost in this case is zero due to the lack of a PV generator and inverter.

PV (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Ren. Frac.
		16000...	$ 0	36,276	$ 708,234	0.040	904,458	0.00
100	100	16000...	$ 230,100	29,468	$ 805,426	0.044	739,408	0.18
150	100	16000...	$ 323,050	25,885	$ 828,417	0.045	662,607	0.26
100	150	16000...	$ 252,200	29,718	$ 832,407	0.046	739,408	0.18
100	160	16000...	$ 256,620	29,768	$ 837,803	0.046	739,408	0.18
170	100	16000...	$ 360,230	24,899	$ 846,342	0.045	641,568	0.28
150	150	16000...	$ 345,150	25,873	$ 850,279	0.046	656,883	0.26
150	160	16000...	$ 349,570	25,923	$ 855,675	0.046	656,883	0.26
170	150	16000...	$ 382,330	24,312	$ 856,979	0.046	623,873	0.29
170	160	16000...	$ 386,750	24,362	$ 862,376	0.046	623,873	0.29
100	250	16000...	$ 296,400	30,218	$ 886,369	0.049	739,408	0.18
100	260	16000...	$ 300,820	30,268	$ 891,765	0.049	739,408	0.18
100	270	16000...	$ 305,240	30,318	$ 897,161	0.050	739,408	0.18
250	160	16000...	$ 535,470	18,629	$ 899,179	0.046	505,975	0.40
100	280	16000...	$ 309,660	30,368	$ 902,557	0.050	739,408	0.18
250	150	16000...	$ 531,050	19,053	$ 903,030	0.047	514,849	0.39
150	250	16000...	$ 389,350	26,373	$ 904,241	0.049	656,883	0.26
260	160	16000...	$ 554,060	18,120	$ 907,817	0.047	495,464	0.41
100	290	16000...	$ 314,080	30,418	$ 907,954	0.050	739,408	0.18
150	260	16000...	$ 393,770	26,423	$ 909,637	0.049	656,883	0.26
170	250	16000...	$ 426,530	24,812	$ 910,941	0.049	623,873	0.29
260	150	16000...	$ 549,640	18,610	$ 912,974	0.047	505,620	0.40
100	300	16000...	$ 318,500	30,468	$ 913,350	0.050	739,408	0.18
150	270	16000...	$ 398,190	26,473	$ 915,033	0.049	656,883	0.26
170	260	16000...	$ 430,950	24,862	$ 916,337	0.049	623,873	0.29
270	160	16000...	$ 572,650	17,646	$ 917,159	0.047	485,698	0.42
100	310	16000...	$ 322,920	30,518	$ 918,746	0.051	739,408	0.18
150	280	16000...	$ 402,610	26,523	$ 920,429	0.050	656,883	0.26

Figure (5-2): The overall results from HOMER.

For the optimal overall result HOMER gives only two systems, as shown in Figure (5-3).


Sensitivity Results | Optimization Results

Sensitivity variables

Max. Net Grid Purchases (kWh/yr) 1,000,0 | Min. Ren. Fraction (%) 0

Double click on a system below for simulation results.

Categorized | Overall | Export... | Details...

	PV (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Net Purchases (kWh/yr)	Ren. Frac.
			16000...	$ 0	36,276	$ 708,234	0.040	904,458	0.00
	100	100	16000...	$ 230,100	29,468	$ 805,426	0.044	739,408	0.18

Figure (5-3): The optimization system results.

From Figure (5-3) there is only one optimal system with a PV system. This system has a PV fraction of 18% with a grid fraction of 82%.

For the optimal alternative system, the PV system and inverter size are 100 KW as shown in Table (5-2) with a capital cost of $185,900and $44,200 for the PV kit and inverter respectively. For the O%M the PV cost was assumed to be zero while the inverter is $9,762.

Table (5-2): The PV system size and cost.

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	100	185,900	0	185,900
Inverter	100	44,200	9,762	53,962

The alternative system with 18% fraction produces 170,155 KWh per year. On the other hand, the system purchases 762,458 KWh per year from the grid.

The system was sold back to the grid at 23,0537 KWh/yr, which is only 2% fraction on the total power consumption while the 98% fraction consumed by the load. The excess electricity is zero as shown in Table (5-3).

Table (5-3): Electrical data from the simulation.

Electricity	Component	Production (KWh/yr.)	Fraction %
Production	Alternative system	170,155	18
	Grid purchase	762,459	82
Consumption	AC primary load	904,487	98
	Grid sale	23,0537	2
	Excess electricity	0.00780	0

For the economic analysis, Table (5-4) shows that the NPC for the system is $805,426, which is higher than the NPC of the grid-only system. In addition, this increase in NPC makes the COE of the alternative system (0.044/KWh) higher than the COE for the grid-only system. The operating cost was reduced to $29,468/yr. This reduction was possible due to the excess of the load requirements being sold back to the grid during the day (when the PV system is generating higher power due to the greater amount of radiation).

Table (5-4): Economic data for the system.

Component	Total ($)
PV system	239,861
Grid purchase	565,565
NPC	805,426
COE	0.044/KWh
Operating	29,468/yr

After the aforementioned analysis comparing the cost of the PV system with a grid only system, HOMER's optimal system was found not to be cost-effective.

One of the HOMER options used here is to force the PV system to cover any fraction of the load and give the optimization result for it. After choosing three different fractions 25%, 50%, 75% of the factory load, the power consumption is considered

5.2 Sensitivity Analysis

5.2.1 First Scenario

5.2.1.1 HOMER Result

- Design System (1):

In the figure below HOMER shows the optimal system that covers 25% of the factory load. The optimal system presented required 26% coverage instead of 25% of the factory load as shown in Figure (5-4).

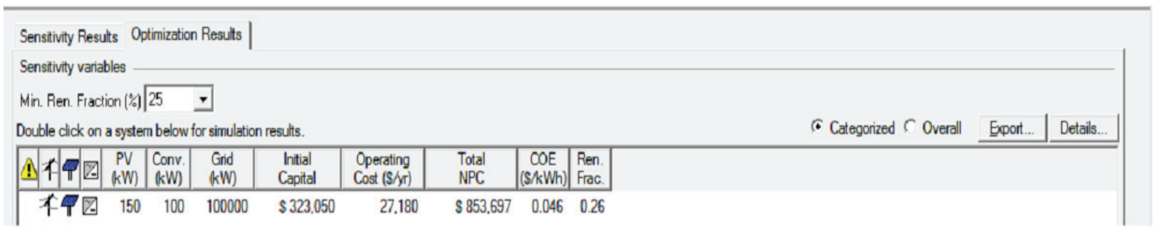


Figure (5-4): Scenario (1), the optimal result for system (1).

With the new system the monthly average electricity production is shown in Figure (5-5).

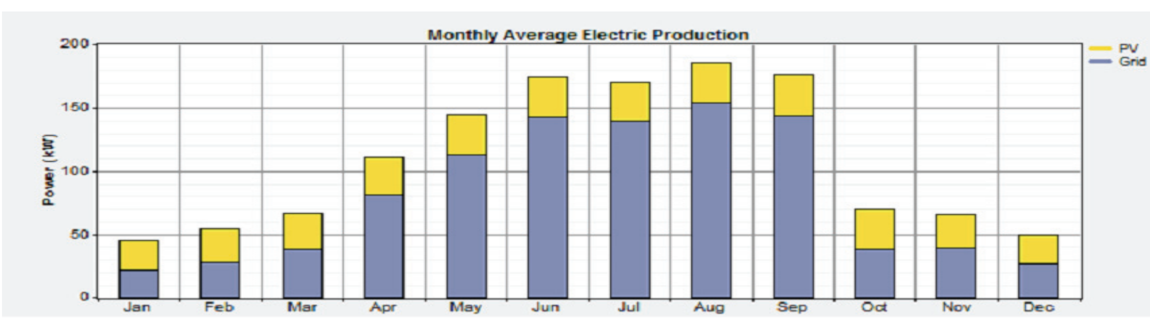


Figure (5-5): The monthly average electric production for system (1).

The new PV system configuration shown in Table (5-5) shows that the new bigger PV panel size obtained for the optimal system is the same size of the inverter. The PV size is 150 KW with a capital cost of $ 278,850 while the maintenance costs are equal to zero. The inverter cost with the regular maintenance equals $53,962.

Table (5-5): Scenario (1) system size and cost for system (1).

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	150	278,850	0	278,850
Inverter	100	44,200	9,762	53,962

Table (5-6) shows the details of the electrical production and consumption. The 26% of the factory load supplied by the alternative system produced 255,232KWh/yr while the rest of the load (74%) supplied by the grid produced 705,404KWh/yr. In this option, the system still gets most of the power from the grid. In addition the system sellback is 5.902 KWh/yr to the grid while the excess electricity is less than 1%.

Table (5-6): Scenario (1) Electrical detail for system (1).

		Production (KWh/yr.)	Fraction %
Production	Alternative system	255,232	26
	Grid purchase	705,404	74
Consumption	AC primary load	904,487	95
	Grid sale	5.902	5
	Excess electricity	42,797	0.6

The cost of the alternative system is $332,811. The NPC, COE and operating cost of the new system are 853697$, 0.046/KWh and 27,180/yr respectively. Most of the power is still purchased from the grid ($520,886) Table (5-7).

Table (5-7): Scenario (1) Economic analysis for system (1).

Component	Total ($)
PV system	332,811
Grid purchase	520,886
NPC	853,697
COE	0.046 /KWh
Operating	27,180 /yr.

- Design System (2):

In Figure (5-6) below HOMER shows the optimal system for a new fraction. The PV system size increased to 330 KW while the inverter size increased to 250 KW.

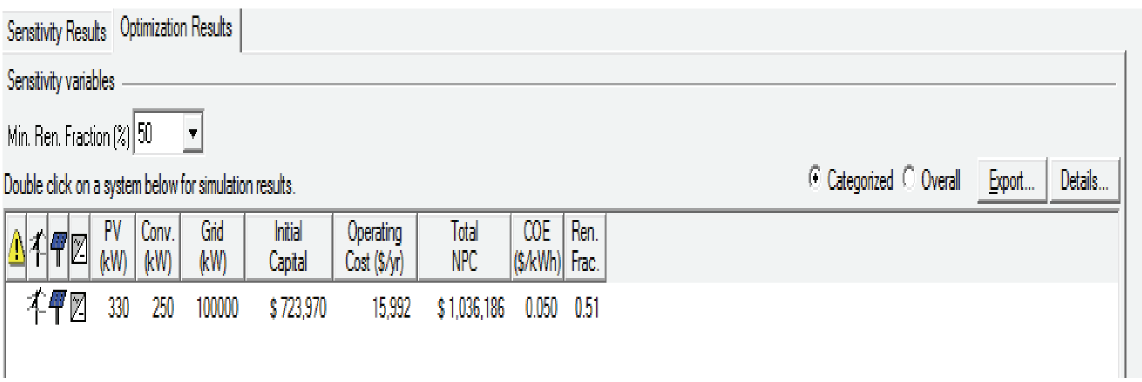


Figure (5-6): Scenario (1), the optimal result for system (2).

The new system covers 50% of the total factory load. The optimal system is to cover 52% instated of 50% of the factory load. Figure (5-7) shows the monthly average electrical production with system 2.

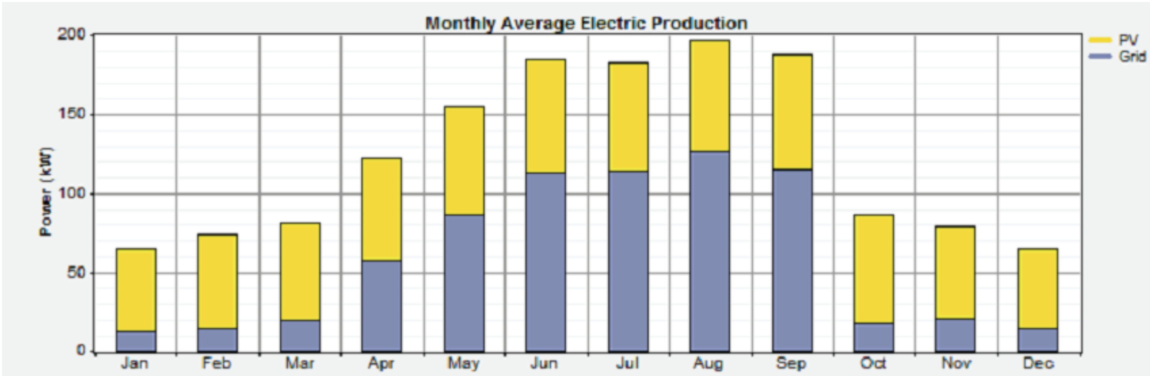


Figure (5-7): The monthly average of electric production for system (2).

The new PV system configuration shown in Table (5-8) shows that the new larger PV panel size costs $613,470 while the new inverter total costs $134,904.

Table (5-8): Scenario 1 system size and cost for system (2).

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	330	613,470	0	613,470
Inverter	250	110,500	24,404	134904

Table (5-9) shows the detail of the electrical production and consumption. The alternative system supplied 52% of the factory load and produced 561,513KWh/yr while the rest of the load (48%) was supplied by the grid and produced 519,993KWh/yr. The system is starting to get a higher amount of power from the PV system than from the grid. In addition, the system sell-back was 158,33 KWh/yr to the grid with excess electricity of less than 1%.

Table (5-9): Scenario (1) Electrical detail for system (3).

Electricity	Component	Production (KWh/yr.)	Fraction %
	Load		
Production	Alternative system	561,513	52
	Grid purchase	519,993	48
Consumption	AC primary load	904,487	85
	Grid sale	158,33	15
	Excess electricity	1,878	0.17

The cost of the alternative system is $748,374. The NPC, COE and operating cost of the new system are 1,036,186$, 0.05/KWh and 15,992/yr respectively. The grid purchase cost is $287,812, as shown in Table (5-10).

Table (5-10): Scenario (1) Economic data for the system (2).

Component	Total ($)
PV system	748,374
Grid purchase	287,812
NPC	1,036,186
COE	0.050 /KWh
Operating	15,992 /yr.

- Design System (3): Covering 75 % of the Total Load

HOMER shows the optimal system for a new fraction in Figure (5-8). The new PV system size is 600 KW while the inverter size is 480KW. The total net present cost is $1,327,560

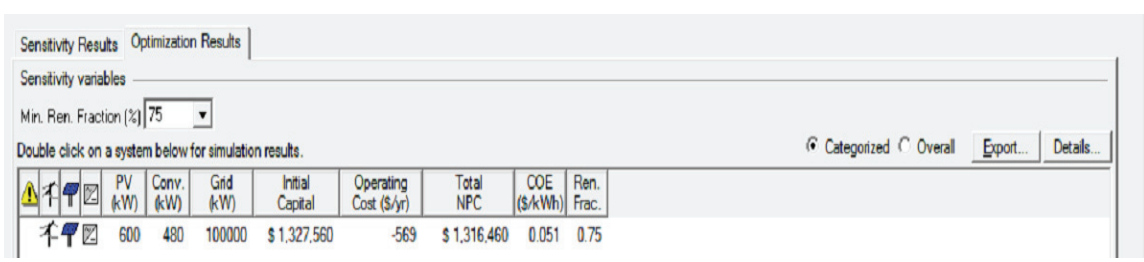


Figure (5-8): Scenario (1), the optimal result for system (3).

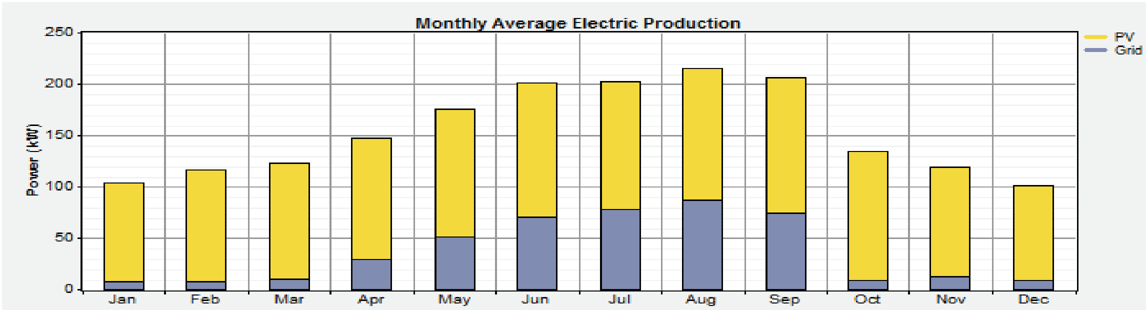


Figure (5-9): The monthly average electrical production.

System 3 covers 75% of the factory load. The optimal system is to cover 76% instead of 75% of the factory load. The Figure (5-9) shows the monthly average electrical production with the new system.

The new PV system configuration shown in Table (5-11) shows that the new bigger PV panel size cost $1,115,400 while the new inverter total cost $259,016.

Table (5-11): Scenario (1) size and cost for system (3).

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	600	1,115,400	0	1,115,400
Inverter	480	222,160	46,856	259.016

Table (5-12) shows the detail of the electrical production and consumption. The 76% of the factory load supplied by the alternative system produced 1,020,929 KWh/yr while the rest of the load (24%) supplied by the grid produced 329,716 KWh/yr. The new system gets most of the power from the PV system rather than from the grid. In addition, the system sellback was 414,655 KWh/yr to the grid while the excess electricity is still less than 1%.

Table (5-12): Scenario (1), Economic analysis for system (3).

Electricity	Component / Load	Production (KWh/yr.)	Fraction %
Production	Alternative system	1,020,929	76
	Grid purchase	329,716	24
Consumption	AC primary load	904,487	69
	Grid sale	414,655	31
	Excess electricity	933	0.07

Table (5-13) shows the cost of the alternative system is $1,374,416, which makes it the highest cost variable. The NPC and the COE of the new system are 1,316,460$, 0.051/KWh respectively. The grid purchase and the operating cost in this system is a negative value that means the system produced more power than the required amount to cover the load and sell it to the grid.

Table (5-13): Scenario1, Economic data for the system (3).

Component	Total ($)
PV system	1374416
Grid purchase	-57,956
NPC	1,316,460
COE	0.051
Operating	-563/yr

The summary table for the results from HOMER for the first scenario is shown in Table (5-14).

Table (5-14): Scenario (1), the summary table for scenario (1).

Load cover by PV	25%	50%	75%
Homer %	26%	52%	76%
PV size / inverter size	150/100	330/250	600/480
COE	0.046	0.050	0.051
NPC	853,697.00	1,036,186.00	1,316,460.00

As we can see in all results presented for the three systems there is little change in the renewable fraction by increasing 1% or 2% for the optimal systems presented by HOMER. The NPC increases with the increasing size of the alternative system because the capital cost increases. The cost of energy also changes with the alternative system change. All the simulation results NPC and COE are higher than the only grid system. On the other hand, system 3 is the only system that benefits by the end of the year (because it sells to grid a larger amount of power than it purchases from the grid).

In order to accept or reject any of the aforementioned systems, further economic analysis was needed, such as an analysis of the payback period and internal interest rates (IRR).

5.2.1.2 Economic Calculation

The calculation was started by calculating factors such as discount rate and CRF to complete the economic study. After that economic equations were used to calculate all the parts needed to calculate the LCC for each system such as the initial cost, the annual maintenance cost, salvage cost and the power purchase. Moreover, all the results were compared to the HOMER results, which used different equations for the economic calculation. In addition the payback of the system and the IRR for all systems was calculated.

Table (5-15): Scenario (1), economic calculation.

Discount rate	0.02	Years	25	CRF	0.051220438
	System1		System2		System3
System size KW	150		330		600
PV					
Price	278,850.00		613,470.00		1,115,400.00
Annual main	0.00		0		0
LCC.main	0.00		0		0
Life time	25.00		25		25
Total price	278850.00		613,470.00		1,115,400.00
Price /w	0.049		0.054		0.052
Inverter	100		250		480
Price	$44,200.00		$110,500.00		$212,160.00
Annual main.	500.00		1250.00		2400.00
LCC main.	9,761.00		24,404.00		46,856.00
Life time	25.00		25.00		25.00
Total price	44200.00		110500.00		212160.00
Price /w	0.42		0.42		0.42
System price					
Capital cost	332,811.00		748,374.00		1,374,416.00
Grid purchase	520,886.00		287,812.00		-$57,956.00
Total cost	853,697.00		1,036,186.00		1,316,460.00
Total power product	960,637.00		1,081,506.00		1,350,646.00
COE	0.046		0.05		0.050
Salvage cost	66,562.20		149,674.80		274,883.20

From Table (5-15) we see similar results as from HOMER software, such as total system cost and the COE. To calculate the payback, the total yearly income gathered from selling electricity to the grid with the various seasonal and weekday changes of tariff were taken into consideration and illustrated in Table (5-16).

Table (5-16): Calculation the total price of sold power.

Total price of power sold		PV system size		
Period	Price c/kw	Sys1	Sys 2	Sys 3
12h	0.032	$31,587.00	$109,686.00	$302,386.00
15h	0.04	$4192	$16723	$35983
10h	0.027	$108	$3048	$12766
26h	0.069	$6910	$28922	$63520
Total price		$1,658.17	$6,256.79	$15,843.23

The electricity rate annual inflation was also considered, this was calculated to be (i) to be equal to the inflation in Saudi Arabia = 4% [58].

5.2.1.3 Payback for scenario (1) systems

1- The payback for system (1):

Table (5-17): Scenario (1), the payback for system (1).

System 1					
Revenues &expenses	Year 0	Year 1	Year 2	Year 24	Year 79
Initial cost &salvage	-$853,697.00			33,281.10	
Power sales		1,658	1,724	4,087	35,337
Cumulative elec. sales		1,658	3,383	64,806	877,307
Simple payback		-852039	-850314	-788891.40	23610.42

From Table (5-17) system (1) will take 79 years (which is more than the project life). This made the system not cost-effective and unacceptable. Since the system was not cost effective and the payback was more than the lifespan of the IRR the resulting negative calculation is not acceptable.

2-The payback for system (2):

Table (5-18): Scenario (1), the payback for system (2).

System 2					
Revenues &expenses	Year 0	Year 1	Year 2	Year 24	Year 52
Initial cost &salvage	-$1,036,186.00			74,837.40	
Power sales		6,257	6,507	15,421	46,244
Cumulative elec. sales		6,257	12,764	244,531	1,045,914
Simple payback		-1029929	-1023422	-791655	9728

As we can see it will take to 52 years to payback the cost (which is more than the project life) as shown in Table (5-18). This makes the system not cost-effective and not acceptable therefore the IRR is not acceptable.

3- The payback for system (3):

Table (5-19): Scenario (1), the payback for system (3).

System 3					
Revenues &expenses	Year 0	Year 1	Year 2	Year 24	Year 38
Initial cost &salvage	-$1,316,460.00			137,441.60	
Power sales		15,843	16,477	39,049	67,620
Cumulative elec. sales		15,843	32,320	619,195	1,362,048
Simple payback		-$1,300,616.77	-$1,284,139.80	-$559,823.56	$45,588.15

From Figure (5-19) as we can see it takes 38 years (which is more than the project life). This made the system not cost-effective and not accepted. Since the system was not cost effective, there was no need to the calculate IRR.

It is evident that the payback is reduced when the quantity of power sold to the grid increases. Since system 3 sells more power to the grid, the system has the least payback time (38 years as opposed to 79 years and 52 years in the other two systems). However, since all three systems require a payback period that exceeds the lifespan of the project, the first scenario is not a cost effect system.

5.2.1.4 Conclusions for Scenario (1)

Comparing all systems to the grid-only system was not cost effective. All the systems have a higher NPC because of the initial cost for the PV system and the fact that the grid system is the only system with a lower COE. In addition, the assumed sellback price is not acceptable because even the system selling the most power to the grid was still economically not acceptable.

5.2.2 Second Scenario

In the second scenario we have changed the feed-in tariff to find a cost effective system, assuming the power utility will pay for electricity at a higher price (0.069c/kw) than they sell the power to the industrial sector.

5.2.2.1 HOMER Result

- Design System (1):

PV system size and cost:

The PV system configuration shown in Table (5-20) shows the same size of the inverter. The PV size is 150 KW with a capital cost of $278,850 while the maintenance is equal to zero. The inverter cost with regular maintenance is equal to $53,962

Table (5-20): Scenario (2) system (1) size and cost.

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	150	278,850	0	278,850
Inverter	100	44,200	9,762	53,962

In this scenario's first system, 26% of the factory load is supplied by the alternative system while the rest of the load (74%) is supplied by the grid, illustrated in

Table (5-21). In addition, the system sells 5.9 KWh/yr to the grid while the excess electricity is less than 1%

Table (5-21): Scenario (2) Electrical data for system (1).

		Production (KWh/yr.)	Fraction %
Production	Alternative system	255,232	26
	Grid purchase	705,404	74
Consumption	AC primary load	904,487	95
	Grid sale	5.902	5
	Excess electricity	42,797	0.6

Table (5-22): Scenario 2 Economic data for system (1).

Component	Total ($)
PV system	332,811
Grid purchase	495,606
NPC	828,417
COE	0.045 /KWh
Operating	25,885 /yr.

From Table (5-22) the only change with the new feed-in tariff is the grid purchase because the price for sellback change makes the grid purchase decrease. This makes the NPC of the system decrease, thus also making the COE decrease. Finally this shows the sellback is effective economically.

- Design System (2):

From Tables (5-23, 24) there is no change in the size and the cost of the optimal system. Also there is no change in the electrical consumption.

Table (5-23): Scenario (2) system (2) size and cost.

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	330	613,470	0	613,470
Inverter	250	110,500	24,404	134904

Table (5-24): Scenario (2) Electrical data for system (2).

Electricity	Component	Production (KWh/yr.)	Fraction %
	Load		
Production	Alternative system	561,513	52
	Grid purchase	519,993	48
Consumption	AC primary load	904,487	85
	Grid sale	158,33	15
	Excess electricity	1,878	0.17

The change in the new scenario took place in the economic analysis portion. The grid purchase was reduced from \$287,812 to \$196,592. Thus the NPC also decreased, which affected the COE. The COE reduced from 0.05/KWh to 0.046/KWh, as shown in Table (5-25).

Table (5-25): Scenario (2) Economic data for system (2).

Component	Total (\$)
PV system	748,374
Grid purchase	196,592
NPC	944,966
COE	0.046/KWh
Operating	11,320 /yr.

- Design System (3):

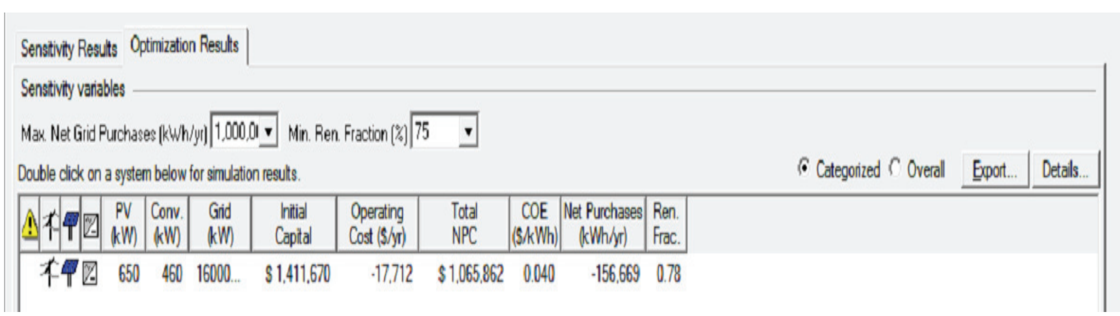


Figure (5-10): Scenario (2), the optimal result for system (3).

For the biggest system fraction coverage of the load, the optimal system from HOMER totally changed. The new system with a different size and cost was obtained, as shown in Figure (5-10). In addition, the fraction also changed from 77% to 79% with a 2% increase from the system in the first scenario. The monthly average electricity production for system3 is shown in Figure (5-11)

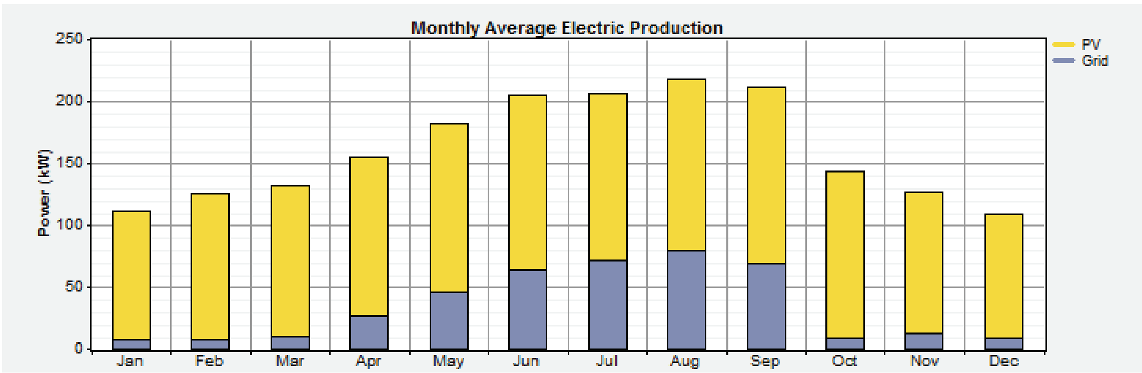


Figure (5-11): Scenario (2) the monthly average for system (3).

For system 3, the new size of the PV system is 650KW while the inverter size is reduced to 460KW. The total cost for the PV kit is $1,208,350. The inverter cost and maintenance cost $248,224 as shown in Table (5-26).

Table (5-26): Scenario (2), PV system size and cost for system (3).

Component	Size (KW)	Capital cost ($)	O&M ($)	Total ($)
PV Kit	650	1,208,350	0	1,208,350
Inverter	460	203,320	44,904	248,224

Table (5-27) shows the details of the electrical production and consumption. When 79% of the factory load was supplied by the alternative system, the system produced 1,106,007 KWh/yr while the rest of the load (21%) supplied by the grid produced 302,759 KWh/yr. The system can cover the load but the electricity needed to operate during the evening and night still comes from the grid. In addition, the system sellback fractions increased to 34% and sold 459,428 KWh/yr to the grid, while the excess electricity was still less than 1%.

Table (5-27): Scenario (2), Electrical data for system (3).

Electricity	Component / Load	Production (KWh/yr.)	Fraction %
Production	Alternative system	1,106,007	79%
	Grid purchase	302,759	21
Consumption	AC primary load	904,487	66
	Grid sale	459,428	34
	Excess electricity	12,061	0.86

Table (5-28) shows the cost of the alternative system is $1,456,574, which makes it the highest cost as the size changed. On the other hand, the NPC and the COE of the new system are 1,036,136$, 0.04/KWh respectively. This is less than in system 3 in the first scenario1, and is due to the fact that the grid purchase increased to $ -390,712 when the feed-in tariff changed in the second scenario.

Table (5-28): Scenario (2), Economic results for system (3).

Component	Total ($)
PV system	1,456,574
Grid purchase	-390,712
NPC	1,036,186
COE	0.040/KWh
Operating	-17,712 /yr.

After running the simulation with the new FIT, the following results were obtained as shown in Table (5-29):

Table (5-29): summary results for the second scenario.

PV % cover from the load	26%	52%	79%
PV/ inverter size	150/100	330/250	650/460
NPC	828,417	944,966	1,065,862
COE	0.045	0.046	0.040
Electricity From the grid (kwh/year)	705,404	519,993	30,759
Electricity Sale to the grid (kwh/year)	42,797	158,397	459,428

5.2.2.2 Economic Calculation

The economic calculation for the three systems for the new scenario is shown in Table (5-30)

Table (5-30): The economic calculation for the second scenario.

Discount rate	0.02	Years	25	CRF	0.051220438
	26%		52%		77%
System size KW	150		330		650
PV					
Price	278,850.00		613,470.00		1,208,350.00
Annual main	0.00		0		0
LCC.main	0.00		0		0
Life time	25.00		25		25
Total price	278850.00		613,470.00		1,208,350.00
Price /w	0.049		0.054		0.056
Inverter	100		250		460
Price	$44,200.00		$110,500.00		$203,320.00
Annual Main.	500.00		1250.00		2300.00
LCC main.	9,761.00		24,404.00		44,903.00
Life time	25.00		25.00		25.00
Total price	44200.00		110500.00		203320.00
Price /w	0.42		0.42		0.42
System price					
Capital cost	332,811.00		748,374.00		1,456,573.00
Grid purchase	495,606		196,592.00		-$390,712.00
Total cost	828,417.00		944,966.00		1,065,861.00
COE	0.044		0.045		0.04
Salvage cost	83,202.8		187,093.50		364,143.25

Economic calculations showed similar results to the results simulated by HOMER. To make the final decision on which system is the optimal system we need to calculate the payback and IRR.

5.2.2.3 The payback for the second scenario

1- The payback for system (1)

Table (5-31): Scenario (2), the payback for system (1).

System 1					
Revenues &expenses	Year 0	Year 1	Year 2	Year 24	Year 61
Initial cost &salvage	-$828,417.00			33,281.10	
Power sales		3,356	3,490	8,272	35,306
Cumulative elec.sales		3,356	6,847	131,170	834,058
Simple pay back		-825061	-821570	-697246.83	5640.52

2- The payback for system (2)

Table (5-32): Scenario (2), the payback for system (2).

System 2					
Revenues &expenses	Year 0	Year 1	Year 2	Year 24	Year 38
Initial cost &salvage	-$944,966.00			74,837.40	
Power sales		11,488	11,947	28,314	49,030
Cumulative elec. sales		11,488	23,435	448,963	987,587
Simple pay back		-933478	-921531	-496003	42621

3- The payback for system (3)

Table (5-33): Scenario (2), the payback for system (2)

System 3					
Revenues &expenses	Year 0	Year 1	Year 2	Year 22	Year 24
Initial cost &salvage	-$1,065,862.00				31,335.52
Power sales		31,336	32,589	71,406	77,233
Cumulative elec. sales		31,336	63,924	1,073,178	1,224,674
Simple payback		-$1,034,526.48	-$1,001,937.54	$7,316.01	$190,147.32

The payback was reduced with the new FiT. In system 1 the payback was reduced from 79 years to 61 years, as illustrated in Table (5-31). System 2 showed a payback reduction from 52 years to 38 years, showin in Table (5-32). In Table (5-33) system 3 showed a payback reduction to 22 years, which is less than the lifetime of the system. That makes system 3 the only cost effective system, as shown in Figure (5-12).

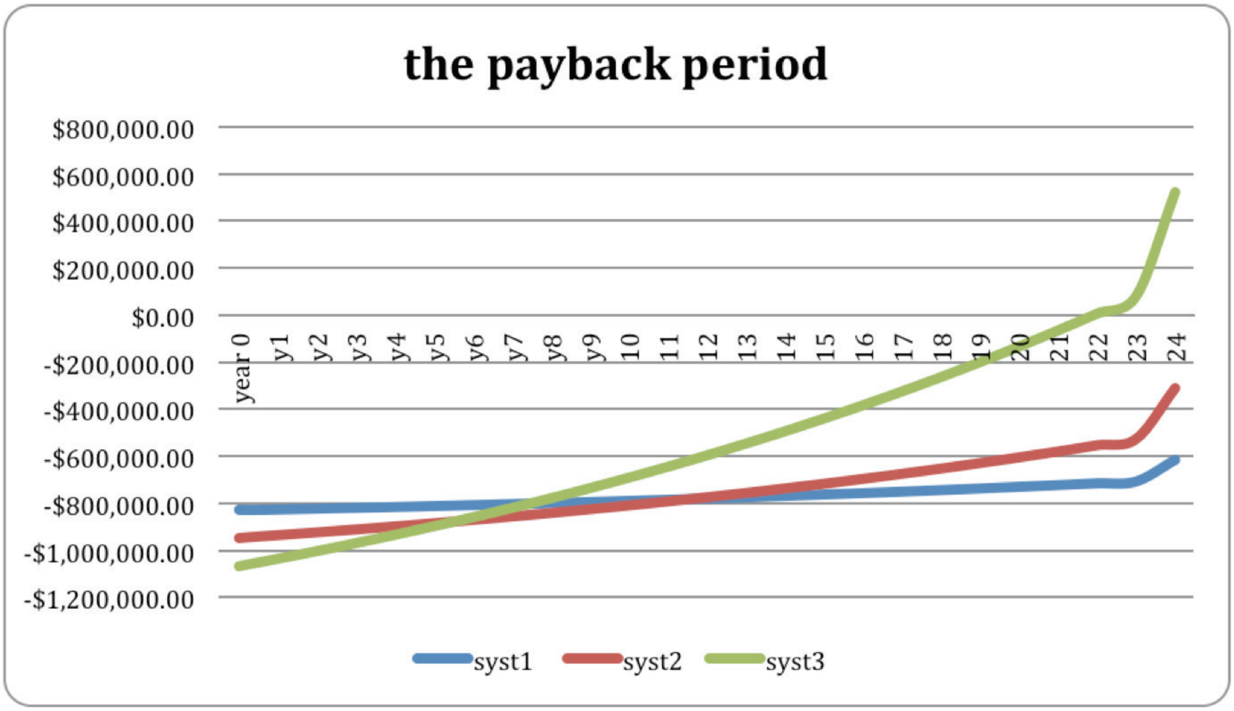


Figure (5-12): The payback for senior (2) for all systems.

After the payback results the last economic test for the system is the internal rate of return (IRR). The IRR for the three systems with the new FiT is shown below:

Table (5-34): Scenario 2 the IRR for the systems.

	Sell back Tariff = 0.069		
	System 1	System2	System3
Year 0	-$828,417.00	-$944,966.00	-$1,065,862.00
Year 1	$3,356.23	$11,487.53	$31,335.52
Year2	$3,490.48	$11,947.04	$32,588.94
Year3	$3,630.10	$12,424.92	$33,892.50
Year4	$3,775.30	$12,921.91	$35,248.20
Year5	$3,926.31	$13,438.79	$36,658.13
Year6	$4,083.37	$13,976.34	$38,124.45
Year7	$4,246.70	$14,535.40	$39,649.43
Year8	$4,416.57	$15,116.81	$41,235.41
Year9	$4,593.23	$15,721.48	$42,884.83
Year10	$4,776.96	$16,350.34	$44,600.22
Year11	$4,968.04	$17,004.36	$46,384.23
Year12	$5,166.76	$17,684.53	$48,239.60
Year13	$5,373.43	$18,391.91	$50,169.18
Year14	$5,588.37	$19,127.59	$52,175.95
Year15	$5,811.90	$19,892.69	$54,262.99
Year16	$6,044.38	$20,688.40	$56,433.50
Year17	$6,286.15	$21,515.94	$58,690.85
Year18	$6,537.60	$22,376.57	$61,038.48
Year19	$6,799.10	$23,271.64	$63,480.02
Year20	$7,071.07	$24,202.50	$66,019.22
Year21	$7,353.91	$25,170.60	$68,659.99
Year22	$7,648.07	$26,177.43	$71,406.39
Year23	$7,953.99	$27,224.52	$74,262.64
Year24	$8,272.15	$28,313.50	$77,233.15
Salvage cost	83,202.75	$187,093.50	364,143.25
IRR	-7%	-2%	3%

For the IRR results, system 3 is the only system with an IRR larger than the discount rate (2%). The other two systems have an IRR less than the discount rate, which makes them unacceptable as illustrated in Table (5-34). The only acceptable system was system 3.

As one of our goals was to reduce the power consumption from the utility, Figure (5-13) describes the power purchase from the grid showing the relation between the system size and the power purchased. System 3 reduced the power purchased from the utility only in the summer, with the amount of power not exceeding 110,573KW in August (the hottest month). That means using system 3 can reduce the power consumed from the grid by 18.2% in the hottest month.

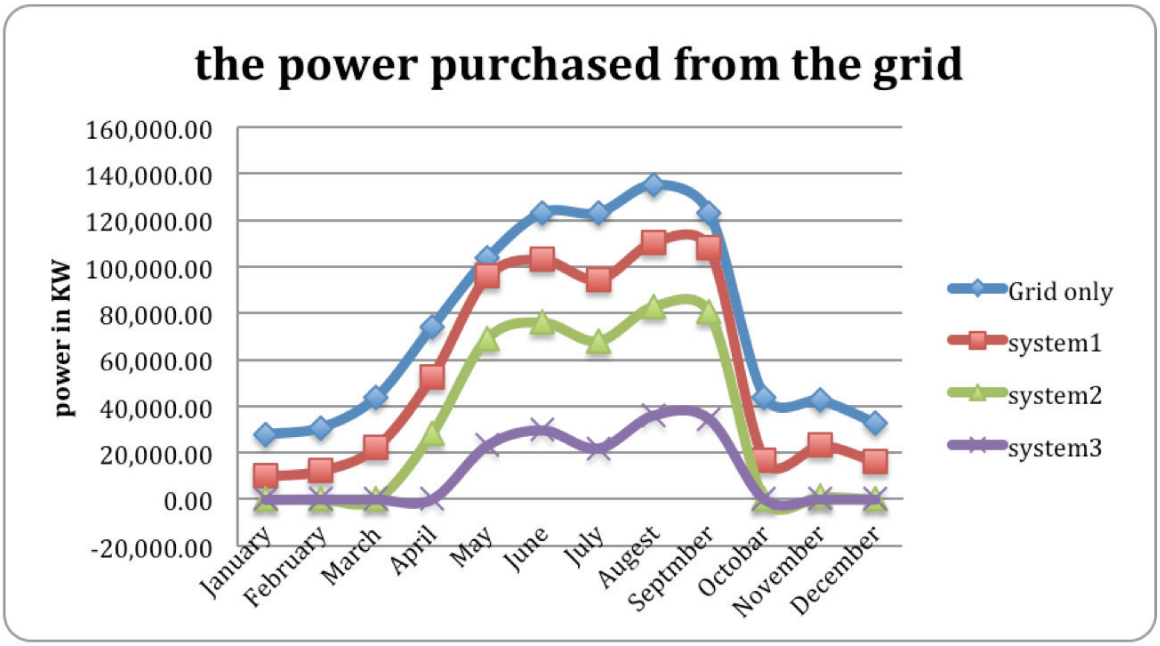


Figure (5-13): The power purchased from the grid.

Conclusions for scenario (2):

The simulation for the second scenario shows the same optimization results for the PV system 1 and system 2 in the electricity consumption but with a change in the NPC and the COE because of the new FiT. On the other hand, system 3 has a new size for the PV and the inverter. System 3 has the best optimization results with the lowest COE equal to the COE on the grid only, and a reduction in power purchased to 21% but with high NPC. In addition, system 3 is the only system that has PB less than the lifetime of the system.

In the last economic test, the IRR only system 3 is acceptable because the IRR is greater than the discount rate.

5.3 The Effects on Payback Period

System 3 in the second sceanrio was chosen as the optimal system for the factory with specification details in Table(5-35). The resulting parameters (load changes and potetial monteray subsidies) can reduce the payback period and in turn make the PV system more efficient.

Table (5-35): The optimal system specification.

System3 (PV=650 KW, inverted = 460KW):	
Power consumption (KW)	904,487
Grid purchased (KW)	30,2759
Power from PV	601,728
Power save %	66.5
Payback	22 year

5.3.1 The Load

With the same PV system size the payback will be changed if the load increases or decreases by any percentage. Any change in the load will affect the power sold to the grid. That means if the load increases the power sold to the grid will decrease by the same percentage. This effect (assuming the factory load change by ± 5% and ± 25%) is illustrated in the following Table (5-36).

Table (5-36): Load change.

	Factory load	+5%	-5%	+25%	-25%
Jan	28000	29400	26600	35000	21000
Feb	30800	32340	29260	38500	23100
Mar	44000	46200	41800	55000	33000
Apr	74000	77700	70300	92500	55500
May	103600	108780	98420	129500	77700
Jun	123200	129360	117040	154000	92400
Jul	123200	129360	117040	154000	92400
Aug	135200	141960	128440	169000	101400
Sep	123200	129360	117040	154000	92400
Oct	44000	46200	41800	55000	33000
Nov	42400	44520	40280	53000	31800
Dec	32800	34440	31160	41000	24600

Figure (5-14, 5-15) shows the change in the load in each month during the year with the assumed percentage.

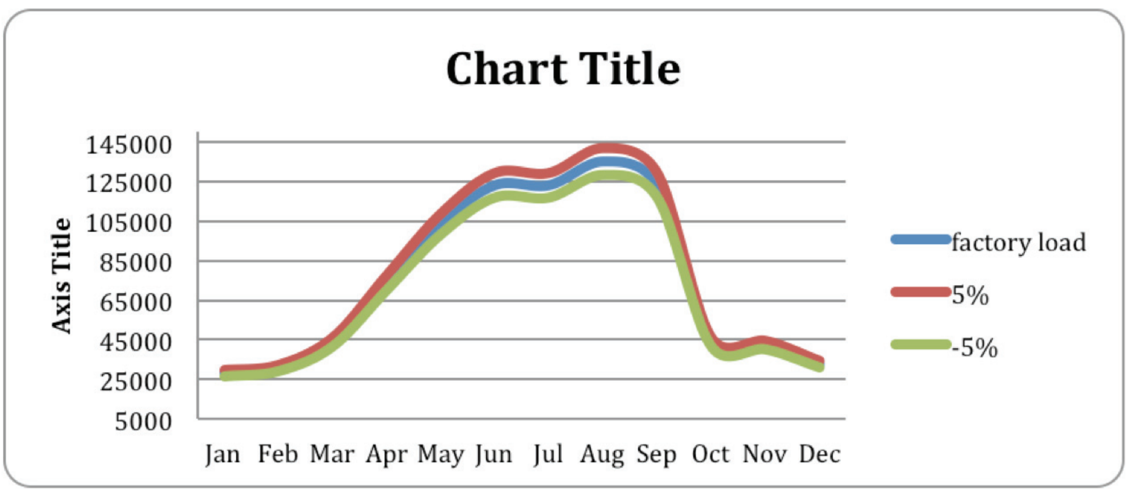


Figure (5-14): Load change by ± 5%.

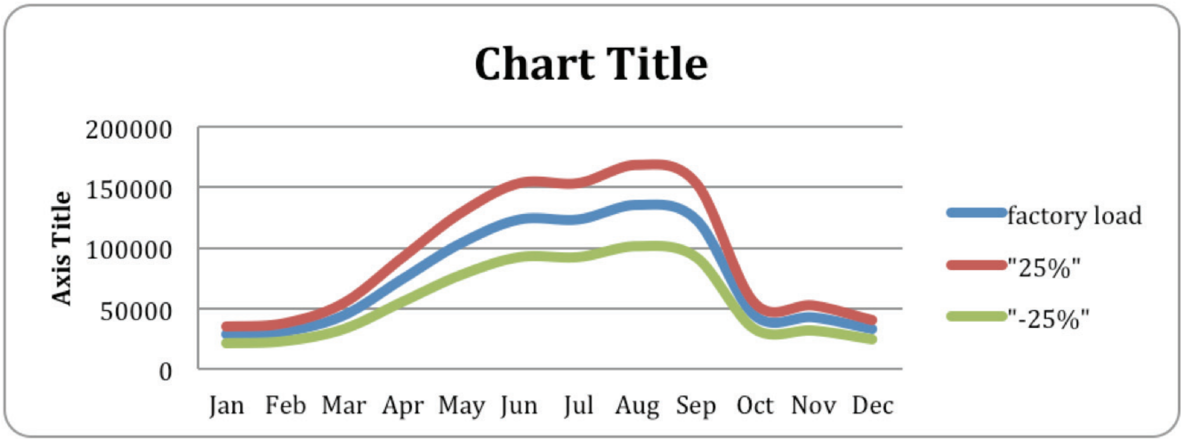


Figure (5-15): Load change by ± 25%.

Changes to the factory load will affect the payback time. We assume that when the load increases by 5% or 25% the power from the PV system that sells back to the grid will decrease by the same percentage. Further, we assume that will also reduce the revenue from using the PV connected grid will increase the power consumed from the utility. Figures (5-16, 5-17) show the change in the payback time with different percentages in the load change.

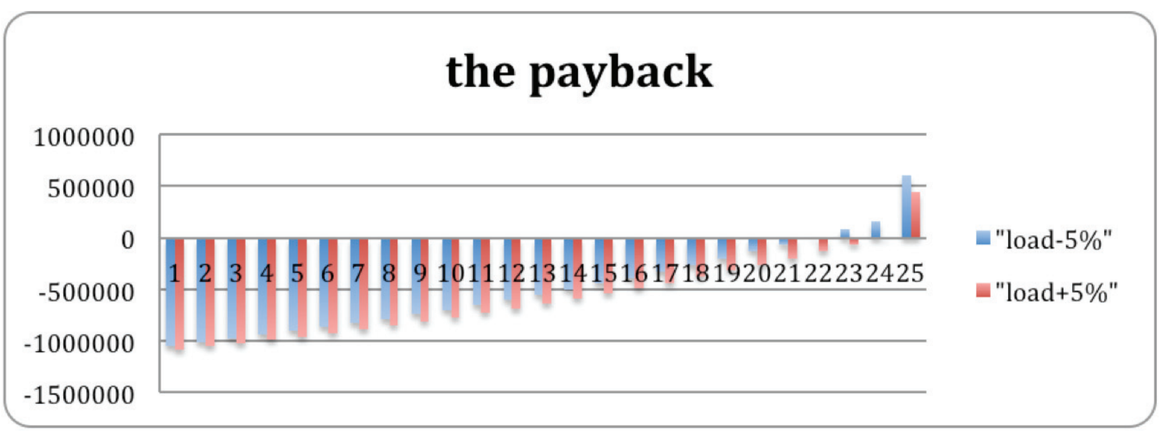


Figure (5-16): The payback for load change by 5%.

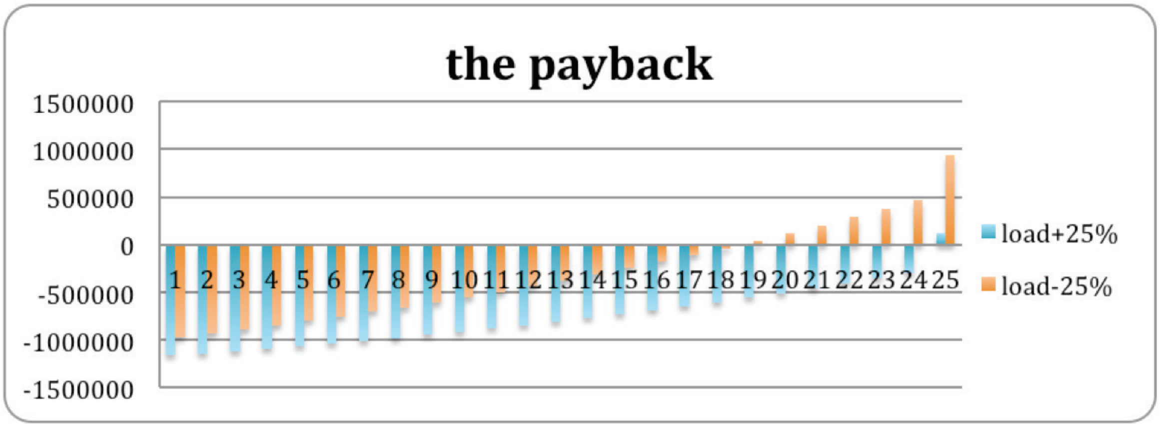


Figure (5-17): The payback for load change by 25%.

Table (5-37) shows the parameter change with load consumption change. First the cost of the system will increase or decrease depending on the change in load. The payback of the system also will change.

Table (5-37): The payback vs. load change.

Load change	+5%	-5%	25%	-25%
Total cost	1,085,397.55	1,046,326.45	1,163,539.75	968,184.25
Power sales	29,768.75	32,902.30	23,501.64	39,169.40
Payback	22	20	23	18

Figure (5-18) shows the relationship between the changes in the load and the payback time. The relationship shows that a reduction in the load consumption will reduce the payback. Reducing the power consumption by 25% will reduce the payback to 18 years as opposed to 22 years with normal consumption.

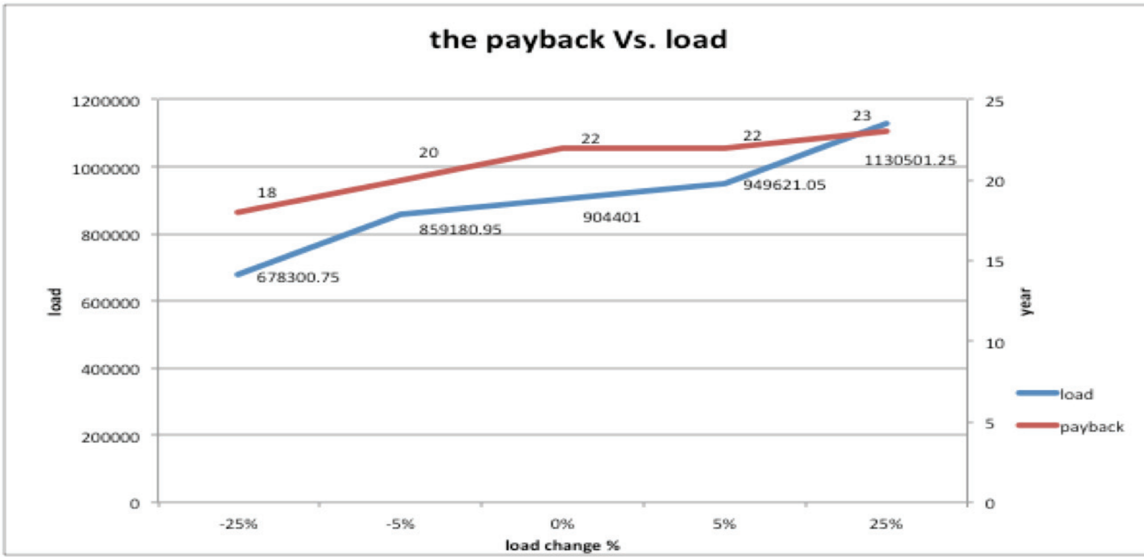


Figure (5-18): Payback vs. load.

5.3.2 Subsidy by the Saudi Arabia Government:

Until now there is has been no government subsidy available for solar energy systems in Saudi Arabia. If we assume that the government will potentially subsidize the initial cost for a PV system by 10%, 15%, or 20 % the initial cost and total cost for the system is shown in Table (5-38).

Table (5-38): The government subsidy table.

Subsidy	0%	10%	15%	20%
Initial cost $	1,411,670	1,411,670	1,411,670	1,411,670
Total subsidy $	0	141,167	211,750.5	282,334
Total initial cost $	1,411,670	1,270,503	1,199,919.5	1,129,336
Total system cost $	1065861	924694	854110.5	783527

After we applied the different subsidy percentages to the system, we recalculated the payback and IRR for each subsidy percentage. The first government subsidy assumption is 10% therefore the initial cost will be $1,270,503 and the total cost will be

$924,694. This reduction in the total cost will reduce the payback to 20 years instead of 22 years. The IRR does not change, as shown in Table (5-39) below.

Table (5-39): The payback with 10% government subsidy.

System 3				
Year	Year 0	Year1	Year2	Y20
Initial cost &salvage	-$924,694.00			
Power sales		31,336	32,589	66,019
Cumulative elec. sales		31,336	63,924	933,112
Simple payback		-$893,358.48	-$860,769.54	$8,417.64
IRR	3%			

The second government subsidy assumption is 15%. This reduces the total cost to $854,110.5, which reduced the payback to 19 years instead of 22 years. The IRR increased by 1% as shown in Table (5-40) below.

Table (5-40): The payback with 15% government subsidy.

System 3				
Year	Year 0	Year1	Year2	Year19
Initial cost &salvage	-$854,110.50			
Power sales		31,336	32,589	63,480
Cumulative elec. sales		31,336	63,924	867,092
Payback		-$822,774.98	-$790,186.04	$12,981.92
IRR	4%			

The last government subsidy assumption is 20%. This decreases the total cost to $854,110.5, which reduced the payback to 18 years instead of 22 years. The IRR increased by 2% to be 5% as shown in Table (5-41) below.

Table (5-41): The payback with 20% government subsidy.

System 3				
Year	Year 0	Year1	Year2	Year18
Initial cost &salvage	-$783,527.00			
Power sales		31,336	32,589	61,038
Cumulative elec. sales		31,336	63,924	803,612
Payback		-$752,191.48	-$719,602.54	$20,085.40
IRR	5%			

Figure (5-19) shows that the government subsidy can reduce the payback and make using the PV system connected grid more attractive to new consumers, especially in the industrial sector, which can accept long run projects.

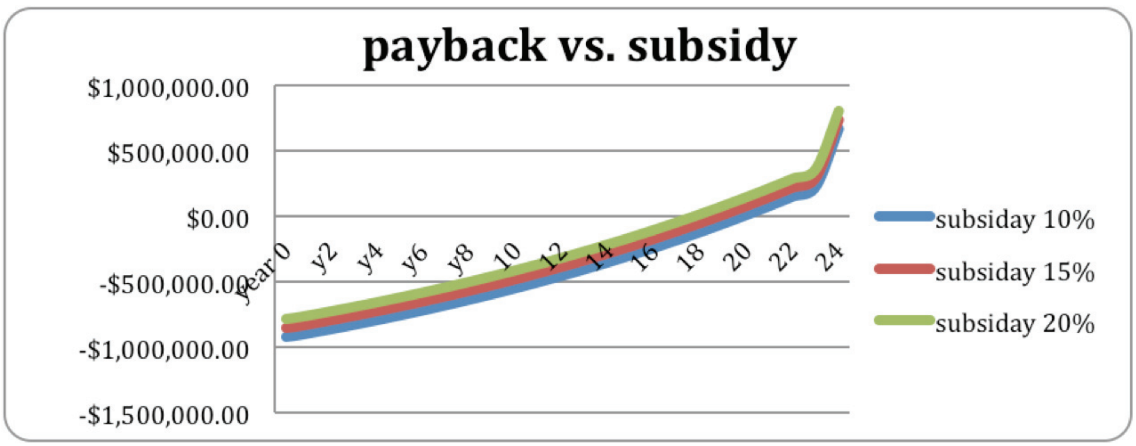


Figure (5-19): The payback vs. subsidy.

As the last point of this study, if we assume the Saudi government will subsidize the PV connected grid in the industrial sector by 20% and the electricity utility applies the new FiT, which was assumed in the second scenario the result would be a reduction in load consumption by the factories by 25%. The optimal system we chose (system 3 in the second scenario) will reduce costs to $685,850.25, illustrated in Table (5-42). Also the payback decreased to 14 years, as shown in Figure (5-20).

Table (5-42): The final PV system cost.

The parameter	Cost $
PV kit cost	1,208,350
Inverter cost	203,320
Total PV system cost	1,411,670
Total with subsidy	1,129,336
Maintenance	44,903
Capital cost	1,174,239
Grid purchase	- 488,388.75
Total cost	685,850.25

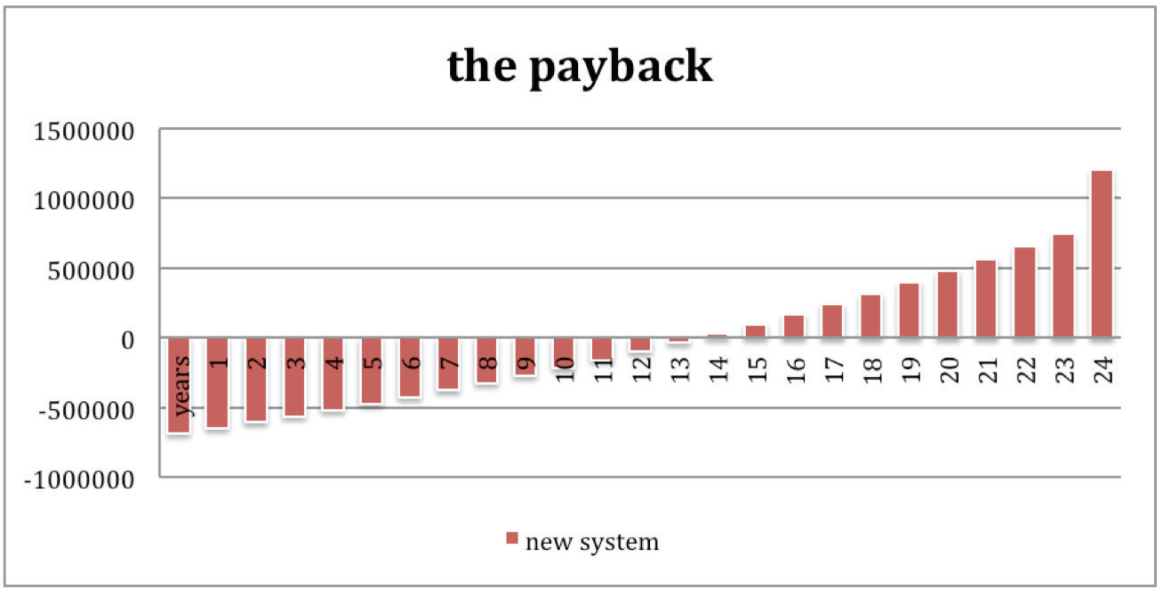


Figure (5-20): The payback for the final system.

CHAPTER 6 CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Conclusion

In conclusion this study used HOMER to simulate a potential application of a grid connected PV system used to generate solar power in KSA. The daily energy consumption used to simulate the system was gathered from a sample factory in the industrial sector of the city of Jeddah. The average daily radiation and temperature was used to assist in the simulation. The cost of the tariff for electricity was gathered from the current utility in KSA. After using HOMER to simulate a potential optimal system two scenarios were studied in depth.

The first scenario assumed FiT and examined three grid connected PV systems used to generate solar power and sell the remaining power back to the grid. The cost of the tariff used in the first scenario was the current tariff charged by the Saudi utility. After an economic analysis this scenario was deemed not cost effective and therefore disregarded.

The second scenario assumed that new FiT charged only at peak hours (i.e the highest tariff currently charged). This was assumed because the PV system would mainly sell back power generated during peak hours. After an economic analysis this scenario was deemed cost effective.

The payback period was studied to determine cost effectiveness. For each scenario, three options were examined: 25% of the power generated from the PV system, 50% of the power generated from the PV system, and 75% generated from the PV system. For both scenarios, option three, in which 75% of the power was generated from the PV system, was chosen as the option with optimal payback. In the second scenario, the combination of the high PV generation and increases in tariff for the sellback price fostered the optimal overall solution. After examining the aforementioned options an examination of a potential subsidy to supplement the cost of the PV system and a potential load decrease improved the payback period even further.

6.2 Contribution

The purpose of this study is to examine the application of a PV grid-connected system as an alternative source of electricity in industrial sector of Saudi Arabia.

This can also be stated as a question: "Does the PV system aid the industrial sector in face of power cuts from the utility and can it be deemed economically acceptable?" this gives rise to some sub-questions which this work answers:

- What is the feed-in tariff and how can it affect the PV system economically?
- How can the payback period be reduced and become more efficient?
- If the Saudi Arabian government gave attention and support to solar energy and subsidizes electricity from the oil it will rollback with revenue.

6.3 Recommendations

1. Saudi Arabia should start applying regulations for use of solar energy, especially the grid-connected system.
2. With the gulf electricity connection using the grid connected PV system, Saudi Arabia will have the opportunity to sell more electricity and increase revenues.

3. In Saudi Arabia, using renewable energy in the second biggest electricity consumption sector will reduce the production of CO_2.
4. The Saudi Electricity Company should support the use of renewable energy in the industrial sector. This support will benefit the company as it will reduce the electricity overload, reduce the number of new stations built, and reduce the heavy load on the stations which will in turn increase the lifespan of generators and reduce the maintenance cost.
5. For factories, this will regularly cut the electricity consumption from the utility and will also generate a second income revenue with long run projects.

6.4 Future Work

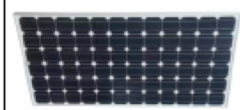
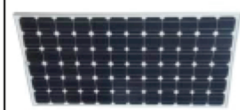
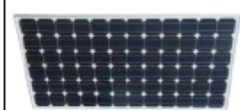
The focus of this thesis has been to find the optimal PV grid-connected system for the example factory using a simulated economic study. However, future work based on this study can be pursued in many directions. Some recommendations are listed below:

1. Investigate the reduction of power consumption of applying PV a grid-connected system to all factories in the industrial city.
2. Examine the use of PV systems for electrical and thermal applications in the industrial sector to show the reduced percentage of power consumption.
3. Study the benefit of using a PV grid-connected system in the industrial sector for the electrical company suppliers to meet the growing city load without adding new utility generation.
4. Combining an additional renewable energy source to the PV system supply to further meet the growing electrical demands. For example wind power.

APPENDIX A: PV System Price

September 2012

Solar Energy DC Price List 2012

SOLAR KITS	PRICES	PICTURES
SOLAR KIT 240W (NEW) 1 Solar panels 240W each - 24VDC 30A - MPPT Charge controller 2 solar cables , 20Ft each with MC4 connectors 2 solar cables, 7Ft eachwith alligator clamps	$519.00	
SOLAR KIT 250W (NEW) 1 Solar panels 250W each - 24VDC 20A - MPPT Charge controller 2 solar cables , 20Ft each with MC4 connectors 2 solar cables, 7Ft eachwith alligator clamps	$529.00	
SOLAR KIT 300W (NEW) 1 Solar panels 300W each - 24VDC 30A - MPPT Charge controller 2 solar cables , 20Ft each with MC4 connectors 2 solar cables, 7Ft eachwith alligator clamps	$639.00	

SMA Sunny Central 500kW Grid Tied DC/AC Disconnect

<< Previous in Over 10kW Inverters

Next in Over 10kW Inverters >>

ONLY: Your cost: $169920

Custom Order, Call 866.274.0642 for Details

Item Number: 330-0083

Manufacturer: SMA
Manufacturer Part No: 330-0083

Max Power Rating: 230
STC: 230
PTC: 203.7
Vmp: 29.5
Imp: 7.8
Voc: 37
Isc: 8.4
Freight Shipping Required

Quantity: 1 ADD TO CART

APPENDIX B: Technical Data for PV System Components

SOLAR PANEL SEDC 300W

ÉNERGIE SOLAIRE SOLAR ENERGY DC inc.

Technical Data:

MODEL	SEDC 300
Max system voltage	1000V

Electrical Data

Under STC (Standard Test Conditions:1000W/m², 25℃, AM1.5)

Maximum Power Output [Pmax]	300 Wp
Tolerance	+ 0 to 5%
Maximum Power Voltage[Vmax]	37.2 V
Open Circuit Voltage [Voc]	46.5 V
Maximum Power Current [Imax]	8.06A
Short Circuit Power Current[Isc]	9.19A

Temperature data:

Temperature coefficients of Pmax	-0.48%°C
Temperature coefficients of Voc	-0.33%/°C
Temperature coefficients of Isc	+0.02%/°C

Safety data:

High Voltage Test:	3000V DC/max, 50µA
Heavy mechanical load	2400Pa (IEC61215)
Allowable hail load	225mg steel ball fall down from 2m height
Junction box	IP65, 1000V TUV certified with 2pcs bypass diode
Cable type	Cable cross section size 4mm2, TUV certified, 3.2ft length
Encapsulation	Low iron tempered glass, 0.12 in thickness, light transmission above 91%, TPT
Frame	Clear anodized aluminum alloy
Operating temperature]	-40 to +185F

Mechanical data

Material	Aluminum
LXB[in]	77 * 39
Thickness[in]	2
Weight[lbs]	60

Certificates

IEC DVE CE

Sample picture

Features & Benefits:

- High efficiency of cells,
- High transmittance, low iron tempered glass with enhanced stiffness and impact resistance;
- Anodized aluminum alloy frame with high mechanical strength for easy installation;
- Anti-aging EVA and high flame resistant back sheet, to provide long-life and enhanced cell performance;
- Outstanding electrical performance under high temperature and low irradiance conditions;
- ±3% tolerance;
- 100% tested by EL(electroluminescence) technology.
- 25 years limited warranty for 80% power output.

TOLL FREE: 1-855-629-5009 WWW.SOLARENERGYDC.COM

- 97% CEC weighted efficiency
- Integrated isolation transformer
- Graphical LCD interface
- Sunny WebBox compatible
- Optional combiner boxes
- Install indoors or out
- UL 1741 / IEEE-1547 compliant

SUNNY CENTRAL 250U / 500U

The ideal inverters for large scale PV power systems

The new Sunny Centrals have integrated isolation transformers and deliver the highest efficiencies available for large PV inverters. A completely updated user interface features a large LCD that provides a graphical view of the daily plant production as well as the status of the inverter and the utility grid. With the optional Sunny WebBox, users can now choose from either RS485 or Ethernet based communications. Designed for easy installation, operation and performance monitoring, the new Sunny Central is the ideal choice for your large scale PV project.

c UL us

Technical Data
SUNNY CENTRAL 250U / 500U

	SC 250U	SC 500U
Inverter Technology	True sine wave, high frequency PWM with galvanic isolation	True sine wave, high frequency PWM with galvanic isolation
AC Power Output (Nominal)	250 kW	500 kW
AC Voltage (Nominal)	480 V_{AC} WYE	480 V_{AC} WYE / Δ
AC Frequency (Nominal)	60 Hz	60 Hz
Current THD	< 5%	< 5%
Power Factor (Nominal)	> 0.99	> 0.99
AC Output Current Limit	300 A_{AC} @ 480 V_{AC}	600 A_{AC} (@ 480 V_{AC})
DC Input Voltage Range	300 – 600 V_{DC}	300 – 600 V_{DC}
MPP Tracking	300 – 600 V_{DC}	300 – 600 V_{DC}
PV Start Voltage (Configurable from 300 – 600 V_{DC})	400 V_{DC}	400 V_{DC}
Maximum DC Current	800 A_{DC}	1600 A_{DC}
Peak Efficiency	97.5%	97.5% (estimated)
CEC Weighted Efficiency	97%	97% (estimated)
Power Consumption	69 W Standby, <1000 W with fans	69 W Standby, <1500 W with fans
Ambient Operating Temperature	−13 to 113 °F at full power output up to 122 °F at reduced power	−13 to 113 °F at full power output up to 122 °F at reduced power
Cooling	Variable-speed forced air	Variable-speed forced air
Enclosure	NEMA 3R	NEMA 3R
Dimensions: W x H x D in inches	110 x 80 x 33	142 x 80 x 37
Weight	4200 lbs	6725 lbs
Compliance	UL 1741, IEEE-1547	UL 1741, IEEE-1547 (pending)

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