# An Economic Analysis of Grid-tie Residential Photovoltaic System and Oil Barrel Price Forecasting: A Case Study of Saudi Arabia

by

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## *Dedication*

*To My parents who love me more than themselves. To my wife who has endured the hardship of my absence.*

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# List of Abbreviations Used

| | |
|---|---|
| **ANN** | Artificial Neural Network |
| **BP** | Back Propagation |
| **BRBP** | Bayesian Regularization with Backpropagation |
| **CC** | Capital Cost |
| **CF** | Cash Flow |
| **GPV** | Grid Connected (-tie) Photovoltaic |
| **GRPV** | Grid-tie Residential Photovoltaic |
| **HOMER** | Hybrid Optimization Model for Electric Renewable |
| **IC** | Initial Cost |
| **LCC** | Life Cycle Cost |
| **LCOE** | Levelised Cost of Energy |
| **LM** | Levenberg Marquardt |
| **MFFNNBP** | Multilayer Feed forward Neural Network with Backpropagation |
| **MLP** | Multi-Layer Perceptron |
| **MSE** | Mean Square Error |
| **NEG** | Net Electricity Generation |
| **NN** | Neural Network |
| **NPW** | Net Present Worth |
| **OBC** | Oil Barrel Consumption |
| **OBP** | Oil Barrel Price |
| **PV** | Photovoltaic |
| **RETscreen** | Renewable Energy Technology screen |
| **RMSE** | Root Mean Square Error |
| **SA** | Saudi Arabia |
| **SHS** | Solar Homer System |

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*In the name of Allah Almighty and the merciful, thanks to Allah for everything*

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# Abstract

The demand for electricity is increasing daily due to technological advancement, and luxurious lifestyles. Increasing utilization of electricity means the depletion of fossil fuel reserves. Thus, governments around the world are seeking alternative and sustainable sources of energy such as the solar powered system. The main purpose of this research is to develop a knowledge base on residential electric generation from the grid and solar energy. This paper examined the economic feasibility of using grid-tied residential photovoltaic (GRPV) system in Saudi Arabia with the HOMER software. Models forecasting the price of oil barrels through artificial neural networks (ANN) were also employed in the analysis. The study shows that an oil-rich country like Saudi Arabia has potential to utilize the GRPV system as an alternative source of energy. This study provides a discussion of the potential for applying solar-powered and an assessment of the performance of existing systems based on collecting output data.

# 1 Chapter 1: Introduction

## 1.1 Overview

In today's climate of growing energy needs an increasing environmental concerns, alternatives to the use of non-renewable and polluting fossil fuels have to be investigated. One such alternative is solar energy. Solar-powered systems are the fastest growing renewable energy sources. There are two types of these solar energy systems: a stand-alone PV (photovoltaic) system and a grid-connected photovoltaic system (GPV). The former is widely used in rural areas and in developing countries. The latter is common in suburban areas and it has become widespread around the world compared to the stand-alone system. A GPV system operates in two ways: by supplying electricity to residential homes and transferring power to the grid. In other words, utility companies pay to GPV system owners for every kilowatt transfer to the grid system although the payments depend on the country and the sellback rate from the utility company. There are two methods to conduct GPV system feasibility study: a PV handbook [1] or independent software, such as, RETscreen [2], PV WATT [3], HOMER [4], and ETAP [5].

In this work, both the PV handbook for economic analysis and the HOMER software have been applied to study the feasibility of grid-tie (or grid connected) residential photovoltaic system (GRPV) in Saudi Arabia (SA). A Hybrid Optimisation Model for Electric Renewables (HOMER) software is an optimization tool used to evaluate the feasibility of renewable energy systems depending on the cost. It deals with stand-alone renewable energy, hybrid models and a combination of renewable and non-renewable sources. In addition, HOMER provides three models: simulation, optimization and sensitivity analysis models.

Beside the necessity of utilizing renewable energy, there is the issue of the fossil fuel deterioration. Fossil fuel is used heavily in daily life, such as in transportation, production of goods and for electricity. Thus, if the price of an oil barrel increases, subsequently living expenses increase  and vice versa. In addition, oil utilization is increasing with population growth. Hence, fossil fuel sources are rapidly depleting. This is also causing the oil barrel price to increase. In order to show this increase in oil production costs, an oil barrel price (OBP) forecast is provided using artificial neural networks (ANN).

Artificial neural networks (ANN) are mathematical models that contain intelligent neurons which can emulate the function of the human brain. ANN models can learn the relationships between input(s) and output(s) (also called target) data whether the relationship is linear or non-linear. However, it is typically used to analyse non-linear relationships between input(s) and target(s). Neural networks use different techniques to approach the relationship between input(s) and output(s), such as radial basis function (RBF) and multilayer perceptron (MLP). In this work, a multilayer feed-forward neural network with back propagation (MFFNNBP) is used. The neural network model for prediction was created in MATLAB (R2011a) environmental version 7.12, the GRPV model was run using HOMER software version 2.81, and the economic calculation was run using Microsoft Excel 2010.

## 1.2 Research Motivation

Since Saudi Arabia is an oil rich country, it is a challenge for this nation to switch from traditional sources to renewable sources. The main motivation for this research is to study solar-powered systems in order to highlight the importance of utilising renewable energy sources as an alternative to conventional sources, such as fossil fuels and coal. The research and development of efficient alternative energy sources is essential for the progress towards a sustainable energy economy. This can include an array of renewable energy generation technologies, including hydroelectric, wind, biomass, geothermal, tidal, and solar powers. One of the leading candidates for large-scale efficient renewable energy production is solar power using photovoltaic systems which convert energy from the sun directly into electricity. The objective here is to investigate if renewable energy sources can be utilized in Saudi Arabia and the requirements for their implementation in that context.

## 1.3 Thesis Objectives and Challenges:

The objective of this research is to study the effect of using a solar powered system in residential areas, particularly in the city of Riyadh, the capital of Saudi Arabia. There are different types of this system that can be used in housing zones. This research studies the grid tie residential photovoltaic (GRPV) system in Saudi Arabia. Saudi Arabia is one of the biggest exporters of petroleum and it has big oil reserves. Thus, the energy produced from burning fossil fuels is considered cheaper than if produced from other renewable energy resources. Furthermore, due to its geographical location, the Kingdom of Saudi Arabia (KSA) has an abundant intensity of solar radiation and long duration of daylight hours. Hence, KSA is a good candidate for solar system applications. This research discusses the obstacles that the GRPV system faces. It also includes a feasibility study, different scenarios and recommendations for overcoming those challenges. The study used HOMER software, MATLAB program and Microsoft Excel for analysis.

## 1.4 Thesis Outline:

There are six chapters in this thesis. Chapter One - Introduction - provides general information about renewable energy sources and the methods of analysis used in this paper, i.e. the artificial neural network prediction techniques.

Chapter 2 includes five sections. The first provides an introduction of solar –powered systems and the factors that must be considered in order for them to be employed as renewable energy sources. Section two consists a summary of all types of materials that can generate electricity from sunlight. Solar radiation and the factors that affect it are discussed in section three. Section four provides details of the components used in solar energy technologies. Finally, solar panels and solar cells are explained in section five.

Chapter 3 provides a literature review focused on solar energy technology, and contains three sections. The first two sections present research on solar system utilization around the world and residential PV system economic studies respectively. The third part summarizes the use of solar-powered systems in Saudi Arabia, its potential and challenges but also synthesizes information on the Saudi Arabian context in general.

Chapter 4 consists of a description of the three methods used in this research: the HOMER software model, economic calculation, and the artificial neural network (ANN) model. Their applications are discussed as well.

Chapter 5 presents the results and analysis. The chapter consists of three sections. The first is composed of the results from both the PV handbook and HOMER software. The second section is the ANN section which shows the training algorithm and the proposed method. Finally, the third section provides the reasons for using the HOMER software and artificial neural network (ANN).

Chapter 6 presents the conclusions derived from this research and recommendations for the Saudi Arabian government in terms of GRPV systems.An appendixes, and a list of references is also given.

# 2 Chapter 2: Solar Powered System

In 1839, A. E. Becquerel discovered that voltage is produced in photovoltaic cells when it is hit by direct light. Since that time, several studies have been conducted to investigate the effect of solar radiation on photovoltaic cells, and the ways to improve its efficiency [6]. This chapter reviews all types of solar energy technologies and the rationale for their use.

## 2.1 Introduction

The world needs clean energy. The utilization of the renewable energy (RE) sources such as solar, biomass, wind and waves, is the solution for a pollution-free environment. Solar cells, which convert sunlight to electricity, are one of the possible choices. The solar cells, i.e. photovoltaic, are expected to be more than a niche supplier of electricity [7]. Utilizing solar energy has many advantages: it is free of charge and provides clean energy where the environmental impact is negligible.

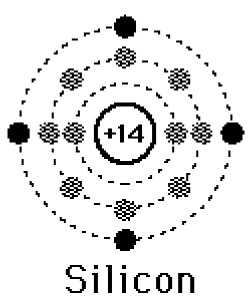
There are factors that make renewable energy sources important. First, approximately one third of the total global population, mainly those living in rural areas of developing countries, has no access to electricity. The other factors include the increasing in global population and load demand. In addition, due to the impact of global warming that is causing climate change and increase in heat, there is an increase in energy demand throughout the world [8]. Hence, many scholars have dedicated their research to the study of renewable energy sources.

Among other renewable energy sources, solar energy is the only renewable energy source that can be utilized in a populated area. Other renewable energy sources, such as wind and biomass, need a large empty space and could not be used in the suburbs.

## 2.2 Solar Cells:

Silicon is the main substance of the majority of PV panels that have been used for solar energy systems. Quartz sand (also known as silicon dioxide) is a pollution-free substance. It is one of the major components of the earth's crust. The atomic number of silicon is 14, which means that fourteen electrons orbit its nucleus. The last four electrons in the fourth valence level are essential to the design of the solar cells. Pristine silicon is neither an insulator nor a conductor. However, at low temperatures, the silicon can act as an insulator due to the strong bond between the electrons (Figure 2.1a). However, direct light towards the silicon, i.e. at high temperatures, would cause a free electron to be released and the silicon can act as a conductor [9].

When sunlight is oriented at a silicon crystal lattice, it causes the release of free electrons with negative charges and leaves behind a broken bond with positive charges. This state, called electron-hole pairs, is shown in Figure 2.1b. The conductivity of the silicon lattice increases as the amount of free electrons increases. The free pairs then move in different directions and no current flow is produced. Thus, there is a need for a chemical mechanism that forces the free pairs (electrons & holes) to move in one direction in order to produce current flow. This chemical mechanism is called the p-n junction.



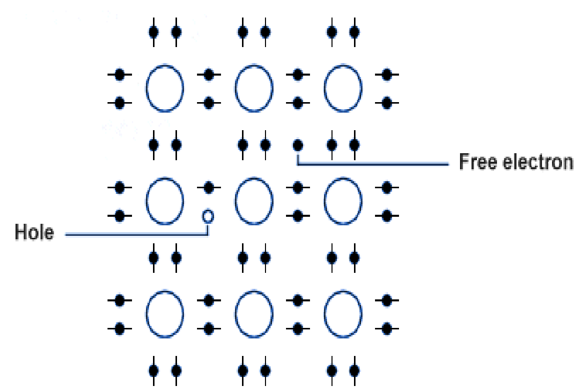
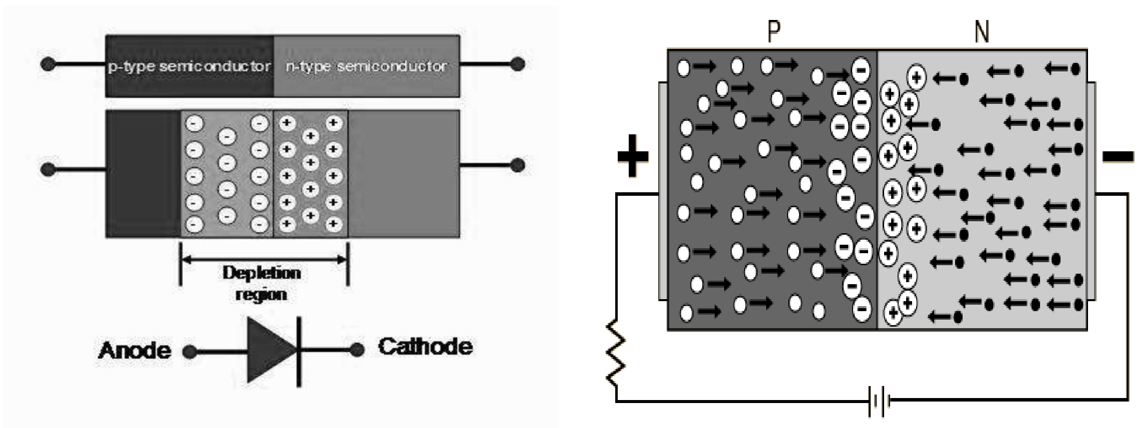




**Figure 2.1** Silicon crystal (a) insulator [10] (b) Conductor [11]

When an n-type material, e.g. boron, comes into contact with a p-type material, e.g. phosphorus, this forms a p-n junction. Thus, doping two layers of silicon with phosphorus and boron, creates a mechanism that forces the free electron-hole pairs to move in one direction, and, thus, current flow (power) is produced. Free electrons are found in the n-type substance, and the holes are situated in the p-type material. Electrons move toward the p-type material and the holes move towards the n-type in the contact area. This movement creates an electric field. At equilibrium when there is no more variation between electron and holes, a depletion region is formed. This depletion region has the characteristics of a diode where current is forced to flow in one direction [9]. Hence, the solar cells work in a similar way as a diode, as shown in Figures 2.2a & 2.2b.




(a) (b)

**Figure 2.2** Silicon Characteristic (a) depletion region [12] (b) Biasing [10]

Figure 2.3 shows an equivalent circuit of solar cells, where $I_D$ the diode current, $I_{ph}$ represents the incoming current from sunlight, and $I$ is the current that flows to the load. The solar cell characteristics of the current and voltage are the same as the diode I-V characteristics. Hence, at dawn, when sufficient sunlight is directed at the PV panel, the current $I$ flows to load while at night $I = I_D$. The operation of the solar cell is expressed mathematically in equations (2-1, 2-2, & 2-3,) where $q$ is the charge on the electron, $\kappa$ is the Boltzmann's constant, $T$ is the temperature in Kelvin, and $I_o$ is the value of the diode reverse current at negative bias [9].

$$I = I_D - I_L \quad (2\text{-}1)$$

$$I_D = I_o \left[ exp\left(\frac{qV}{kT}\right) - I \right] \quad (2\text{-}2)$$

$$I = I_o \left[ exp\left(\frac{qV}{kT}\right) - I \right] - I_L \quad (2\text{-}3)$$

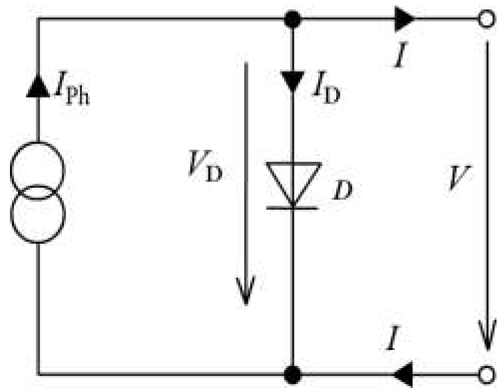



**Figure 2.3** Solar cell equivalent circuit [13]

The output current from the PV panels is referred to as direct current (DC). The watt peak $W_p$ is the solar cell power unit. Often, manufacturers provide the PV panel output under standard test conditions (STC). Standard test conditions are 25 $^{o}$C, 1000W/m$^2$ and where air mass equal to 1.5. AM, i.e. Air Mass is the path length of the sunlight spectrum that penetrates the atmosphere and reaches the earth. The number 1.5 refers to the inverse cosine law of the sun path-length angle, 48$^{o}$, where it hits the PV panel [9]. The majority of researchers choose an air mass equal to 1.5. However, other sunlight angles could be considered. For instance, AM 2 represents the sunlight position at 60 degrees. In this work, we use AM 1.5.

In general, solar cells are classified in four categories arranged below from the most efficient type to the least efficient based on their primary component, silicon:

### 2.2.1 Monocrystalline Silicon

Often, monocrystalline silicon has a silver colour and is cut in pseudo-squares and hexagonal shapes. Monocrystalline cells are made from uncontaminated liquefied silicon using a doping process. It is considered the most effective type of PV system and has an expensive manufacturing process. Efficiency of monocrystalline silicon cells is around 12-16% with a total area of seven square meters per kilowatt peak, [9] as shown in Figure 2.4a.

### 2.2.2 Multi-crystalline Silicon or Poly-crystalline Silicon

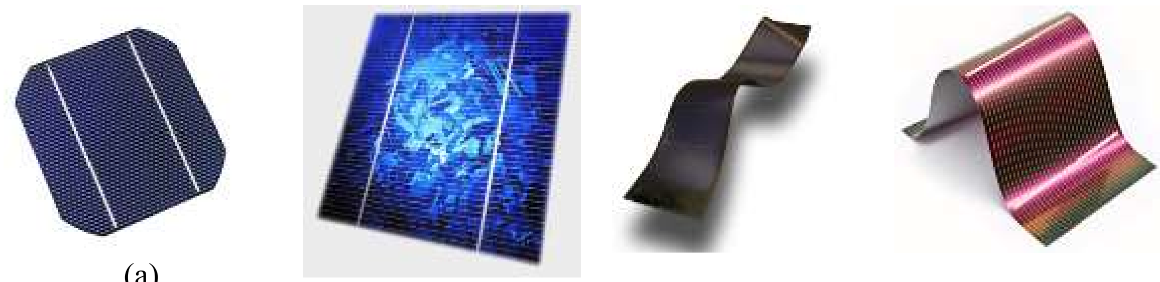
Poly-crystalline silicon (Figure 2.4b) has two advantages over the mono-crystalline type: it has lower manufacturing cost and a low feed stock tolerance. The poly-crystalline cells utilize the moulding process. Another advantage is that its square or rectangular shape makes it easy to install and utilize [1]. However, the multi-crystalline silicon has less efficiency (at ~ 11-15%) than the mono-crystalline silicon. Poly-crystalline cells often have a blue colour and a shiny appearance. The required area to produce one kilowatt is $8m^2$ [9].

### 2.2.3 Amorphous Silicon (a-Si)

Amorphous silicon (a-Si) is a thin film technology, (Figure 2.4c) which has been used since 1980s in calculators and watches. However, presently, a high energy output PV system uses amorphous silicon. The a-Si has a non-complicated manufacturing process and low cost. The main drawback is its relatively low efficiency, which is around 6-8%. Amorphous silicon needs an area of sixteen square meters ($16m^2$) to produce one-kilowatt peak. Its practicality is demonstrable in building frontage. [9]

### 2.2.4 Other Materials:

Beside silicon, there are other types of semiconductor materials that can convert sunlight into electricity. These types represent a significant advancement in thin film technology. The process involves doping a variety of substrates on an ultra-thin layer of semiconductor material . Copper Indium Diselenide (CIS) and Cadmium Telluride (CdTe) are two well-known materials in PV module production that can produce current from sunlight (Figure 2.4d).



(a) (b) (c) (d)

**Figure 2.4** (a) Monocrystalline silicon cell [17] (b) Multicrystalline silicon cell [18] (c) Amorphous [19] (d) Copper Indium gallium selenide CIGS [15]

## 2.3 Solar Radiation

Solar irradiation is the amount of sunlight (photon) energy that reaches an area for an hour. It is expressed in watt-hour per square meter ($Wh/m^2$). The power from the sun is approximately 175,000-terra watt (TW) [14]. Hence, solar radiation data is a crucial factor for successful planning and implementation of PV systems. Furthermore, the degree of solar irradiation affects the voltage output of the PV module. Therefore , significant consideration should be given to the orientation and inclination of the PV array during the installation of a rooftop PV system.

There are three approaches to find the solar radiation data namely: meteorological stations, satellites, and a combination of meteorological and satellite sources [14].

## 2.4 Types of Solar System

In general, there are two main categories of photovoltaic systems: grid connected (also known as gird-tied) systems, and stand-alone PV systems. [9]

### 2.4.1 Stand-Alone PV System

Stand-alone PV system, shown in Figure 2.5, supplies the customer load only during daylight. Since the solar system works only during daylight, hence stand-alone PV systems need storage banks to store electricity and use it at night. The standalone PV system is not able to supply the load for the whole day. Hence it usually comes in a hybrid system model where a PV system is combined with other renewable or non-renewable sources of energy such as, wind, or diesel generators.

The parts of the stand-alone PV system are PV cells, a battery, mounting, and wiring. The majority of standalone PV system applications are used in rural areas in developing countries, where people need power for living necessities, such as, lighting, heating, and cooking. It is also used where the grid extension considered inefficient and not cost effective [9].

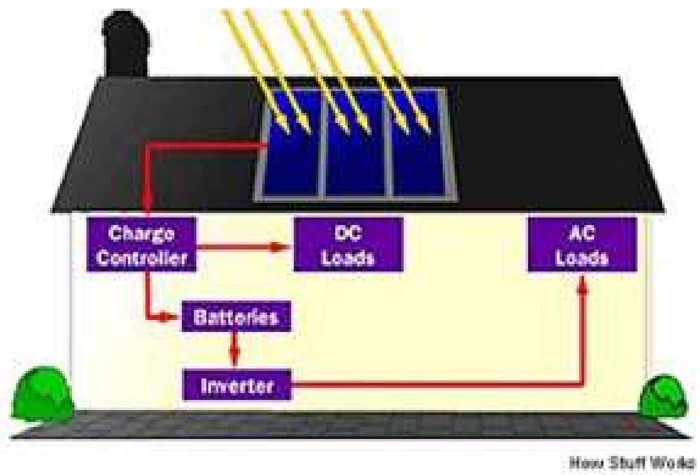



**Figure 2.5** PV Stand-alone System [15]

### 2.4.2 Grid connected PV System

Grid connected residential photovoltaic (GRPV) systems are now common in suburban regions. Due to government incentive programs, GRPV system utilization has increased. For instance, Germany, Spain, and the United States have become leaders in providing incentive programs for grid-tied PV system.

PV grid-connected (also known as utility-interactive or grid tied) systems, shown in Figure 2.6, are designed to operate in parallel with the electric utility (grid.) This means that when there is an extra output of power which is not used by the house, it is sent to the grid. Conversely, when the demand of a house is higher than the PV's power output, or it is nighttime and the PV system is off, electricity is imported from the grid. Hence, the grid and the PV system are complementary. The size of this type of system can range from 1kWp to several kWp. [14]

In addition to GRPV systems, grid tie PV system can be used in a larger area. For instance, PV power plants, where the systems range between 1MWp-50MWp. Here, the PV system implemented in remote areas, where there is no limitation of landscape and nothing prevents the sunshine, such as, shedding, and trees.

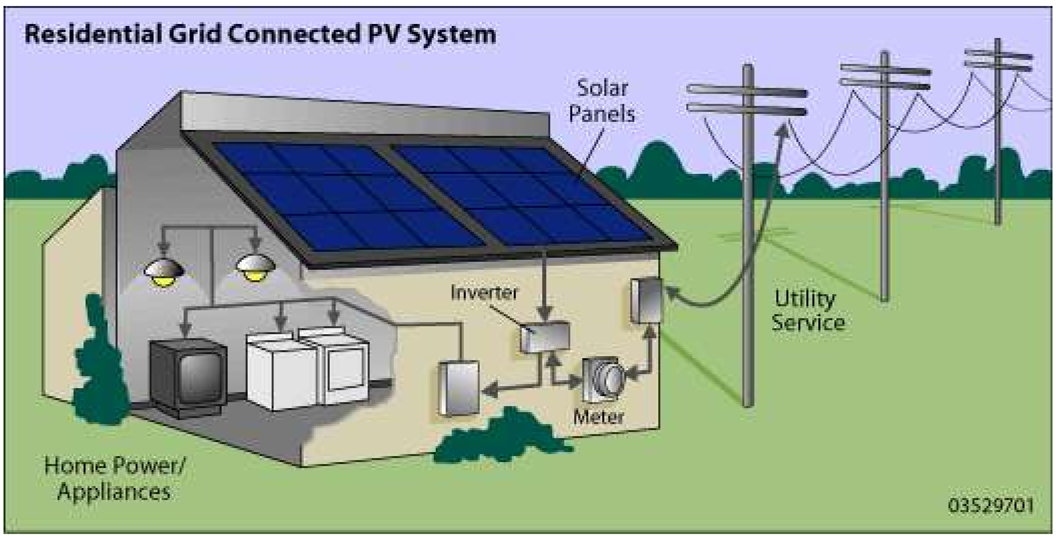



**Figure 2.6** Grid connected PV system [16]

As shown in Figure 2.6, a Grid connected PV system consists of [9]:

#### *2.4.2.1 PV Modules*

It is the main component in any PV systems, with each module consisting of a number of solar cells that convert sunlight into electricity. A solar cell is made from a thin layer of semiconductor.

#### *2.4.2.2 PV Junction Box:*

This junction box gathered the wires from all the PV panels.

#### *2.4.2.3 Inverter:*

The inverter converts DC, i.e. direct current produced from PV array to AC (alternate current), and makes sure that the transmitted power to the grid matches the grid properties. This means that the transmitted power has the same voltage, and frequency.

#### *2.4.2.4 Digital Net Meter:*

A PV digital meter is used to provide details of the amount of energy transferred to the load or to the grid. Net metering is used for selling extra electricity to the grid. Thus, it helps to reduce the network peak load. In addition, it aids to reduce the cost of the GRPV system. Hence, a digital net meter could help to make the utilization of the GRPV system feasible.

#### *2.4.2.5 System Protection:*

A PV system needs a protection system to isolate the panels and the Inverter from the network in case of short circuit. In fact, this is an essential part of any PV system to prevent damage to the PV array.

#### *2.4.2.6 Mounting Tool:*

The solar home system (SHS) is always connected to the roof of the house. Hence, mounting tools are used to prevent PV panels from falling.

## 2.5 Solar Panels

Solar cells need to be protected and covered to be able to operate for the entire life of a project without defects. In other words, solar cells need to be encapsulated to survive handling, installing, and weather changes. Solar panels contain a number of solar cells connected together and surrounded by an aluminium frame and covered with glass on the top. A group of solar panels connected together is called an array. Encapsulating solar cells is reliable and efficient because it protects the cells [9].

# 3 Chapter 3: Literature Review

Like all other renewable energy (RE) sources, solar-powered technologies are expensive. The implementation of any solar energy system, either in residential, industrial or rural areas, requires a financial assessment. This assessment should consider all the factors that affect the system, such as solar radiation intensity, sunlight duration, government rebate programs, total costs and electricity tariffs. Future solar home system (SHS) owners can then make their decisions depending on the assessment. This chapter synthesizes a review based on current research on residential solar energy technologies in regards to their applications and economic costs. It also includes a literature review of the application of the solar energy technologies in Saudi Arabia.

The chapter consists of three sections:

1. Studies on Residential Solar-Powered Systems in Different Countries
2. Economic Studies in Solar Home System (SHS)
3. Solar energy use in Saudi Arabia.

## 3.1 Studies on Solar Energy Systems in Different Countries

The rapid depletion of reserves of traditional sources of energy and the over dependence on limited fossil fuels for electricity generation have increased interest in a solar powered system as a potential source of energy. Hence, governments around the world has started to consider PV installation to generate electricity in different areas. Table 3.1 shows the top five countries using photovoltaic installation.

### 3.1.1 Germany

Germany has become the leader in PV installation due to the high rate of energy tariffs and the desire to decrease dependence on oil importation. Thus, the parliament in Germany has required that, utility power providers should buy electricity from the GRPV system owners above the market rates. The feed-in tariff in Germany for GRPV system owners is between 0.5 to 0.6 $/kWh [20].

**Table 3.1** Ranked countries in PV installation [21]

| Rank | Country | Total PV installation (MW) |
|---|---|---|
| **1** | Germany | 17200 |
| **2** | Spain | 3800 |
| **3** | Japan | 3600 |
| **4** | Italy | 3500 |
| **5** | Unite States | 2500 |

### 3.1.2 Ireland

Zhe Li et al. (2011) [9] examined the economic reliability of using PV system in residential areas in Ireland. The article provides an accurate method to study the economic viability of residential solar systems using the HOMER software program and Microsoft Excel. Their research included eight samples of solar PV systems in different areas of Ireland. The article concluded that the solar home system (SHS) is not a reliable solution to the current situation in Ireland because of the high capital cost. Also, it emphasized the need of government support and low rate banking loan for the success of solar home systems.

### 3.1.3 United States of America

In the U.S.A., 25 states have renewable “portfolio standards” (RPSs). These standards are meant to assign a percentage of renewable energy penetration to supply electricity and replace the traditional source. For example, 20% PV penetration by 2020 in California and 25% PV penetration in New York by 2013 is expected. Moreover, other states offer incentives, such as cash back or rebates, for solar home system (SHS) owners [20].

Sedghisigarchi *et al* (2009) [22] examined two aspects of residential PV systems in the United States namely: the technical, and the economic factors. On the one hand, the technical factors, such as tilt angle, geographical locations and shading, have a significant impact on the electricity generated from solar cells. To clarify, countries that are nearer to the equator receive higher solar radiation than countries located far from the equator. PV modules are sensitive to shading. On the other hand, PVs incentive programs, tax payments and income have an essential influence on customers who are interested in utilizing solar home systems. For instance, the policies of the state of New York and Arizona proved to be profitable while the West Virginia PV policy appears not to have succeeded.

G.E. Palomino et al. (2002) [3], investigated the performance of several residential power systems in new homes being constructed in the United States. The study shows that the failure of any part of the solar home system, such as an inverter, has an enormous impact on the system performance. Hence, design redundancy and good installation and maintenance are required.

### 3.1.4 Argentina

Robinson Alazraki et al (2007) [29], examined the impact of the Renewable Energy Project for the Rural Electricity Market (PERMER) which utilized small-scale PV systems in homes, schools and public buildings in Argentina. The project's aims were to replace traditional energy sources, such as candles and kerosene lamps, with PV electrical systems to provide a better life quality and reduce the indoor air pollution in rural areas. However, they found that technical barriers had to be overcome before the project was implemented. Their study proved that it is able to change peoples' lifestyle in rural areas, improve the performance of students and teachers, create new educational activities, increase social life, and reduce the need of traditional sources. The authors recommended that the government of Argentina should extend the project to other rural areas in the country. It also showed that project finance is an important barrier that needs to be resolved before the project starts.

### 3.1.5 MENA Countries

Antonis Tsikalakis et al (2011) [24], reviewed the utilization of solar powered systems in the Middle East and North African (MENA) countries. The study demonstrated the potential of solar energy systems in Morocco, Algeria, Egypt, Palestine, and Lebanon.

Additionally, it showed the contribution of each country towards the utilization of renewable energy and protecting the environment.

#### *3.1.5.1 Morocco*

Under the supervision of the Ministry of Energy and Mines in Morocco, the CDER (Centre de Developpement des Energies Renouvelables) is responsible for renewable energy programs. Since 1978, the CDER has initiated three programs for rural area electrification using solar energy systems: the PNER (National Program for Rural Electrification) from 1978 to 1991, the pilot program of rural pre-electrification program (PPER) in 1995 and the PERG (Global Rural Electrification Program). The electrification of rural areas using solar-powered system had a massive impact on people's lives. It changed their lifestyle as watching television increased, created jobs, improved students' performance in school, improved farming using the solar pump and helped people communicate using mobile phones [24].

#### *3.1.5.2 Algeria*

The Ministry of Energy and Mining deals with energy trade policies while the Ministry of Environment deals with sustainable development & environmental protection policies. In 1988, the Renewable Energy Development Centre (CDER) was established, specializing in R&D in renewable energy. Since then, a program for the electrification of rural areas has been initiated. The government aims to obtain 5 % of their total energy from solar powered systems and other hybrid system by 2015 [24].

#### *3.1.5.3 Egypt*

The New and Renewable Energy Authority (NERA) is responsible for introducing renewable energy technologies in Egypt. There are seven photovoltaic companies in Egypt. Solar Water Heaters (SWH) systems are most commonly used for solar energy in Egypt. Around 500,000 $m^2$ of SWH has been installed in a commercial area. However, renewable energy utilization in Egypt is slower than in Morocco and Algeria. Egypt plans to have 20% of their total electricity generation from renewable energy sources

[24].

#### *3.1.5.4 Palestine*

The Palestinian Energy and Environment Research Centre (PEC) and the Energy Research Centre (ERC) are responsible for research and development (R&D) of conventional and renewable energy. The electrification of 90 houses in a rural area using a solar home system (SHS) via two projects was a significant step. Another current project focuses on street lighting in community sites using solar panels [24].

#### *3.1.5.5 Lebanon*

The exploitation of the solar system in Lebanon is considered to be the lowest among MENA countries. Since Lebanon's civil war, there has not been a ministry responsible for energy policies. The only relevant department that exists is the Ministry of Energy and Water (MoEW) since the 1970s. The National Council of Scientific Research (CNRS) is responsible for R&D in all sectors. Hence, Lebanon still has a long way to invest in RE [24]. There are factors limiting the use of the solar system in MENA countries. These include the lack of government support and the competitive price of electricity from conventional sources. Meanwhile, MENA countries are endeavouring to utilize solar energy systems with some countries creating milestones for obtaining a certain proportion of their energy from renewable sources within the next five years.

### 3.1.6 European Countries

The European Photovoltaic Industry Association (EPIA) report has predicted three scenarios for the development of PV systems in Europe [25]. The first is a 4% penetration with no change in the electricity system, but this requires a PV industry to work on reducing the cost of PV systems. The second scenario is an '*Accelerated growth*' target with a 6% penetration which will include a small change in the electrical system. The last scenario '*Paradigm Shift'* is a 12% penetration and a wider change of state in the market strategies. Furthermore, the objective of the Kyoto Protocol, which many European countries have signed, is to reduce the emission of greenhouse gases from industrialized nations [25]. Hence, countries under the Kyoto Protocol are requested to enforce emission reduction projects to ensure that they will reach the required target.

### 3.1.7 Malaysia

Ahmed [26] discussed the design of solar energy schemes for electricity production in Malaysia. The paper provided a residential load profile by calculating the total load of the appliances in one house. It also discussed the designing steps of solar home system, such as choosing an adequate battery size and cost estimation

### 3.1.8 India

Bansal et al. (2000) [27] discussed the consolidation of PV technology in a cafeteria building in New Delhi. The idea was to design a life model in order to show the advantages of using a solar energy system and to educate the public. The paper concludes that the implementation of PV system affects the environment, building skyline, and, the ability of PV panels to be integrated in building design. The model is considered the first of it is kind in India.

## 3.2 Residential PV System & Economic Studies

Solar renewable energy has two drawbacks; its intermittent nature and the high initial cost. This section discusses a background of work done in residential solar system economic studies.

Vigneswaran Applasamy [2] calculates the life cycle cost (LCC) of a stand-alone residential PV system in Malaysia. The authors focuse on the cost effectiveness of three types of solar cells namely: Mono-crystalline, Poly-crystalline, and thin-film. The analysis was applied to a family of four members. RETscreen (Renewable Energy Technology) program has been used to calculate the cost of the stand-alone PV system, and then the cost per kilowatt-hour for a period of 25 years has been derived. Finally, the article shows that the price per kWh for the stand-alone PV system is five times higher than the price of electricity supplied from conventional sources in Malaysia.

In the same issue, Bhuiyan et al. [28] examine the feasibility of using a stand-alone PV system in rural areas in Bangladesh and compare it with a non-renewable energy sources. The method of economic calculations includes net present value (NPV) analysis, system cost, capital costs, maintenance costs, replacement costs, and economic factors. The study concludes that the life cycle cost, (LCC) of PV systems is lower than the LCC cost of gasoline and diesel generator in Bangladesh.

Lazou et al. [29], consider the economic feasibility of stand-alone residential PV system supplying electricity for a house of four members in European and Mediterranean cities. A load profile has been assumed, and then the optimal sizes of system components are calculated. It concludes that a solar home system with battery storage in high solar radiation cities can meet a house electricity demand without the need of a back-up generator. In addition, cities with lower solar radiation should consider a hybrid system as an economical solution.

Simburger [30] compare the financial performance of investing in a solar home system and investing in stocks and bonds in the United States. It shows that not only the GRPV system will save the homeowner money on the electric bill but also it can provide a modest income to the homeowner. Hence it is a profitable investment.

Corrigan [31], use linear programming to calculate the optimal dispatch strategy for a standalone PV system. An average household daily load profile is divided up into 24 intervals to represent each hour of the day. The energy system comprises of PV panels to supply house demand during sunlight, and a storage system (battery) to supply load demand at night. Three different examples are shown with their savings. Hence, the proposed control strategy of residential solar system with storage has proven it is possible to reduce the electricity bill.

Cucchiella et al. [25], investigate the optimization of economics and environment factors for a GRPV system in Italy. Three scenarios have been analysed economically namely: self-financing, full amount bank loan, and partial amount bank loan. The internal rate of return (IRR), were found to be 8%, 10%, and 8% respectively. In addition, 51% of the incoming money is from exporting electricity to the grid, 27 % electricity bill reduction, and 18% of tax deduction. Hence, for the three scenarios, utilizing a grid connected solar home system is profitable. What's more, PV SHS has zero effect on the environment for the whole project life.

## 3.3 Solar System Applications in Saudi Arabia:

The Kingdom of Saudi Arabia (KSA) is fortunate to have a high intensity of solar radiation. Thus, Saudi Arabia is a promising candidate for the utilization of photovoltaic systems in both small and large-scale applications. This section reviews Saudi Arabia's historical and present policies as well as future applications of solar home systems.

### 3.3.1 Kingdom of Saudi Arabia

Saudi Arabia (SA) is located between latitudes $31^o$ N and $17.5^o$ N and longitudes $50^o$ E and $36.6^o$ E [32]. The Red Sea and the Arabian Gulf surround SA from West and East respectively. Saudi Arabia has 14 provinces distributed in five districts: the Central region, the Eastern region, Western region, Northern region, and the Southern region. The population of Saudi Arabia is 26,136,977 with a gross domestic product (GDP) of 6.77% [33]. Saudi Arabia is the largest country in the Middle East with a total area of 2,149,690 $km^2$ [34]. Since the discovery of oil, Saudi Arabia has become well known for this desired resource. Thus, it is one of the largest oil producers and owns one fifth of all known oil reserves in the world.

The Saudi Electricity Company (SEC) supplies electricity to 80% of the Kingdom. However, there are still remote areas that have not received electricity. Using the grid system to supply remote areas is not reasonable. Hence, this is a potential area where solar technology could work, but this is not the only place. Saudi Arabia intends that solar system utilization will also contribute to the national grid to meet Saudi Arabia's peak demand [36].

### 3.3.2 History of Solar Power in Saudi Arabia

The Kingdom of Saudi Arabia is one of the world's most productive solar regions with some of the highest summer temperatures ever recorded on earth. The Saudi Arabian government has declared that it wants to become a major solar producer, but its investments amount to much less than 50 Megawatts whereas several countries have added thousands of Megawatts a year to the generation of power from solar energy. Saudi Arabia has been interested in solar applications since 1960. Table 3.2 shows a brief history of projects and applications of solar power in Saudi Arabia. In 1980, Saudi Arabia and the United States initiated the Saudi Arabian-United States Program for cooperation in the Field of Solar Energy (SOLERAS). This program's goal was to conduct a research in order to make any village independent of the central system of power production. Therefore, Saudi Arabia was the first country in the Middle East that conducted this kind of research [32].

**Table 3.2** A brief history of solar application in SA [32]

| Year | Applications |
|---|---|
| **1960** | PV beacon by a French company in Al-Madinah Al-Munnawara's airport |
| **1969** | Beginning of research in a university project. |
| **1977** | Energy Research Institute (ERI) for R&D of solar technology in KACST |
| **1977-1997** | A first cooperation project program between SA and US named SOLERAS |
| **1980** | Two projects conducted by SOLERAS in two villages: Al-Jubaila and Al-Uyaina |
| **1986-1991** | Germany-SA cooperative program for RD&D of solar hydrogen power HYSOLAR |
| **1987-1990** | 2kwh PV system in the solar village |
| **1996** | 4kwh PV system for agriculture use in Muzahmia village |
| **1994-2000** | The Saudi Atlas project for solar radiation measurement |
| **2010** | First solar powered water desalination plant in SA |

Solar technology needs accurate measurements of solar radiation. In 1994, Saudi Arabia initiated the Saudi Atlas Project (SA-Atlas) with the Energy Research Institute at King Abdulaziz City for Science and Technology (ERI-KACST) and the National Research Energy Laboratory (NERL) in the United States. Twelve stations have been built in different locations around the country, as shown in Figure 3.1. At these locations, different measurements are taken, such as global horizon irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance, air temperature, and humidity. All data are sent to a central station in Riyadh known as the solar village. In addition, since 1970, there have been 40 stations around the kingdom where global solar radiation (GSR) and sunshine duration are recorded.


**Figure 3.1** Locations of Solar Villages in SA [37]

### 3.3.3 Solar Potential in Saudi Arabia

There are several factors which encourage the use of solar power in the Kingdom of Saudi Arabia (KSA). KSA receives enormous irradiation around 12425 terrawatt-hour (TWh) of electricity that is enough to supply electricity to the kingdom for 72 years [38]. There is a large space available in SA to harvest the sunlight as well. All of these factors qualify SA as a candidate to harvest the sunlight using solar system. However, until now the utilization of the solar system has been inefficient.

### 3.3.4 Obstacles Solar Power to Saudi Arabia

Since the discovery of oil , Saudi Arabia has become a rich nation. Although oil is considered beneficial, it has also been harmful. One of the essential problems that solar technology faces is the cheap price of oil in Saudi Arabia. Another barrier is that the tariff of supplying electricity from conventional sources is lower than the charge of supplying electricity from renewable sources. Moreover, dust has a large effect on solar cells' performance. It can reduce solar energy by 10-20%. Finally, the Saudi government provides funding programs for oil products and electricity but not for renewable energy sources.

### 3.3.5 Solar Application in Saudi Arabia

Rehman et al. [8] conducted an economic analysis of utilizing a 5MW grid connected solar power plant in 41 locations around Saudi Arabia. RETscreen software was used to obtain the total energy produced from the model and for the economic costs. The economic analysis showed that the price of energy produced from the solar system ranged between 20 to 30 cents. It is worth mentioning that the information that was entered into the RETscreen software assumed the efficiency to be around 28.3% and 18.7%. 28.3% is considered to be high since the maximum efficiency achieved so far is around 20%.

Aljarboua [38] discussed Saudi Arabia's possible strategies towards increasing renewable energy sources. The reliability and future of renewable energy, in terms of solar, wind, hydro, and biomass fuel, were investigated. It was found that solar and wind could be utilized in the energy production in Saudi Arabia if the Saudi government increased the charge of conventional electricity by 756% and 287% respectively. Moreover, due to the high initial cost of renewable energy and their low efficiency, it was suggested that Saudi Arabia should not move towards renewable energy. The article did not discuss the reduction of pollution from utilizing renewable energy or the preservation of fossil fuels for the next generation.

Almogren et al. [43] examined a hybrid model of solar-hydrogen energy to be used in Saudi Arabia. It concluded that Saudi Arabia should exploit renewable energy, or else, it would face an oil deficit in the future.

Shawl et al. (2009) [5] studied the effect of 90 $W_p$ grid-connected PV systems on the voltage profile in the distribution network. The study was conducted using PVSYS software and ETAP software. The study focused on the effect of power generated from a rooftop solar system in the low voltage distribution network. It showed that using a rooftop PV system not only helped to improve the voltage profile but also reduced the peak load demand from 13kW to 12kW. In addition, there was no limit to the number of houses which used to install rooftop PV systems .

An economic study analyzing a hybrid PV system in Dahran (Eastern District of SA) was conducted by Shaahid et al. [40]. The authors used the HOMER software to obtain the optimal solutions. The article showed that combining renewable (solar) and non-renewable (diesel generator and battery) sources provided the user with benefits from both sources. This included reduced maintenance for the diesel generators, high load from PV generation, and minimal number of working hours for the diesel generators. The main objective of this article was to emphasize the effect of PV system penetration in residential load demand. However, using a diesel generator in residential areas could cause noise and air pollution.

### 3.3.6 Future Projects in Saudi Arabia

The investment in solar energy has reached 136 $ billion dollars in 2011 with a total production of 65 gig watts of electricity. The production of PV panels, although it increased by 2 percent every year, is considered small compared with the world's needs for electricity. [64]. According to [65], Saudi Arabia is planning to invest US$109 billion in solar energy.

The Minister of Saudi Arabian petroleum and Mineral Resources oil Mr. Al-Naimi suggested to a French newspaper in 2008 that Saudi Arabia was planning a strategy to increase solar technology and eventually become a solar power exporter. Moreover, in

June 2011, Mr. Al-Naimi reinforced this statement by declaring that SA is planning to produce an amount of electricity from solar energy that is equivalent to the amount of electricity generated by crude oil. Below is a description of the ongoing projects in Saudi Arabia. Detailed information on all the projects are shown in appendix C.

1. In 2010, King Abdullah University of Science and Technology (KAUST) implemented a two-Megawatt hour rooftop solar system, with a total of 3332 MWh/year.
2. Saudi Aramco North Park project has 10 MWh of solar modules covering an area of 4,450 parking spaces. The project was expected to be completed in 2011.
3. In January 2012, King Abdullah Financial District (KAFD) was planning to implement 200 kW rooftop solar systems. KAFD uses sustainable architecture and aims to obtain the LEED Gold which is an eco-certificate.

# 4 Chapter 4: Solution Methods

## 4.1 Hybrid Optimization Model for Electric Renewables (HOMER)

### 4.1.1 Introduction

HOMER is a simulation and optimization software tool. It is consists of renewable energy technology models that evaluate renewable technologies based on cost and availability resources. It is a tool which simplifies the task of evaluating design options for both on-the-grid and off-grid-connected systems. It consists of three different modules: simulation module, optimization module, and sensitivity analysis module. In this section, a description of the process for creating a HOMER model and a discussion of the HOMER software features are provided.

### 4.1.2 Process

The HOMER software can examine different types of renewable energy, such as wind, biomass, solar, and hydro. This thesis focuses only on solar energy. This section describes the procedure of using HOMER software to analyse the hypothetical effects of implementing a grid-tie PV (GPV) system model in the residential areas of Riyadh city, the capital of Saudi Arabia.

#### *4.1.2.1 Create the PV Module*

The first step in applying HOMER software is to determine the parts of the model. In chapter two, we have shown the components of a grid-connected PV system. However, not all of the components are used in HOMER. The components of the system that are used consist of PV panels, inverters, grids and the primary load as shown in Figure 4.1. Once the selection of the model is complete, the parts need to be defined, as shown in Figure 4.2. Subsequently, the characteristics of each component must be defined..

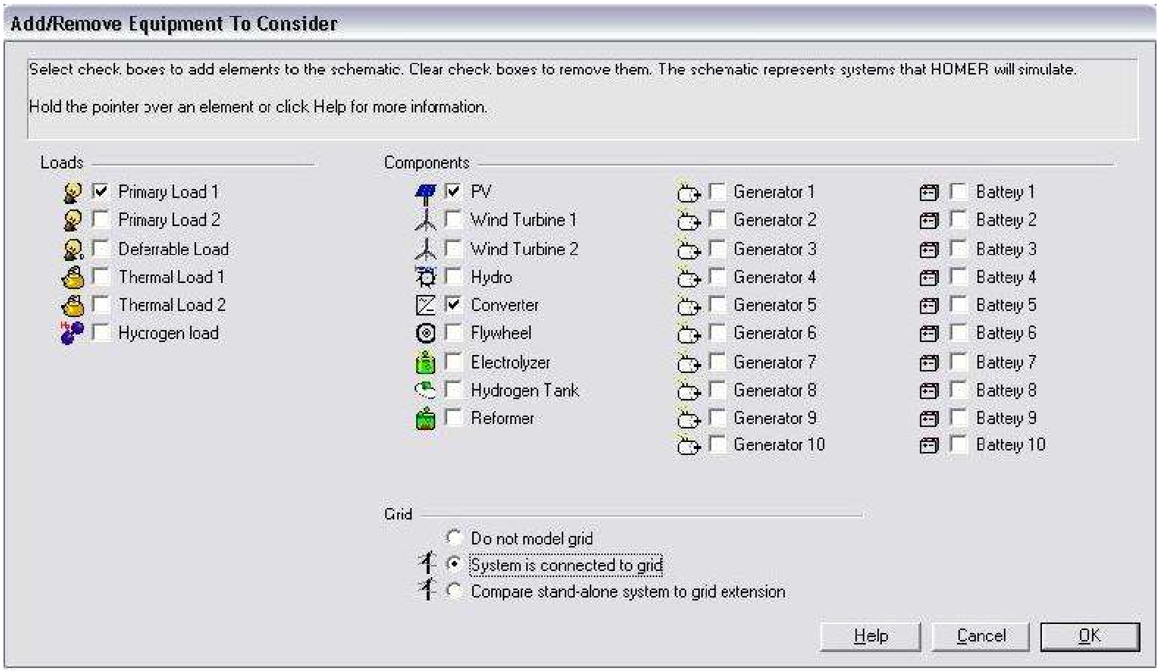



**Figure 4.1 Selecting PV system component [41]**

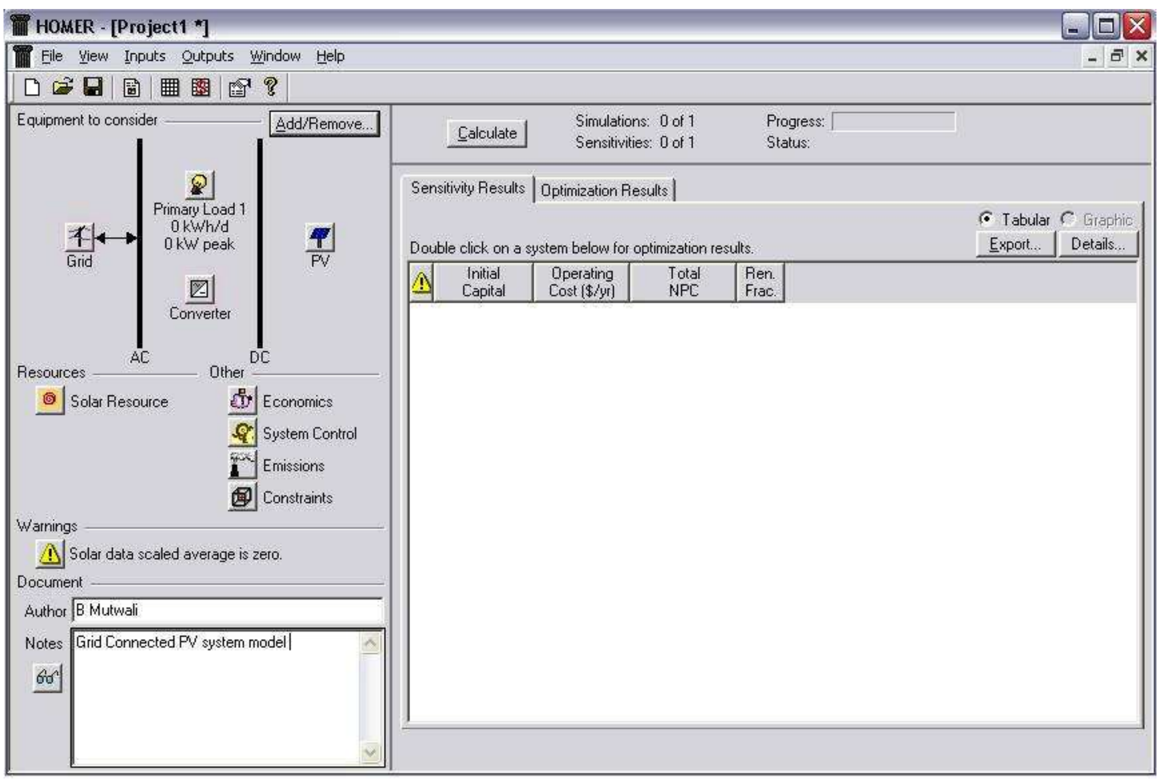



**Figure 4.2** Grid Connected PV model in the HOMER window [41]

### *4.3.5.1. Defining the PV features.*

This part is related to the PV panels. As shown in Figure 4.2, none of the components have been connected to the system Bus bar except the grid. For the PV panels, we choose the model number NU-U245P1 solar panel from Sharp Company. Details of the panels are shown in appendix A. There are five fundamental factors that must be entered namely: the price per kilowatt peak ($/kW$_p$), the sizes of the system in kW, the project life in years, the temperature effect on the percentage, and the panel efficiency in percentage, as appears in Figure 4.3.

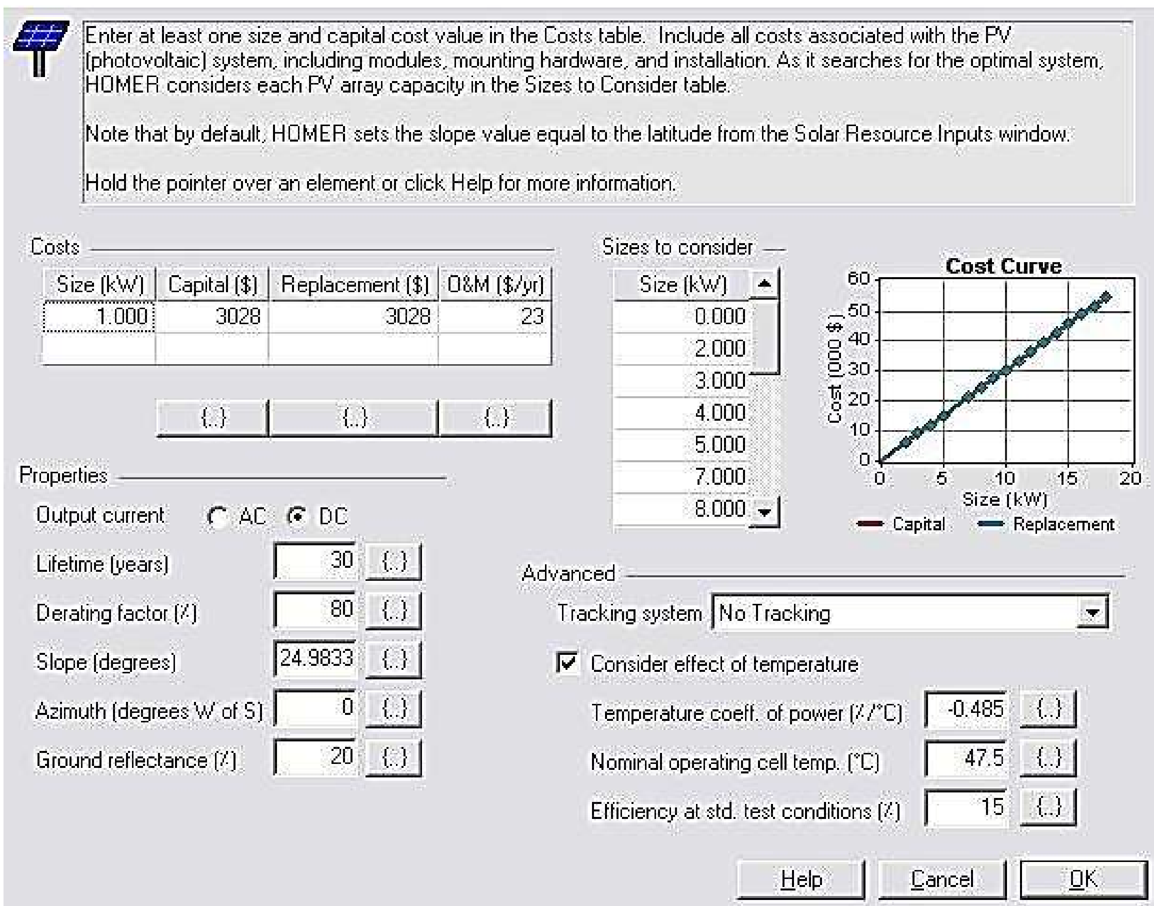



**Figure 4.3** PV panel features [41]

### *4.1.2.2 Defining the Load*

The primary load here represents the residential load. HOMER software can generate a load profile of 8760 hours (one year), if it is provided with any 24-hour system load demand. However, in this case a residential load profile has been calculated using load demand provided by the Saudi Electric Company (SEC). Details on how the load calculated are described in the economics section. The load profile is then uploaded to the HOMER system as shown in Figure 4.4.

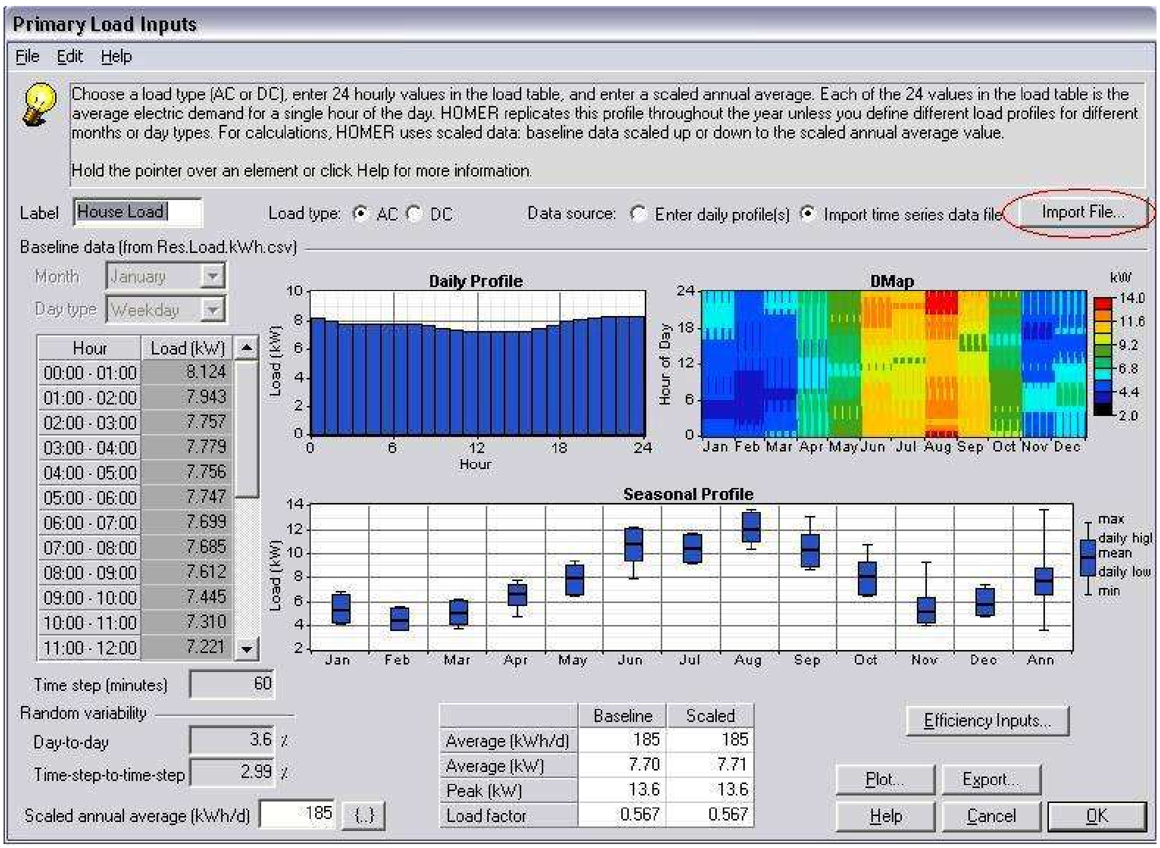



**Figure 4.4** Importing Residential Load Profile [41]

#### *4.1.2.3 Defining the Solar Radiation*

Solar radiation data are essential elements in PV calculation. The accuracy of the radiation data helps to provide accurate results. There are two sources where solar radiation data can be obtained: meteorological centre of the country, and websites that provide satellite data [56, 57]. In this study, King Abdulaziz City of Science & Technology (KACST) have provided the solar radiation data. Hence, the solar radiation data file is imported to the HOMER software as in Figure 4.5.

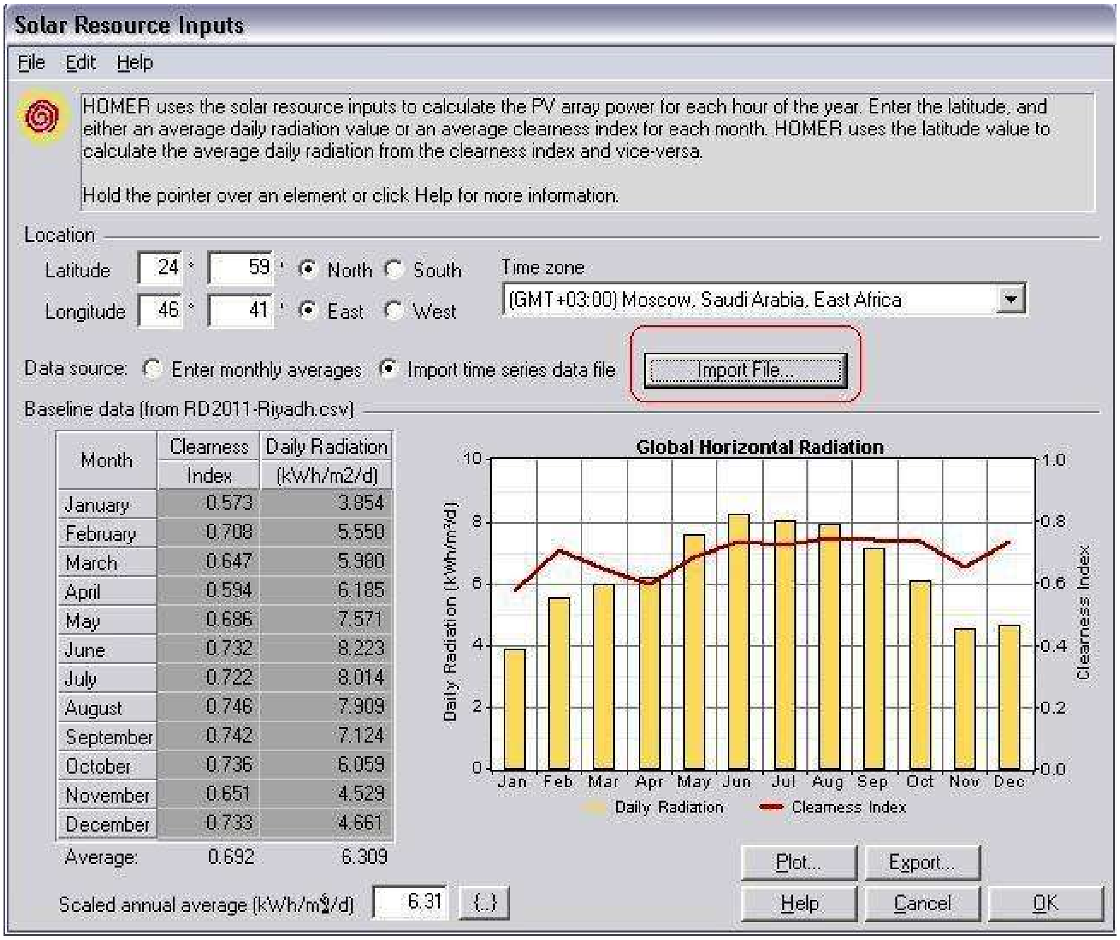



**Figure 4.5** Solar Radiation Date of Riyadh [41]

#### *4.1.2.4 Defining Grid Features*

The Saudi Electricity Company (SEC) has eight tier rate schedule where the cost per kilowatt-hour increases as the total amount of supply energy increases. Table 4.1 shows the eight tiers of SEC for residential areas in Saudi Arabia.

This feature could not be implemented directly into HOMER. A modification has been used to imitate the SEC bill (Figure 4.6). In this part also, the price of energy transfer to the grid, the sell back price, is included.

**Table 4.1** Saudi Electric Company Tariff [37]

| Tier No. | KWh usage | Rates SR |
|---|---|---|
| 1 | **1-2000** | 0.05 |
| 2 | **2001-4000** | 0.10 |
| 3 | **4001-6000** | 0.12 |
| 4 | **6001-7000** | 0.15 |
| 5 | **7001-8000** | 0.20 |
| 6 | **8001-9000** | 0.22 |
| 7 | **9001-10000** | 0.24 |
| 8 | **10000 and up** | 0.26 |

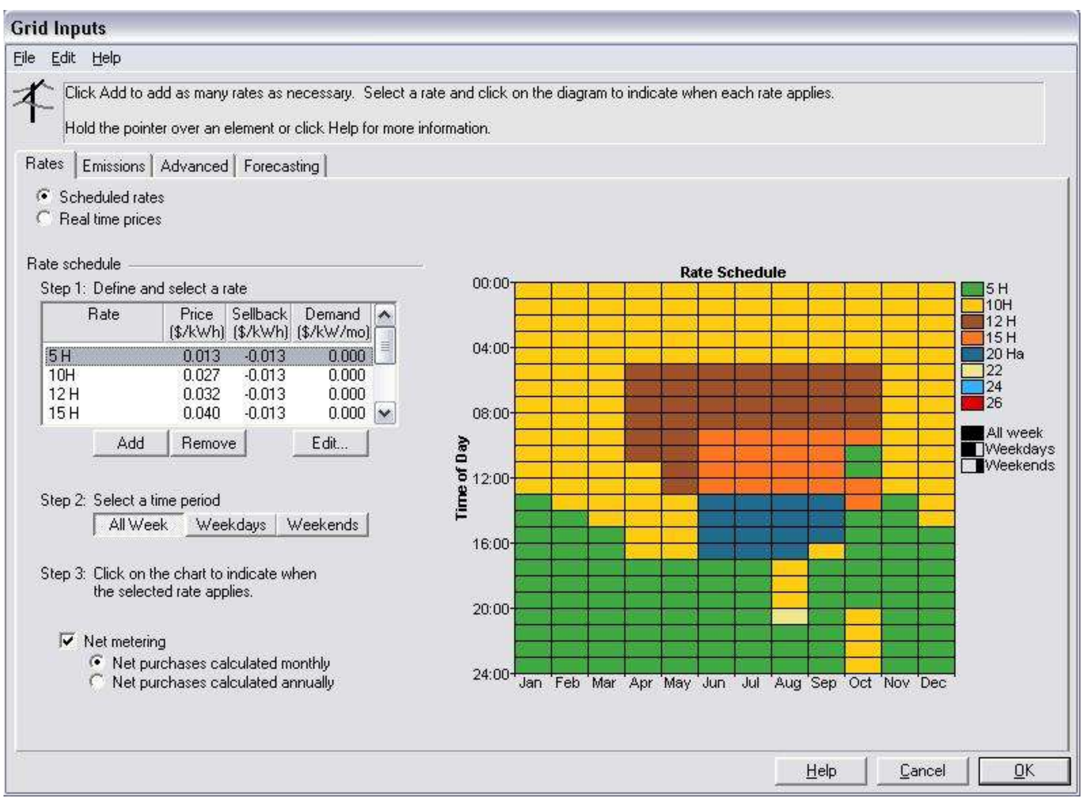



**Figure 4.6** Grid features [41]

#### *4.1.2.5 Inverter Features*

There are four important data for the inverter: the price per kilowatt $/kW, the efficiency (%), the lifetime (years), and the size of the inverter that need to be taken under consideration, Figure 4.7. In this study, the Sunny Boy grid tie inverters have been used in system calculation. Details of the inverter are given in appendix A.

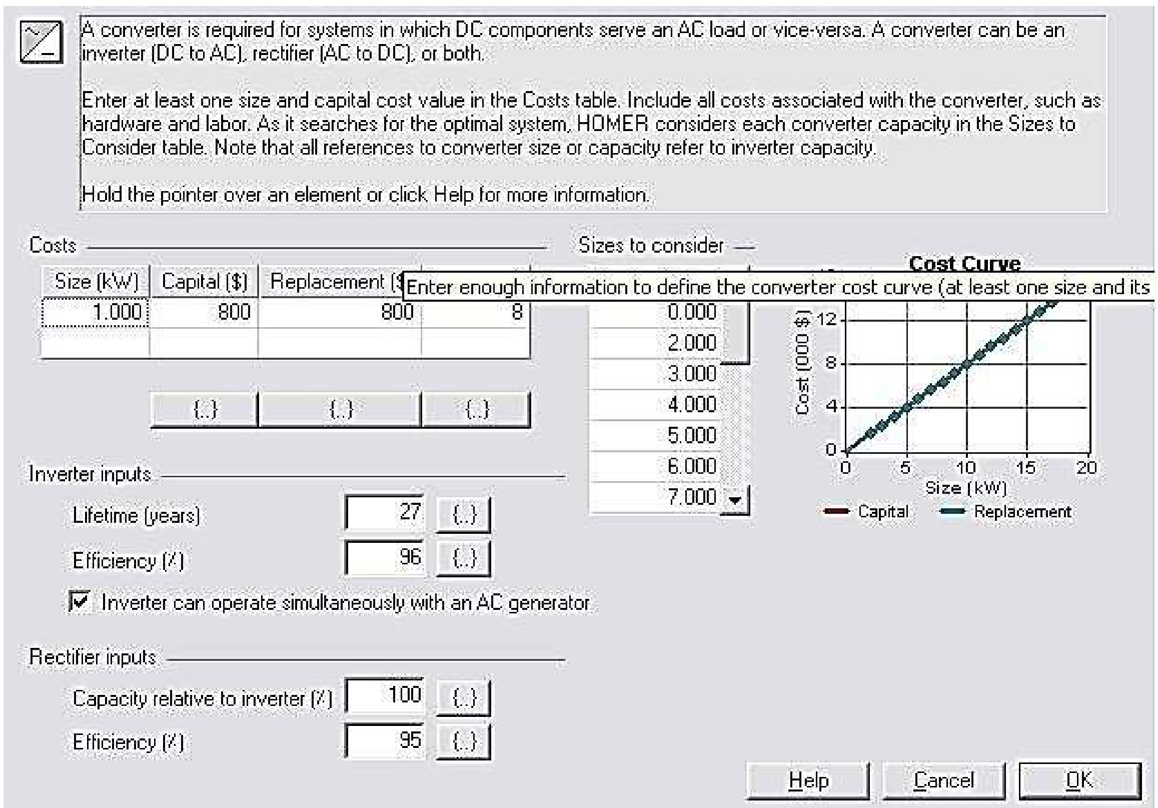



**Figure 4.7** Inverter features **[41]**

#### *4.1.2.6 Other Factors*

The other information that needs to be provided for the HOMER software are: the economic conditions, system control, temperature, and constrains.

The economic parts deal with: project life years (25 years), fixed cost, and annual real interest rate. There are two types of system fixed cost namely: fixed capital cost, and fixed operation and maintenance cost (O&M). The former is mandatory cost paid no matter the size of the project, such as, paper works, and permission to install PV system. The latter is dealing with any mandatory charge of O&M, such as, the money charged by the *Saudi Electric Company* (SEC) for supplying electricity. Last yet importantly, the annual real interest rate is the real interest rate after including the nominal interest rate and the inflation rate.

In the system control part, the simulation time and the dispatch strategy must be specified. The HOMER software has two-dispatch strategy: load following strategy, and cycle charging strategy. The former is used to obtain optimum solution when the system has a combination of renewable energy sources. The latter is used when system has one/non-renewable energy.

The temperatures of Riyadh have been gathered from the Jeddah Regional Climate Center (JRCC) [42]. Then the temperature data imported into HOMER software.

Finally, the constraints deal with the minimum rate of renewable energy penetration of the system. Thus, the minimum penetration of renewable energy was set to 0%, 4%, 5%, 10%, 15%, 20%, 25% and 30%.

#### *4.1.2.7 Simulate the Defined Model*

After feeding all the above information to HOMER software, the model is ready for simulation. HOMER software provides three models: simulation model, the optimization model, and sensitivity model.

#### *4.1.2.8 Simulation Model*

The load profile contains the load demand for each hour in the year, i.e. 8760 hours. Thus, HOMER starts to simulate the system through calculating the flow of energy to and from each component of the system, i.e. HOMER performs an energy balance calculation for each hour in the year and for each system size. Then it stipulates whether the proposed model meets the load demand or not. Furthermore, HOMER approximates the operating cost, installation cost, and maintenance cost of the system for the entire lifetime of the project (i.e. 25 years) [41].

#### 4.1.2.9 *Optimization Model*

The next step after model simulation is to achieve the optimal solution. Thus, HOMER presents a list of constellations that show the net present value and the life cycle cost of each system size [41].

#### 4.1.2.10 *Sensitivity Model*

Each part of the grid connected PV system described here, has a sensitivity option; where a range of information can be used. Figure 4.8 shows the sensitive variables at the PV panels that can be changed in order to investigate their influence to the system. For instance, the tilted angle of the PV array (24.9833$^{o}$) can be examined to determine the effect of the angle change in the total power produced by the PV array. Hence, HOMER simulates system configuration for the range of tilted angle that provided by the user [41].

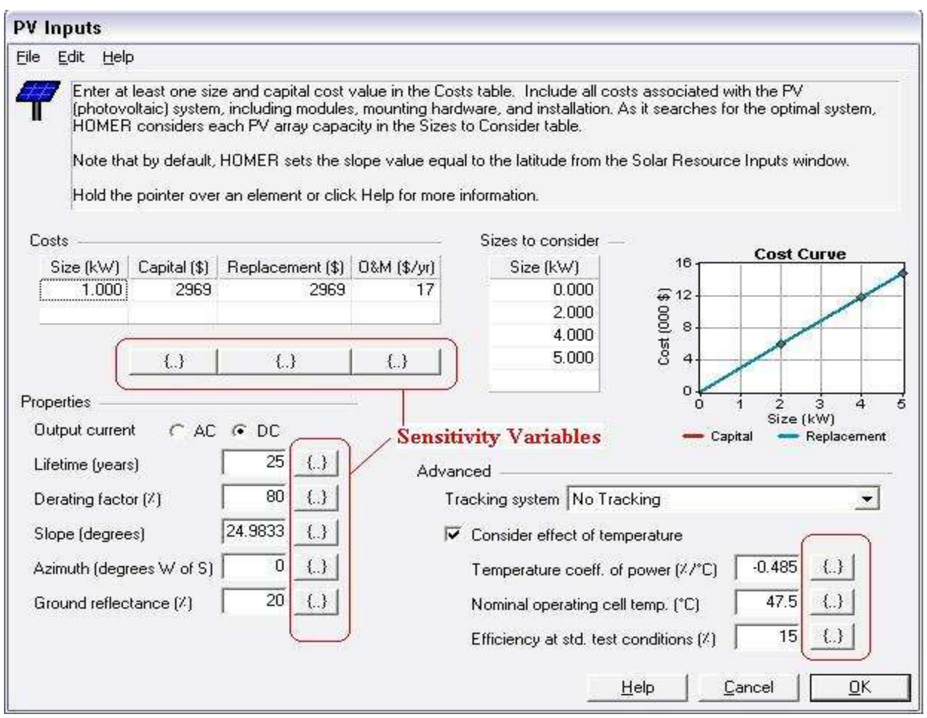



**Figure 4.8** Sensitivity Analysis [41]

### 4.1.3 Calculation

Details in the entire calculation that done by HOMER are explained in the manual [41]. However, necessary calculations are provided here.

#### *4.1.3.1 PV Characteristic*

There is important information regarding the PV panels needed to calculate the number of PV arrays, the efficiency, and the output power under standard test condition (STC). In the above calculation, we used the sharp PV array NU-U245P1. The data sheet of this panel provides the information illustrated in table 4.2 (appendix A):

**Table 4.2** Sharp Soar Panels Parameters (Appendix A)

| | |
|---|---|
| **Max. Power** | 245 W |
| **Open circuit voltage ($V_{oc}$)** | 37.3 V |
| **Short Circuit Current** | 8.7 A |
| **Max. Power voltage ($V_{mp}$)** | 30.4 |
| **Max. Power current ($I_{mp}$)** | 8.08 |
| **Module efficiency** | 15 % |
| **Dimension** | 994X1640 mm |
| **Nominal temperature** | 25 |
| **NOCT (Nominal operating cell temperature)** | 47.5$^{o}$ |
| **Temperature coefficient (Voc)** | -0.485%/$^{o}$C |

The efficiency of the cell can be exemplified as [9]:

$$eff = \frac{\frac{Vmp*Imp}{1000}}{\frac{Wedith*Length}{1*10^6}} \tag{4-1}$$

The number of panels, $N_{PV}$ can be found using the following equation [9]:

$$N_{PV} = \frac{System\ Size}{Module\ Size} \tag{4-2}$$

The NOCT., i.e. nominal operating cell temperature and the temperature coefficient rates are used to calculate the maximum output power under high (low) temperature in summer (winter). For instance, -0.485%/°C means that when the temperature increase above the NOCT (47.5°), the maximum power voltage will be decreased by 0.485% for each degree. Thus, if the temperature of the PV modules reaches up to 70°, then the maximum power voltage $V_{mp}$, will be decreased by [9]

$$V_{mp} = V_{mp} + V_{mp} * \frac{TC}{100} * (Temperature - Nominal\ temperature)$$

$$V_{mp} = 30.4 + 30.4 * \frac{-0.485}{100} * (70^o - 47.5^o) = 26.67\ V \qquad (4\text{-}3)$$

On the contrary , if the array temperature reduced in winter to *-5* Celsius, the maximum voltage will be increased to reach 33.6 V.

The fill factor (FF) is a measure used to emphasize the cell performance, which reflect the solar cell quality. [9]

$$FF = \frac{I_{mp} * V_{mp}}{I_{oc} * I_{sc}} \qquad (4\text{-}4)$$

The ideal cell gets unity, where the current held up right up to the short circuit value then reduced suddenly to zero at maximum power point (MPP) [9].

#### *4.1.3.2 PV Output*

Photovoltaic output power calculated using the following expression [41]:

$$P_{PV} = Y_{PV} F_{PV} \left[\frac{G_t}{G_{t,STC}}\right] \left(1 + \alpha\left(T_c - T_{c,STC}\right)\right) \qquad (4\text{-}5)$$

Where:

$Y_{PV}(kW) = Peak\ output\ power\ multiply\ by\ Solar\ cell\ efficiency$,

$F_{PV}$ = the duration factor for the PV system,

$G_t$ = the solar radiation in kW/m$^2$ depending on the latitude and longitude,

$G_{t,STC}$ = the solar radiation under standard test condition,

$\alpha$ = the temperature coefficient of power in $\%/C^o$,

$T_{c,STC}$ the solar cell temperature under STC.

$T_c$ = the cell temperature each hour of simulation in $C^o$ and it is calculated using the following formula:

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT})\left\{\frac{G_t}{G_{t,NOCT}}\right\}\left\{1 - \frac{\eta_{STC}(1 - \alpha T_{c,STC})}{\tau\beta}\right\}}{1 + (T_{c,NOCT} - T_{a,NOCT})\left\{\frac{G_t}{G_{t,NOCT}}\right\}\left\{\frac{\alpha\eta_{STC}}{\tau\beta}\right\}} \tag{4-6}$$

Where:

$T_a$ = the ambient temperature,

$T_{c,NOCT}$ = the nominal operating cell temperature (NOCT),

$T_{a,NOCT}$ =293K,

$G_{,,NOCT}$ = the solar radiation at NOCT always around 0.8 kW/m$^2$,

$\eta_{STC}$ = PV module efficiency,

$\alpha$ = the temperature coefficient of power in $K/C^o$,

$\tau$ = the solar transmittance of any cover of the PV array in %.

#### *4.1.3.3 Electricity Cost*

The energy charge calculated using the following equation [41]:

$$C_{GE} = \sum_i^{rates}\sum_j^{12} E_{GP_{i,j}} * C_{P_i} - \sum_i^{rates}\sum_j^{12} E_{GS_{i,j}} * C_{PS_i} \tag{4-7}$$

Where:

$E_{GP_{,,,j}}$ = the energy grid purchase (supplied) from the grid to load at month ***j*** and the hour ***i***,

$C_{P_{i,}}$ = the price of electricity at the time ***i***,

$E_{GS_{i,j}}$ = the energy transfer that amount back to the grid at month ***j*** and rate ***i***,

$C_{PS_{i,}}$ = the cost of sellback power at the rate ***i***.

#### *4.1.3.4 System Cost Summery*

HOMER applies economic analysis for each system size to obtain the optimal solution. All the economic calculations are described in the economic analysis section.

## 4.2 Economic Analysis

In order to start the economic calculation, the residential load profile needs to be stipulated.

### 4.2.1 Generating a Residential Load Profile

At the beginning the load demand of Riyadh for the year 2011, has been gathered from the Saudi Electricity company (SEC). Next, the total load for the whole year was calculated. Then we find the percentage of each month compared with the total load. The result is shown in table 4.3:

**Table 4.3** Riyadh Monthly Load Rates

| Month | Riyadh load MW/Month | Percentage (%) |
|---|---|---|
| **January** | 4,208,134 | 5.69 |

| Month | Riyadh load MW/Month | Percentage (%) |
|---|---|---|
| **February** | 3,567,643 | 4.82 |
| **March** | 3,998,574 | 5.41 |
| **April** | 5,290,141 | 7.15 |
| **May** | 6,411,274 | 8.67 |
| **June** | 8,656,646 | 11.71 |
| **July** | 8,372,391 | 11.32 |
| **August** | 9,574,560 | 12.95 |
| **September** | 8,276,328 | 11.19 |
| **October** | 6,655,142 | 9.00 |
| **November** | 4,140,882 | 5.60 |
| **December** | 4,800,606 | 6.49 |
| **Total** | **73,952,321.00** | **100.00** |

The allowed maximum load of the residential areas is approximated using the breaker sizes provided by the Saudi Electric Company (SEC), [Appendix B]. This helps to give us the maximum load per hour for the entire house. This load is assumed to be maximum where all the appliances and equipment at the house are working. Table 4.4 shows the maximum connected load allowed and the breaker sizes depending on the house size in square meters ($m^2$). In this thesis, the sizes of the houses that are considered are between 300 to 700 $m^2$. Thus, the average sizes and the average maximum allowed load have been calculated from the table. After that, the maximum load converted from volt amber hour (VAh) to kilowatt-hour (kWh) by multiplying VAh with the power factor 0.85.

Another modification has been applied to the result by multiplying the maximum load with 1.5, because most of the houses in Riyadh consist of two storey, and the result is only for one floor. Multiplying the maximum load by 2 provides a high electricity load, and un-practical electricity bill. This electricity bill does not match electricity bills that have been used to test the system. Hence, multiplying by 1.5 was the best. Using all the calculated data, we can now find the load profile for a residential area table 4.5.

**Table 4.4** Breaker Sizes with respect to house size (Appendix B)

| **Residential maximum load in VAh** | **House Size ($m^2$)** | **Breaker size (Amber)** | **Residential maximum load in VAh** | **House Size ($m^2$)** | **Breaker size (Amber)** |
|---|---|---|---|---|---|
| **46000** | 300 | 100 | **73000** | 500 | 200 |
| **47000** | 301 | 150 | **75000** | 534 | |
| **50000** | 325 | | **76000** | 525 | |
| **53000** | 350 | | **80000** | 550 | |
| **56000** | 375 | | **83000** | 575 | |
| **60000** | 400 | | **86000** | 600 | |
| **63000** | 425 | | **90000** | 625 | |
| **66000** | 450 | | **91000** | 630 | |
| **68000** | 465 | | **93000** | 631 | 300 |
| **69000** | 466 | 200 | **96000** | 650 | |
| **70000** | 475 | | **100000** | 700 | |
| **Average per hour** | | **72772.727** | **Avg in Wh** | | **92785.22** |

**Table 4.5** Residential Monthly load Profile

| Months | Residential Total Load per Month Wh/month |
|---|---|
| **January** | 3,928,163 |
| **February** | 3,007,999 |
| **March** | 3,732,545 |
| **April** | 4,778,887 |
| **May** | 5,984,726 |
| **June** | 7,820,044 |
| **July** | 7,815,369 |
| **August** | 8,937,556 |
| **September** | 7,476,481 |
| **October** | 6,011,971 |
| **November** | 3,740,696 |
| **December** | 4,336,662 |
| **Total (Wh/year)** | **67,571,098.82** |

Next, the cost of electricity charged by the SEC is calculated using the defined tariff in SEC website [51]. Table 4.6 shows the monthly usage of electricity of 20,000 kWh. The prices are shown in Saudi Riyal (SR) and US dollar, where 1 U.S. $=3.75 S.R. There is a meter service charged by SEC every month equal to 21 SR (5.6 US$). Hence, we use equation 4-8 to find the charge for electricity consumption (A kWh/month) by SEC.

**Table 4.6** SEC Electricity Charge for a 20,000k Wh/month

| KWh usage | 20,000 | Rates | Calculate | Tier No. | Price (SR) | Price $ |
|---|---|---|---|---|---|---|
| 1-2000 | 2,000.00 | 0.05 | 18,000.00 | 1 | 100.00 | 36.36 |
| 2001-4000 | 1,999.00 | 0.10 | 16,001.00 | 2 | 199.90 | 72.69 |
| 4001-6000 | 1,999.00 | 0.12 | 14,002.00 | 3 | 239.88 | 87.23 |
| 6001-7000 | 999.00 | 0.15 | 13,003.00 | 4 | 149.85 | 54.49 |
| 7001-8000 | 999.00 | 0.20 | 12,004.00 | 5 | 199.80 | 72.65 |
| 8001-9000 | 999.00 | 0.22 | 11,005.00 | 6 | 219.78 | 79.92 |
| 9001-10000 | 999.00 | 0.24 | 10,006.00 | 7 | 239.76 | 87.19 |
| 10k and up | | 0.26 | 10,006.00 | 8 | 2,601.56 | 946.02 |
| | | | Total | 20,000 | 3,950.53 | 1,436.56 |
| | | | **Meter Service** | | **21.00** | **5.60** |
| | | | Total | | 3,971.53 | 1,442.16 |

$$\begin{gathered}
A1 = IF(A - 2000) > 2000 \Rightarrow A1 = 2000 \,\&\, B1 = A - 2000 \\
ELSEIF\ A > 0 \Rightarrow A1 = A \\
ELSE\ A1 = 0 \\
A2 = IF(B1 - 1999) > 1999. \Rightarrow A2 = 1999 \& B2 = B1 - 1999 \\
ELSEIF\ \ B1 > 0 \Rightarrow A2 = B1 \\
ELSE\ A2 = 0 \\
A3 = IF(B2 - 1999) > 1999 \Rightarrow A3 = 1999 \& B3 = B2 - 1999 \\
ELSEIF\ B2 > 0 \Rightarrow A3 = B2 \\
ELSE\ A3 = 0 \\
A4 = IF(B3 - 999) > 999 \Rightarrow A4 = 999 \& B4 = B3 - 999 \\
ELSEIF\ B3 > 0 \Rightarrow A4 = B3 \\
ELSE\ A4 = 0 \\
A5 = IF(B4 - 999) > 999 \Rightarrow A5 = 999 \& B5 = B4 - 999 \\
ELSEIF\ B4 > 0 \Rightarrow A5 = B4 \\
ELSE\ A5 = 0 \\
A6 = IF(B5 - 999) > 999 \Rightarrow A6 = 999 \& B6 = B5 - 999 \\
ELSEIF\ B2 > 0 \Rightarrow A6 = B5 \\
ELSE\ A6 = 0 \\
A7 = IF\ B6 > 0 \Rightarrow A7 = B6 \\
ELSE\ A7 = 0
\end{gathered} \tag{4-8}$$

$$\mathrm{SEC_{Bill}} = \text{Fixed cost} + \text{Running Cost} \tag{4-9}$$

$$\text{Fixed Cost} = \text{Meter service charge} \tag{4-10}$$

$$\text{Running Cost} = \mathrm{A1} * 0.05 + \mathrm{A2} * 0.1 + \mathrm{A3} * 0.15 + \mathrm{A4} * 0.2 + \mathrm{A5} * 0.22 + \mathrm{A6} * 0.26 \tag{4-11}$$

### 4.2.2 Economic Calculation

Now we are ready to start the economic calculation of the solar home system (SHS). Below are the procedures to calculate the SHS cost and profit, i.e. income cash flow and outcome cash flow.

#### *4.2.2.1 Future Worth (F)*

Future worth represents the sum of money obtained or spends after n years. It is expressed mathematically as [1]:

$$F = P(1 + i)^n \tag{4-12}$$

Where:

***F***= the future worth,

***P***= the present worth,

***i*** = is the real discount rate.

#### *4.2.2.2 Present Worth of Future Sum (P)*

The present worth of a future sum corresponds to the present value of the money spent/receive over n years. It is demonstrated by [1]:

$$\mathrm{P} = \mathrm{F}(1 + \mathrm{i})^{-\mathrm{n}} \tag{4-13}$$

#### *4.2.2.3 Present Worth of Uniform Series*

The present worth of a uniform series of money (Ann) represents the value of the annual amount that received/spend, such as annual maintenance, operating, and replacement cost. It is exemplified by [1]:

$$P_{Uni} = \mathrm{Ann} * \frac{[(1+i)^n - 1]}{[i*(1+i)^n]} \tag{4-14}$$

#### *4.2.2.4 Discount Rate*

There are two types of interest rate namely: nominal interest rate, and real interest rate. The nominal interest rate is the rate for borrowing money from the bank. On the other hand, the discount rate (i.e. real interest rate) is the rate where inflation rate has been included in the calculation. The real interest rate is shown in equation 4-15:

$$i_r = \frac{i_n - f}{1+f} \tag{4-15}$$

Where:

$i_n$ = the nominal interest rate,

$i_r$ = the real interest rate,

f = the inflation rate.

The real interest rate of Saudi Arabia is given by the Saudi Arabian Monetary Agency (SAMA). SAMA is the central bank of Saudi Arabia and responsible for national currency (i.e. Saudi Riyal), government expenses, and rate exchange. Hence, according to SAMA the real interest rate in Saudi Arabia is 2% [59].

#### *4.2.2.5 Life Cycle Cost (LCC)*

The life cycle cost (LCC), i.e. levelized energy cost (LEC) corresponds to the cost per kWh for the entire project life. It is exemplified by [1]:

$$LEC = \frac{NPW * CRF}{E} \tag{4-16}$$

Where:

***NPW*** = the net present worth of the entire project,

***E*** **=** is the total energy in kWh for the total period of the project which is 25 years,

***CRF*** = the capital recovery factor. It is expressed mathematically as [1]:

$$CFE = \frac{m(1+m)^n}{(1+m)^n - 1} \tag{4-17}$$

Where ***m*** is mathematically equivalent to the real discount rate ***i***.

The net present worth of the project (NPW) is exemplified as:

$$\text{NPW} = \text{IC} + \text{Main} + \text{Rep} - \text{Svg} \tag{4-18}$$

$$\text{IC} = \text{PVC} + \text{Eng. C} + \text{Inv. C} + \text{BOS} \tag{4-19}$$

Where

***IC*** **=** the initial cost (capital cost) of the system. The capital cost includes the PV array cost (PVC), the engineering cost (Eng. C), the inverter cost (Inv. C), and the balance of the (i.e. BOS) system cost. The BOS is the fees of interconnection, mounting structures, and wiring.

***Main*** **=** the maintenance cost of the solar system.

***Rep*** = the replacement cost of any parts of the system such as inverters, and batteries. In this thesis the inverter does not need to be changed during the life of the project.

***Svg*** **=** the salvage cost of the solar system at the end of the project life.

#### *4.2.2.6 System Parameters*

Table 4.7 demonstrates the values of the parameters that have been used in the economic calculation of the GRPV system module.

**Table 4.7** PV system Parameters [29]

| | |
|---|---|
| **Engineering cost (Eng. C)** | 10% * IC |
| **BOS costs ($/Wp)** | 0.2 |
| **Maintenance cost** | 1% * IC |
| **Installation Cost** | 13% * IC |
| **Salvage Cost (Svg)** | 10%*IC |

In order to show the benefit of using a PV system, the saving in oil fuel barrel has been calculated. Furthermore, the reduction in the $CO_2$ (Carbon dioxide) emissions is exploited to indicate the benefit for the environment. Table 4.8 shows the parameter of the oil barrel consumption and $CO_2$ reduction:

**Table 4.8** Other Parameter [25]

| | |
|---|---|
| **One barrel of oil produces ( kWh)** | 1628 |
| **1KWH produce Kg** | 0.56 |

## 4.3 Artificial Neural Network (ANN)

### 4.3.1 Introduction

An artificial neural network is a processing program that imitates the human brain using interrelated artificial neurons to find a relationship between input and output vectors, i.e. the main process of the artificial neural network is to map the nonlinear (or linear) relationship between the input(s) and output(s) vectors. The ANN has adaptivity features that change the network structure each time a new input flows through the network. The output and input could be one vector each or multiple vectors.[43]

In this thesis, ANNs were used to predict the value of oil barrels prices (OBP). Consequently, different variables were used to find an accurate model for OBP.

The design of neural network has seven steps:

1. Gathering the data.
2. Creating the network.
3. Configuring the network
4. Training the network.
5. Validating the network
6. Simulating the network.
7. Using the network.

Description of these steps is shown in the next sections.

### 4.3.2 Neural Network Structure

Neurons are the basic unit in the artificial neural network (ANN). Each neuron is considered a computation unit that produces its output by using a transfer function called the activity function. In Figure 4.9, a typical sample of an artificial neuron is shown. Each input ($p_i$) is multiplied by a weight ($w_i$). Weights are the strengths of the connection between inputs and neurons and between neurons in different layers. Next, all the weighted inputs are summed together. After that, a bias *(b)* is added to the sum of the weighted inputs $\sum(w_i p_i)$. The transfer function *(f)* is then applied to the result to produce the output *(a)*. [43]

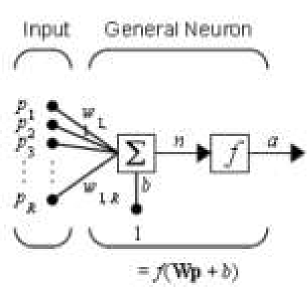



**Figure 4.9** Simple Artificial Neuron [43].

The output of each neuron as a function of the input signals is exemplified as:

$$y = \sigma(\textstyle\sum_i^n w_i p_i + b) \tag{4-20}$$

Where: $\sigma$ is the activity function, which could be a linear function 'purelin' or a nonlinear function such as logistic, hyperbolic, or tangent function. Figure 4.10, shows three types of transfer functions that can be used by the neurons to map the output. In these models, the tangent function (tan-sigmoid), the logistic function (log-sigmoid), and the linear function (purelin) were used in the simulation.

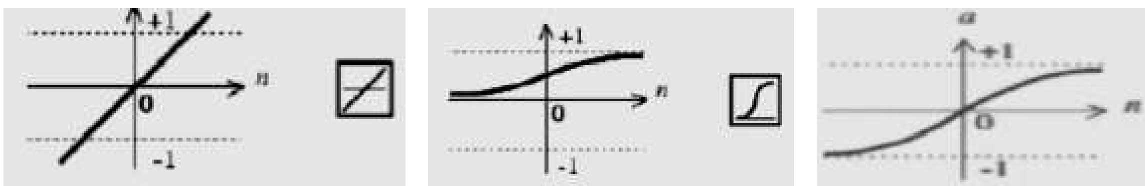



**Figure 4.10** Examples of Activity Function, purelin (left), log sigmoid (middle) , tan sigmoid (left) [43]

Figure 4.11, shows two equivalent two-layer neural networks. In both Figures, R represents the number of elements in the input matrix sized R X 1. S is the number of neurons in the hidden layers and *a* is the output vector. [43]

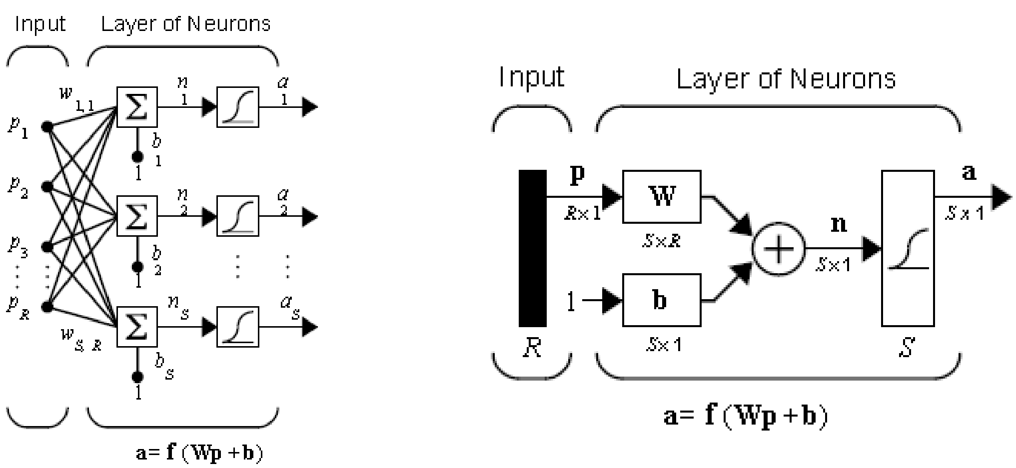



**Figure 4.11** Two layer Neural Network Architecture [43]

There are many types of artificial neural networks (ANN) for linear and non-linear problems. For example, ANNs can be feed forward neural networks, radial basis function (RBF) networks, Kohonen self-organizing networks, recurrent networks, simple recurrent networks, Hopfield networks, the Echo state networks, the long short term memory networks, stochastic neural networks, Boltzmann machine, associative neural network (ASNN), holographic associative memory, instantaneously trained networks, spiking neural networks and neuro-fuzzy networks. We focus on the multilayer feed forward neural network with back propagation (MFFNNBP), i.e. multilayer perceptron (MLP) with backpropagation algorithm. [44]

The function between the input and output can be written as [43]:

$$y = f(x; w) = \sigma(w_n \sigma(w_{n-1} \sigma(w_{n-2} \sigma \dots (w_1 x) \dots)) \qquad (4\text{-}21)$$

Where:

$y$ = the output matrix,

x = the input vector

w = the matrix containing the neuron weight.

### 4.3.3 Neural Network Rules (Algorithm)

The main objective of any neural network is to map the relationship between the input and output using the computed unit - neurons. A neural network algorithm has three steps:

1. Creating the neural network.
2. Training Stage.
3. Simulating Stage.

#### *4.3.3.1 Creating the network*

Neural networks depend on the type of data and the desired goal. In this case, a feed-forward neural network was created using the command *newff*. This command creates a feed-forward network and initializes the weights and biases of the network. Before using the data, there are two steps to be done, namely: data processing and data division. In data processing, the data is normalized to be in a range between -1 and 1 using the following equation:

$$\tilde{X} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{4-21}$$

Where:

$\tilde{X}$= the normalized data

$X_i$= the input data before normalize.

$X_{min}$= the minimum number in the input/output vector.

$X_{max}$= the maximum number in the input/output vector.

In data division, the data is divided into three sets: training sets, testing sets and error sets to avoid overfitting [43].

#### *4.3.3.2 Training Stage:*

A neural network uses training sets to relate the behaviour of the input(s) and output(s). A set of data (usually input and output or input only) are introduced to the network. Then, the network assigns a weight for each input and a bias for each layer. The input is multiplied by its weight as it enters the neuron. After that, the neuron uses the transfer function to find the best fit for that weighted input. Once this process is applied to the entire input data, one iteration (or ***epoch***) has been completed. This process is repeated until the best fit is obtained or the maximum number of epochs are reached. At the end of each epoch, the learning rule (LR) is used to modify the weight and bias of the network so the best fit can be obtained . This modification can be supervised, where each input has its target (output), or unsupervised, where weights and biases are modified in response to the new input. The change in weights and biases can be expressed mathematically as [45]:

$$w(x+1) = w(x) + 2 * \eta * e(x) * T^T \qquad (4\text{-}23)$$

$$b(x+1) = b(x) + 2 * \eta * e(x) \qquad (4\text{-}24)$$

Where η is the learning rate. The best learning rate can be calculated as follows [45]:

$$\eta < \frac{1}{\max\left(\text{eigenvalue}(x^T x)\right)} \qquad (4\text{-}25)$$

#### *4.3.3.3 Simulation Stage:*

After using the training data and achieving the required fitting, the network is tested to test the validity of the model. Hence, the data are simulated.

### 4.3.4 Multi-Layers Feed-forward Neural Network with Back propagation (MFFNNBP)

Figure 4.12 shows a three layer neural network. The first layer consists of four inputs. The hidden layer (second layer) contains the neurons. The hidden layer in the system often has a nonlinear transfer function, such as the log-sigmoid or the tan-sigmoid. The output layer (the third layer) contains the output vector. The output layer has a linear transfer function (purelin) to provide a wide range of solutions. The following command was used to create this network:

$$net = newff(minmax(p), [no.of\ neuron, no.of\ output], \{'tansig',\ 'purlin'\}) \qquad (4\text{-}26)$$

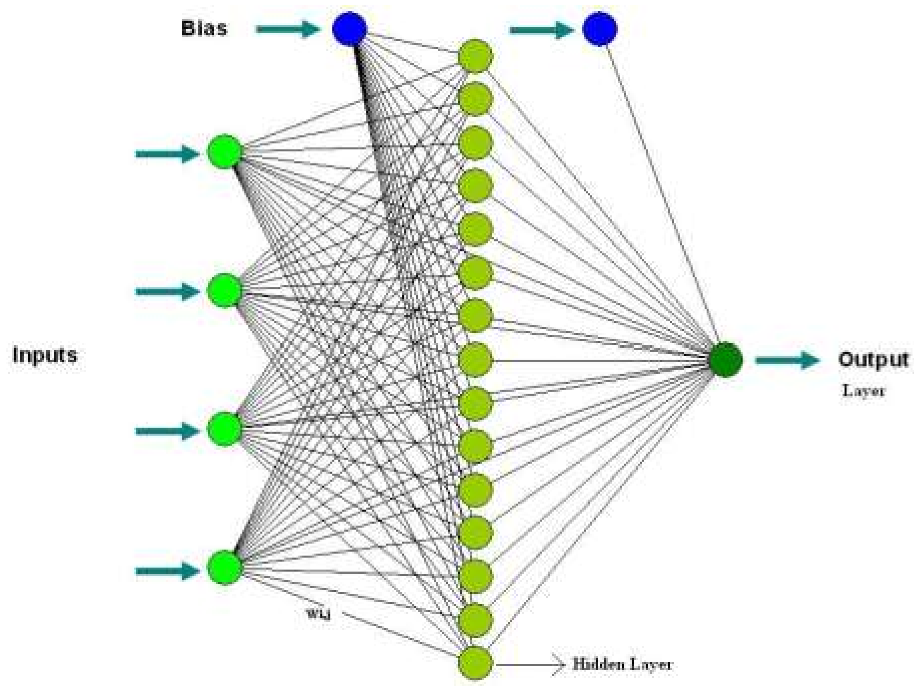



**Figure 4.12** Two-layer feed-forward Network Architecture [46]

The back propagation (BP) is a learning algorithm. The main idea of this technique is to reduce the error of the network through changing the weights and biases. The BP technique is supported by the gradient descent rule. Hence, the weights are moved in the opposite direction of the gradient. This is the simplest form of the BP technique. However, there are other more complicated techniques that have utilized BP to provide a more accurate result. [43]

The BP algorithm uses a different optimization technique to change the weights and reduce the error. For example, there can be variable learning rates, resilient BP, conjugate gradient algorithms, line search routines, Quasi-Newton algorithms and Levenberg-Marquardt methods. Details about these algorithms are given in the neural network toolbox manual [43]. In this study, the data were stored and used repeatedly until an optimum solution was obtained.

### 4.3.5 Training Algorithms

In this work, there are three training algorithms used in forecasting

#### *4.3.5.1 Levenberg Marquardt (trainlm)*

The Levenberg-Marquardt algorithm has a faster training approach of Newton's method without calculating the Hessian matrix. This method is implemented in MATLAB as *trainlm* [43].

#### *4.3.5.2 Bayesian Framework (trainbr)*

The Bayesian framework function used to determine the optimal regularization parameters automatically. This function is implemented in the neural toolbox as a *trainbr* [43].

#### *4.3.5.3 BFGS Quasi-Newton Algorithm*

This method is based on Newton's method to approximate Hessian matrix without calculating the second derivative.

Details about those training algorithms are explained in the next chapter.

### 4.3.6 Error Function

The main objective of using a supervised neural network is to minimize the error between the actual target and the neural network output. The mean square error (MSE) is the parameter that must be minimized. The Widrow-Hoff method, which also known as the least mean square error (LME), is adjust the weights and biases of the network to minimize the mean square error (MSE). The mean sum square (equation 4-27) of the net error is considered as the typical performance function that is used for data training. [45]

In equation 4-26, $\boldsymbol{e_i}$ is the error between the actual target $\boldsymbol{T_i}$ and the neural network output $\boldsymbol{P_i}$, and $\boldsymbol{N}$ is the number of data samples [45].

$$MSE = \frac{1}{N}\sum_{i}^{n}[e_i(x)]^2 = \frac{1}{N}\sum_{i=1}^{n}[T_i(x) - P_i(x)]^2 \tag{4-27}$$

Another measure that has been used regularly to measure the performance of the prediction model is the root mean square error (RMSE). RMSE describes how closely the model fit the data. Moreover, it measures the mismatch between each point in the model. The RMSE expressed mathematically as [45]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(\hat{x}(t) - x(t))^2} \qquad (4\text{-}28)$$

Where $\hat{x}(t)$ is the predicted value, $x\ (t)$ is the actual value, and N is the number of prediction data.

### 4.3.7 Avoid Over-Fitting

Over- fitting or over- training is one of the neural network drawbacks. During training the error between the output and target become smaller. Then when new data are introduced to the system the error becomes large or very small. This leads to an over-fitting situation. To avoid that, there are three methods used to avoid over-fitting namely: modifying the mean square error performance function, using automated regularization, and using early stopping. The first method based on introducing a new element to the mean square error. This element includes the sum of squares error of the net weights and biases in the network. This element is used to improve the generalization. It is called the ***msereg***. The MSE regularization method is exemplified in equations 4-29 & 4-30 [43].

$$msereg = \gamma * mse + (1 - \gamma) * msw \qquad (4\text{-}29)$$

$$msw = \frac{1}{N}\sum_{i=1}^{n} w_i \qquad (4\text{-}30)$$

Where:

$\boldsymbol{e_i}$ = the error between the actual target $\boldsymbol{T_i}$ and the network output $\boldsymbol{P_i}$,

$\boldsymbol{N}$ = the number of data samples,

$\gamma$ = the performance ratio.

The second method is using automated regularization using the MATLAB command *trainbr*. The trainbr is using a Bayesian framework process that gives random values for the weights and biases. These random values have a variance distribution that aid to avoid overfitting [43].

Early stopping method aims to divide the data into three sets: training set, validation set, and test set. During the training process, the error on the training set is decreasing, causing a decrease in the error of the validation set. Those two errors are compared with each other every epoch. Once the error on the training set starts to increase above the error in the validation set with a certain limit, the training stop. This happens to prevent data overfitting. The test set is used in the comparison between different algorithms. Hence, it is not used during the training [43]

### 4.3.8 Neural Network Review

The artificial neural network (ANN) has a significant amount of literature focused on its forecasting applications. In a population prediction study, Chen Han-Jan et al. [43] used a logistic equation and the back propagation (BP) neural network to obtain the population forecast for the next 30 years. The article concluded that using the logistic function in neural network led to an accurate result of the training data with a remarkably low error. However, the prediction data were not accurate as the training data. The logistic equation was used for a 30 year forecast, and, then, the BP neural network was used to obtain a curve fitting. In addition, the study's analysis considered population development as a problem of chaos.

Bong et al. (2008) [47] applied a comparison between two methods in long term electricity demand forecasting. The two methods were the linear regression analysis method (RA) and artificial neural network (ANNs). The ANNs algorithms used were the multilayer perceptron (MLP) with back propagation (BP). Besides the electricity demand input factors which were used in the system forecasting, economic and social factors were also added to investigate their effects on the output. The article concluded that the regression analysis method needed a large amount of data to obtain an accurate result. In contrast , the MLP algorithm provided an accurate result with a variable size of data (15, 20 & 25 years). In addition, using economic and social as input factors in the MLP network were reported to have a trivial effect on the result.

Haidar et al. [49] implemented a three layer feed-forward neural network model with a BP algorithm to predict the crude oil spot price during the short term. Two groups of input data were used crude oil future price and inter-market data. The study aimed to find the optimal model that could provide an accurate data for risk management analysis. The paper concluded that using heating oil spot price in forecasting help to provide a multistep prediction.

Zimberg [50] proposed an ANFIS (Adaptive Neuro-Fuzzy Inference System) model to predict the price of crude oil. West Taxes Intermediate (WTI) and Brent crude oil spot price were utilized in the ANFIS program. The proposed model used the component needed for oil production as the main input to the system. However, the article did not offer any details on these inputs. The article concluded that the ANFIS module has a low error distribution and provided a compelling forecast. There were some missing details in this article, such as information about the fuzzy model, type of neural network and tables for the membership function.

Zalloi [44] investigated a fuzzy-based model combined with ANN to forecast the Sidi Kerir Iran Light Spot price. The ANN was used to help minimize the error. The model inputs included several factors that have a significant impact on the price of crude oil in Iran. For instance, war, OPEC policy, economic disaster, earthquakes, volcanoes, and terrorist attack were added to obtain an accurate prediction. Root mean square error (RMSE), directional statistics ($D_{stat}$) and goodness-of-fit ($R^2$) are used as an evaluation of the error model. The model provided accurate results and showed a low RMSE and directional static above 80%. They concluded that the model is valid.

Yu et al. (2008) [45] introduced a new concept for crude oil price forecasting. Their model utilized the "*divide-and conquer*" principle which divides the crude oil price in a finite number of small tasks, and then conquers these tasks to obtain a general formula for the oil price data. This proposed model was called empirical mode decomposition

(EMD) -based neural network ensemble learning. Since the crude oil price has nonlinearity and non-stationary characteristics, the EMD technique decomposed these characteristics into a finite number of intrinsic mode functions (IMFs). Then, the feed-forward neural network (FFNN) was used to map each function. Finally, an adaptive learning neural network (ALNN) was used to gather the output of each FFNN and predict the crude oil price. An ARIMA model was used for comparison. The results showed that the proposed model was proven to be better than the ARIMA model because the proposed model had a low RMSE and high $D_{stat}$.

Kooros et al. [55] studied the impact of oil on employment. The article showed that oil price have a significant effect on the unemployment rate, GDP, and inflation rate. In other word, an increase in oil prices means forcing consumers to spend more money on oil and less money on other things, and it causes an increase in the unemployment rate. This causes a reduction in economic activities and disbursing money.

# 5 Chapter 5: Results and Discussion

This chapter shows results obtained from the HOMER software, economic calculations, and artificial neural network (ANN) modelling. This section is divided into three subsections. The first combines the results from HOMER software and the economic calculation to show the reliability of solar home system. The following subsection focuses on the ANN results and model validation. Finally, the last subsection discusses all results obtained from all methods

## 5.1 HOMER and Economic Results:

### 5.1.1 Introduction

The economic calculations carried out in HOMER software are different from those discussed in section 4.2.2. However, both methods have the same objective that is to study the system reliability. In other words, both methods provide details of the cash expenditure and earning from installing a GRPV system. This helps PV future owner to make the decision of purchasing GRPV system or not. Hence, the results from both methods are shown in this chapter.

Two scenarios are presented here. Each scenario presents the simulation, the optimum, and the sensitivity results. The system model is shown in Figure 5.1.

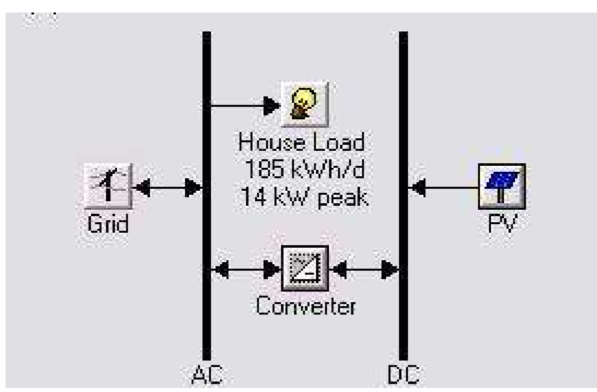



**Figure 5.1** Solar Home System (SHS)

### 5.1.2 First Scenario

#### *5.1.2.1 Defining the SHS components:*

The first scenario focuses on the present price of the PV panel. The cost per watt peak of the Sharp NU-U245P1 is 2.15$. The price does not include installation, engineering, and wiring costs. Thus, we use 3.028 $\$/W_p$ as the price which includes all these cost components. HOMER requires the capital and replacement price of one kilowatt. The same price was used in both cases. Also, the maintenance fee was entered to HOMER as $23\$/kW_p$.

The first component of the solar home system is the PV module sizes of each module. The available space in any house rooftop in Saudi Arabia is between 80 to 150 square meters with an average of 120 $m^2$. One PV panel size is 994mm width by 1640mm length with a total area of 1.63 $m^2$. Thus, a 120 $m^2$ is enough to fit 73 PV panels with a total system output of 18 kilowatt. Hence, the sizes of the system that entered in HOMER software were between 2 to 18 kW as shown in Figure 5.2. Furthermore, solar panel efficiency, temperature, and tilt angle were entered.

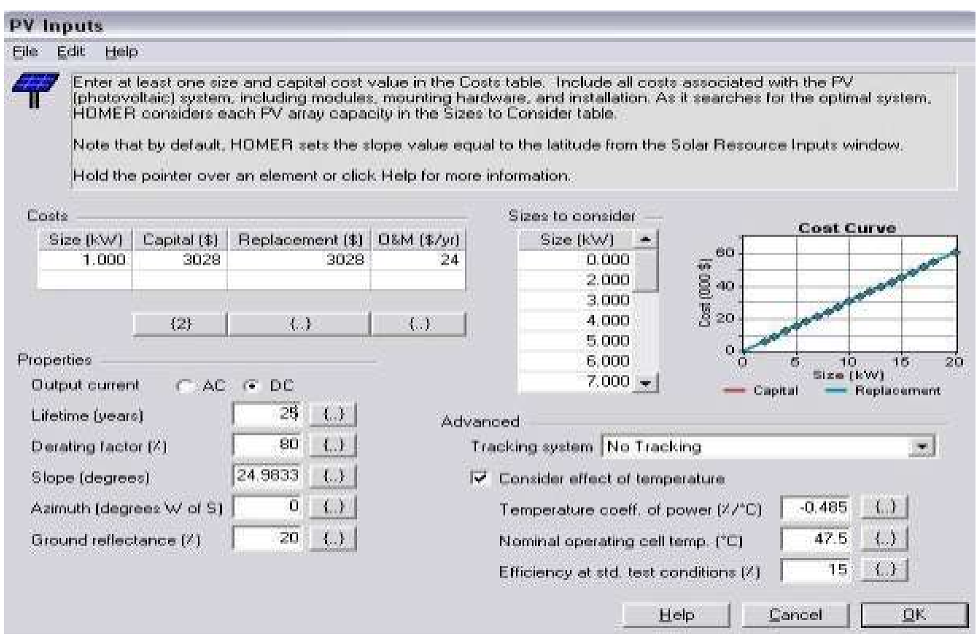



**Figure 5.2** PV array information

The second part of the solar home system is the inverter sizes which were chosen to be between 2 to 18 kW, same as the sizes selected for the PV array. The capital prices for inverters are between 700-1000 dollar per kilowatt, with an average of 800 $/kW, Figure 5.3.

The load profile is another part of solar home system. A home load profile was calculated and entered into the system. Figure 5.4 shows the load profile of a two story household housing between 6 to 8 members.

Finally the grid features, such as, the size of the grid, the sellback cost per kilowatt (Figure 5.5), and emissions were entered into the system. Ref [25] informs that one kilowatt of electricity is the result of burning 2.56 kWh of fossil fuels and; therefore, a 0.53 kg of $CO_2$ is released in the air which was used in the emission table in the HOMER software.

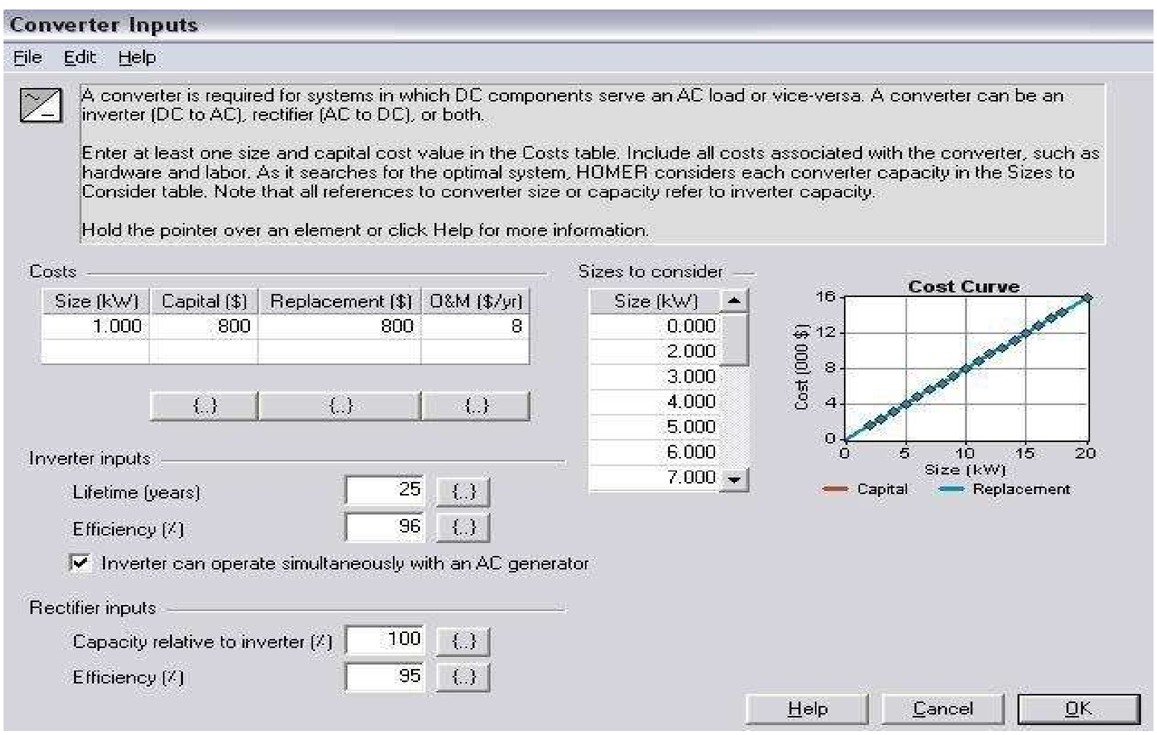



**Figure 5.3** Inverter Features

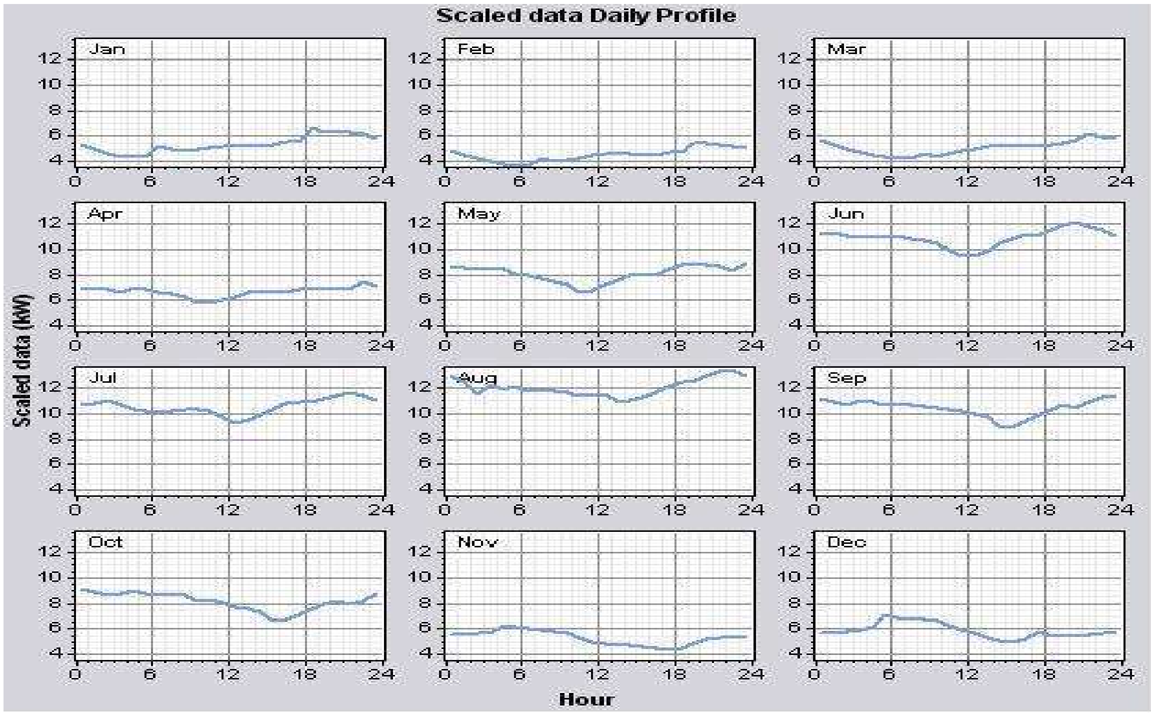



**Figure 5.4** Load Profile for one year

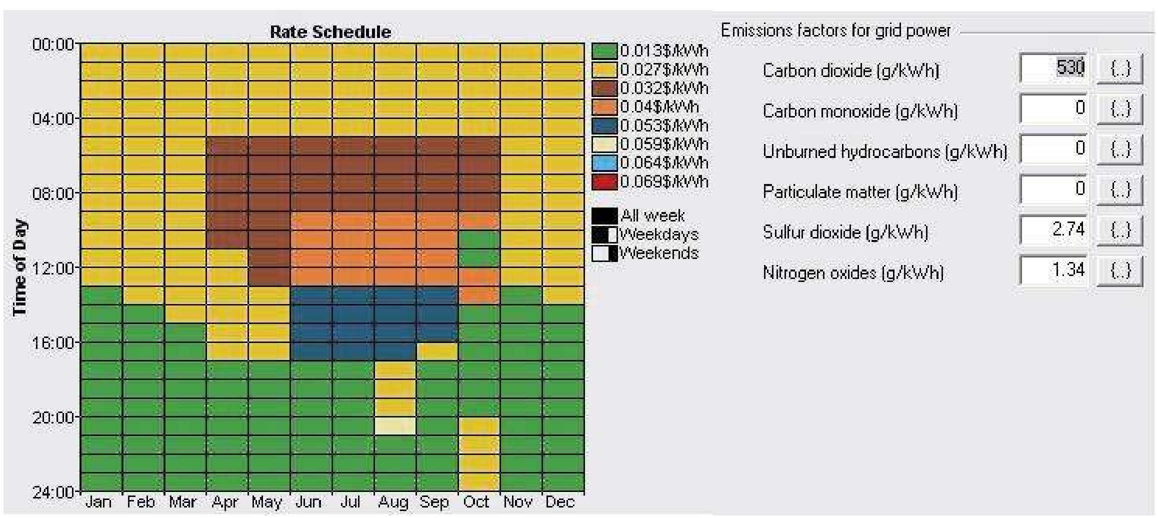



**Figure 5.5** Grid Rates & Emission

### *5.1.2.2 Results*

#### *5.1.2.2.1 Simulation*

Once the data of the whole module have been loaded, the module is simulated. During simulation, HOMER software calculates the energy balance of the system for the 8760 hours of each year of the project life, i.e. HOMER software calculates the system feasibility for 25 years. In this case, there are 361 scenarios for HOMER to simulate.

##### *5.1.2.2.2 Optimum Solutions*

Once the simulation is complete, two choices were obtained namely: the overall, and the categorized. The overall selection shows all different types of the solar system combinations with their initial value, total cost, operating cost, levelized cost, and renewable penetration percentage, as shown in Figure 5.6. The first choice is to use the grid only to supply the load demand. Following this, different sizes combination of the PV array, inverter, and grid are also shown.

The categorized option shows only the optimal solution for the system. This optimal result is considered the practical solution among other solution. Figure 5.7 shows two optimal solutions for the system: one without using renewable energy (i.e. only grid) and the other one is with renewable energy, in this case here the solar panels. This section, examines the grid only solution, while the PV solution is discussed in the subsection on sensitivity solution.

Double click on a system below for simulation results. ○ Categorized ● Overall

| PV (kW) | Conv. (kW) | Grid (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Net Purchases (kWh/yr) | Ren. Frac. |
|---|---|---|---|---|---|---|---|---|
| | | 1000000 | $ 0 | 1,778 | $ 34,705 | 0.026 | 67,525 | 0.00 |
| 2 | 2 | 1000000 | $ 7,656 | 1,706 | $ 40,959 | 0.031 | 64,326 | 0.05 |
| 2 | 3 | 1000000 | $ 8,456 | 1,712 | $ 41,879 | 0.032 | 64,326 | 0.05 |
| 2 | 4 | 1000000 | $ 9,256 | 1,718 | $ 42,799 | 0.032 | 64,326 | 0.05 |
| 3 | 2 | 1000000 | $ 10,684 | 1,666 | $ 43,205 | 0.033 | 62,797 | 0.07 |
| 2 | 5 | 1000000 | $ 10,056 | 1,724 | $ 43,719 | 0.033 | 64,326 | 0.05 |
| 3 | 3 | 1000000 | $ 11,484 | 1,670 | $ 44,086 | 0.033 | 62,727 | 0.07 |
| 2 | 6 | 1000000 | $ 10,856 | 1,730 | $ 44,639 | 0.034 | 64,326 | 0.05 |
| 3 | 4 | 1000000 | $ 12,284 | 1,676 | $ 45,006 | 0.034 | 62,727 | 0.07 |
| 2 | 7 | 1000000 | $ 11,656 | 1,737 | $ 45,559 | 0.035 | 64,326 | 0.05 |
| 4 | 2 | 1000000 | $ 13,712 | 1,650 | $ 45,921 | 0.035 | 62,016 | 0.08 |
| 3 | 5 | 1000000 | $ 13,084 | 1,682 | $ 45,926 | 0.035 | 62,727 | 0.07 |
| 4 | 3 | 1000000 | $ 14,512 | 1,628 | $ 46,296 | 0.035 | 61,132 | 0.09 |
| 2 | 8 | 1000000 | $ 12,456 | 1,743 | $ 46,479 | 0.035 | 64,326 | 0.05 |
| 3 | 6 | 1000000 | $ 13,884 | 1,688 | $ 46,846 | 0.036 | 62,727 | 0.07 |
| 4 | 4 | 1000000 | $ 15,312 | 1,634 | $ 47,213 | 0.036 | 61,127 | 0.09 |
| 2 | 9 | 1000000 | $ 13,256 | 1,749 | $ 47,400 | 0.036 | 64,326 | 0.05 |
| 3 | 7 | 1000000 | $ 14,684 | 1,694 | $ 47,766 | 0.036 | 62,727 | 0.07 |
| 4 | 5 | 1000000 | $ 16,112 | 1,640 | $ 48,133 | 0.037 | 61,127 | 0.09 |
| 2 | 10 | 1000000 | $ 14,056 | 1,755 | $ 48,320 | 0.037 | 64,326 | 0.05 |
| 3 | 8 | 1000000 | $ 15,484 | 1,701 | $ 48,686 | 0.037 | 62,727 | 0.07 |
| 5 | 3 | 1000000 | $ 17,540 | 1,598 | $ 48,736 | 0.037 | 59,928 | 0.11 |
| 5 | 2 | 1000000 | $ 16,740 | 1,645 | $ 48,855 | 0.037 | 61,569 | 0.09 |
| 4 | 6 | 1000000 | $ 16,912 | 1,646 | $ 49,053 | 0.037 | 61,127 | 0.09 |

**Figure 5.6** Overall Simulation Results [41]

Double click on a system below for simulation results. ● Categorized ○ Overall

| PV (kW) | Conv. (kW) | Grid (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Net Purchases (kWh/yr) | Ren. Frac. |
|---|---|---|---|---|---|---|---|---|
| | | 1000000 | $ 0 | 1,778 | $ 34,705 | 0.026 | 67,525 | 0.00 |
| 2 | 2 | 1000000 | $ 7,656 | 1,706 | $ 40,959 | 0.031 | 64,326 | 0.05 |

**Figure 5.7** Categorized Simulation Results [41]

As shown in Figure 5.7, by choosing the grid supply, the operating cost is 1778 $/year with a levelized cost of 2.6 cents per kilowatt, and a total cost of 67,525 dollars for 25 years. Figure 5.8 shows the monthly purchased loads of the house with its cost. Note that, there is not any sold energy because there is not any other source for supplying energy rather than the grid. Furthermore, since the electricity charge rate in Saudi Arabia is low, the charge on the energy bill is also low. In other countries, such as Nova Scotia, Canada, the charge rate is 13.36 cent/kWh and thus the electricity bill has a higher cost than the one in Saudi Arabia. Table 5.1 shows the price of electricity in Nova Scotia - Canada) for the same load. The annual cost of electricity in Nova Scotia is approximately 5 times the annual cost of electricity in SA. The next section illustrates a GRPV system model.

| Month | Energy Purchased (kWh) | Energy Sold (kWh) | Net Purchases (kWh) | Peak Demand (kW) | Energy Charge ($) |
|---|---|---|---|---|---|
| Jan | 3,924 | 0 | 3,924 | 7 | 78 |
| Feb | 3,006 | 0 | 3,006 | 6 | 62 |
| Mar | 3,728 | 0 | 3,728 | 6 | 79 |
| Apr | 4,767 | 0 | 4,767 | 8 | 114 |
| May | 5,976 | 0 | 5,976 | 9 | 144 |
| Jun | 7,800 | 0 | 7,800 | 12 | 231 |
| Jul | 7,808 | 0 | 7,808 | 12 | 232 |
| Aug | 8,920 | 0 | 8,920 | 14 | 298 |
| Sep | 7,481 | 0 | 7,481 | 13 | 214 |
| Oct | 6,021 | 0 | 6,021 | 11 | 152 |
| Nov | 3,766 | 0 | 3,766 | 9 | 80 |
| Dec | 4,328 | 0 | 4,328 | 7 | 94 |
| Annual | 67,525 | 0 | 67,525 | 14 | 1,778 |

| Pollutant | Emissions (kg/yr) |
|---|---|
| Carbon dioxide | 35,788 |

**Figure 5.8** Grid Purchase (kWh/month) & Amount of Emission

**Table 5.1** Energy Charge in Canada (Halifax-NS)

| Month | kWh/month | Energy Charge $ |
|---|---|---|
| January | 3,924 | 523.30 |
| February | 3,006 | 400.88 |
| March | 3,728 | 497.17 |
| April | 4,767 | 635.73 |
| May | 5,976 | 796.96 |
| June | 7,800 | 1040.21 |
| July | 7,808 | 1041.27 |
| August | 8,920 | 1189.57 |
| September | 7,481 | 997.67 |

| Month | kWh/month | Energy Charge $ |
|---|---|---|
| October | 6,021 | 802.96 |
| November | 3,766 | 502.23 |
| December | 4,328 | 577.18 |
| | **Total** | **9005.13** |

#### *5.1.2.2.3 Sensitivity Solutions*

The sensitivity case in HOMER software provides an option for testing the effects of all the parameters that has an influence on the solar system, such as the cost $/W$_p$, the tilt angle, the temperature, the maintenance cost, the replacement cost, the renewable energy penetration rates, the maximum grid purchase and the PV panel efficiency. In this thesis, two sensitivity cases are tested: the maximum grid purchases kWh/year, and the minimum renewable energy. Hence, in each case HOMER runs an energy balance calculation to find the optimal solution using different combinations of sizes from PV panels and inverters.

The maximum grid purchase in the sensitivity case here, in kWh/year, is used to force the system to use renewable energy while grid supply is limited. Although, the grid charge is lower than the solar rates, the objective was to observe the solar system penetration on the load demand and its effect. Since the maximum load for the house is 67,525 kWh/year, the sensitivity cases were chosen to be between 70,000 to 40,000 kWh/ year. The sensitivity option of the maximum load purchase is shown in Figure 5.9.

The minimum renewable energy penetration rate is used, in the sensitivity analysis, to observe the effect of using solar source while the grid source is not restricted. The rates used were between 3% and 40%. This wide range of rates provides a variation of the solar system sizes and cost. Hence, this helps to obtain more optimal solutions under different condition.

Figure 5.9 shows the sensitivity case ranges for purchase from the grid and minimum renewable energy rate. In these two cases, the total simulation is 361 (simulation) X 171 (sensitivity), this gives a 61,731 simulation processes. HOMER took 55 minutes to complete the simulation.

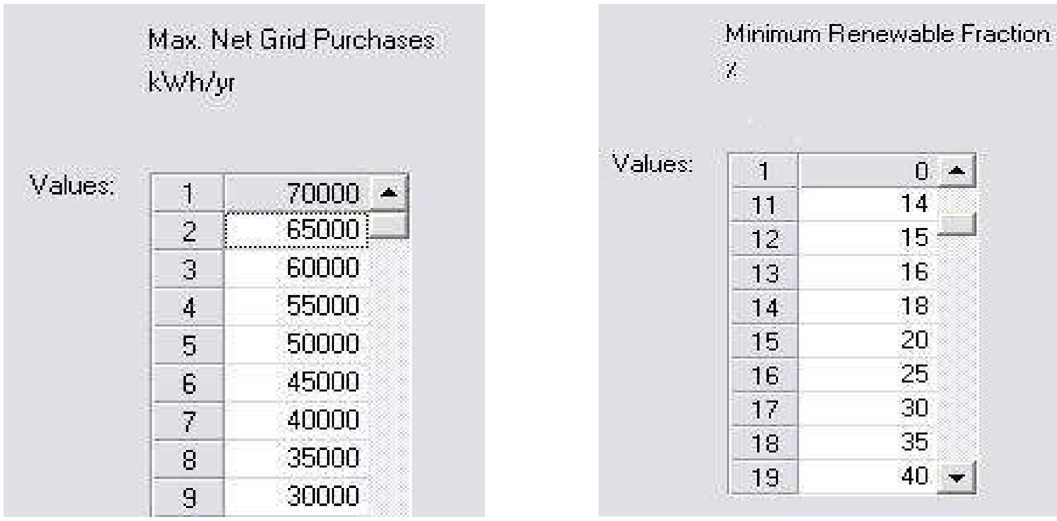



**Figure 5.9** Sensitivity Analysis [41]

Table 5.2 shows the optimal solution for the entire sensitivity cases that have been chosen. The maximum grid purchase of a 70,000 kWh/year has been removed because it has the same PV and inverter sizes as the 65,000 kWh/year. Note that as the maximum grid supply reduced, the penetration percentage loses its ability until the system supplies the surplus load. Furthermore, the inverter sizes were not matched with the solar system size. This leads to excess electricity, which is electricity produced by the solar panels and not being used by the load or the network. However, this excess power is low. In order to avoid the excess electricity, the inverter size should match the solar system size, and this leads to an increase in the solar home system cost. Thus, HOMER neglects this excess electricity to provides a feasible solution.

**Table 5.2** HOMER Optimal Solutions

<table>
<tr><th colspan="2" rowspan="2">Max. Grid Purchase (kWh/year)</th><th colspan="18">Min. Renewable Penetration Rate%</th></tr>
<tr><th>0</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>12</th><th>14</th><th>15</th><th>16</th><th>18</th><th>20</th><th>25</th><th>30</th><th>35</th></tr>
<tr><td rowspan="2">65000</td><td>PV size</td><td>2</td><td>2</td><td>2</td><td>3</td><td>3</td><td>3</td><td>4</td><td>4</td><td>5</td><td>6</td><td>6</td><td>7</td><td>7</td><td>8</td><td>9</td><td>11</td><td>14</td><td>17</td></tr>
<tr><td>Inverter size kW</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>3</td><td>3</td><td>3</td><td>5</td><td>4</td><td>5</td><td>5</td><td>6</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">60000</td><td>PV size</td><td colspan="9">5</td><td>6</td><td>6</td><td>7</td><td>7</td><td>8</td><td>9</td><td>11</td><td>14</td><td>17</td></tr>
<tr><td>Inverter size kW</td><td colspan="9">3</td><td>3</td><td>4</td><td>4</td><td>5</td><td>5</td><td>6</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">55000</td><td>PV size</td><td colspan="14">8</td><td>9</td><td>11</td><td>14</td><td>17</td></tr>
<tr><td>Inverter size kW</td><td colspan="14">6</td><td>6</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">50000</td><td>PV size</td><td colspan="16">11</td><td>14</td><td>17</td></tr>
<tr><td>Inverter size kW</td><td colspan="16">8</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">45000</td><td>PV size</td><td colspan="16">15</td><td>14</td><td>17</td></tr>
<tr><td>Inverter size kW</td><td colspan="16">9</td><td>9</td><td>10</td></tr>
<tr><td rowspan="2">40000</td><td>PV size</td><td colspan="18">18</td></tr>
<tr><td>Inverter size kW</td><td colspan="18">11</td></tr>
</table>

#### *5.1.2.3 Economic Calculation*

Following the simulation is the feasibility analysis. HOMER software provides full details for each solar system model including the net present worth (NPW), cash flow (CF), initial capital (IC, also called capital cost CC), operating cost, and levelized energy cost (LEC, also called life cycle cost LCC). However, the way that HOMER software exploit to calculate system feasibility is slightly different from the economic calculation in the PV handbook [1]. Table 5.3 shows the energy balance equations for both ways. On the one hand, both ways are almost the same and the only difference is that there are more details in the economic calculation which have not been used by HOMER, such as, engineering cost, balance of system cost, and installation cost. On the other hand, both ways provide enough details that can be used to analyze the system, and help GRPV system future customers to make their decision. In order to show the similarity and differences between the two methods, one case from table 5.2 is chosen and analysed. This section is divided in two parts. The first part includes HOMER economic calculation illustrated in Table 5.3a. The second part shows the results using the economic calculation (Table 5.3b) [1].

**Table 5.3** Economic Calculation Using HOMER and Other Economic Equations

| a-HOMER Calculation [41] | b- Economic Calculation [1] |
|---|---|
| $NPW = \sum_{n=1}^{n=25} \frac{CF}{(1+i)^n} - CC$<br>$CF = \frac{CC[i(1+i)^n]}{[(1+i)^n - 1]}$<br>$i_r = \frac{i_n - f}{1+f}$<br>$COE = \frac{Total\ Annulize\ cost}{Total\ Supplied\ Load}$ | $F = P(1+i)^n$<br>$\mathrm{P = F(1+i)^{-n}}$<br>$P_{Uni} = \mathrm{Ann} * \frac{[(1+i)^n - 1]}{[i * (1+i)^n]}$<br>$LEC = \frac{NPW * CRF}{E}$<br>$CRF = \frac{m(1+m)^n}{(1+m)^n - 1}$<br>$\mathrm{NPW = IC + Main + Rep - Svg}$<br>$\mathrm{IC = PVC + Eng.C + Inv.C + BOS}$ |

### *5.1.2.3.1 HOMER Economic Results*

From Table 5.2, a full detail is provided for one case. Then brief data are provided for the rest of the cases. The case where the grid purchase is 60,000 kWh/year and has a solar penetration rate between 0 to 15% was chosen. The system in this case has a 5 $kW_p$ PV system and a 3kW inverter. Figures 5.10 to 5.16 show HOMER results for the chosen solar system case.

Figures 5.10, 5.11, & 5.12, provide details for the load, PV panels, and inverter respectively. The solar system and the local grid have shared to supply electricity for residential load demand of 67,525 kWh/year with a rate of 12% (8,330 kWh/year) and 88% (59,928 kWh/year) respectively. The mismatch between the inverter size and the PV system cause an excess electrical output of 417 kWh/year. The solar system operates for 4,168 hours per year that is almost 48% of the number of hours in one year (8760). Moreover, a 0.098 $ is the cost of each kilowatt-hour produced by the PV system. Hence, according to the PV operating hours per year, grid-tie residential PV (GRPV) system is suitable to be used in Saudi Arabia.


**Figure 5.10** System Load Supply

| Quantity | Value | Units |
|---|---|---|
| Rated capacity | 5.00 | kW |
| Mean output | 0.95 | kW |
| Mean output | 22.8 | kWh/d |
| Capacity factor | 19.0 | % |
| Total production | 8,330 | kWh/yr |

| Quantity | Value | Units |
|---|---|---|
| Minimum output | 0.00 | kW |
| Maximum output | 4.28 | kW |
| PV penetration | 12.3 | % |
| Hours of operation | 4,168 | hr/yr |
| Levelized cost | 0.0980 | $/kWh |

**Figure 5.11** System PV Details

| Quantity | Inverter | Rectifier | Units |
|---|---|---|---|
| Capacity | 3.00 | 3.00 | kW |
| Mean output | 0.87 | 0.00 | kW |
| Minimum output | 0.00 | 0.00 | kW |
| Maximum output | 3.00 | 0.00 | kW |
| Capacity factor | 28.9 | 0.0 | % |

| Quantity | Inverter | Rectifier | Units |
|---|---|---|---|
| Hours of operation | 4,168 | 0 | hrs/yr |
| Energy in | 7,914 | 0 | kWh/yr |
| Energy out | 7,597 | 0 | kWh/yr |
| Losses | 317 | 0 | kWh/yr |

**Figure 5.12** System Inverter Details

Figure 5.13 shows the monthly grid supply cost for the residential load, and the total $CO_2$ emission that released in the air. Compared to the grid only system, a $5kW_p$ solar system has reduced the total emissions with 11%. Moreover, grid purchases here are approximately 14% less than the grid only that shown in Figure 5.8. Hence, PV system proves it is reliability in reducing the electricity bill.

| Month | Energy Purchased (kWh) | Energy Sold (kWh) | Net Purchases (kWh) | Peak Demand (kW) | Energy Charge ($) | Demand Charge ($) |
|---|---|---|---|---|---|---|
| Jan | 3,377 | 0 | 3,377 | 7 | 66 | 0 |
| Feb | 2,365 | 0 | 2,365 | 6 | 47 | 0 |
| Mar | 3,073 | 0 | 3,073 | 6 | 63 | 0 |
| Apr | 4,177 | 0 | 4,177 | 8 | 97 | 0 |
| May | 5,304 | 0 | 5,304 | 9 | 124 | 0 |
| Jun | 7,128 | 0 | 7,128 | 12 | 202 | 0 |
| Jul | 7,122 | 0 | 7,122 | 12 | 201 | 0 |
| Aug | 8,233 | 0 | 8,233 | 14 | 268 | 0 |
| Sep | 6,830 | 0 | 6,830 | 13 | 186 | 0 |
| Oct | 5,364 | 0 | 5,364 | 11 | 136 | 0 |
| Nov | 3,221 | 0 | 3,221 | 9 | 68 | 0 |
| Dec | 3,735 | 0 | 3,735 | 7 | 80 | 0 |
| Annual | 59,928 | 0 | 59,928 | 14 | 1,538 | 0 |

| Pollutant | Emissions (kg/yr) |
|---|---|
| Carbon dioxide | 31,762 |

**Figure 5.13** System Grid and Emission Details

In Figure 5.14, the total system cost for the entire project life period, i.e. 25 years is 48,736 dollars. The levelized cost of energy is 0.037 dollars per kilowatt-hour that is 40% higher than the grid only system shown in Figure 5.7. This shows that the grid-connected residential PV system has a higher cost than the grid system only.

System Architecture: 1,000,000 kW Grid | 3 kW Rectifier
5 kW PV
3 kW Inverter

Total NPC: $ 48,736
Levelized COE: $ 0.037/kWh
Operating Cost: $ 1,598/yr

**Figure 5.14** System Summary

Figures 5.15 and 5.16 provide details for the cash flow (in or out) for the whole system as total payment and yearly payment respectively. The only earned cash is the one from selling solar system parts at the end of the project. The annual cost of the system is 2,496 $/year and that includes 62 % (1538 $) of grid acquisition, and 38% (958$) for solar systems. Furthermore, the annual cost of the GRPV system here is 40% higher than using grid only to supply the load. This is due to the high capital cost of the solar system (17,540 $). Hence, this affects the solar system from being economically feasible, and makes the grid only options to be the best.

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 15,140 | 0 | 2,343 | 0 | -1,538 | 15,945 |
| Grid | 0 | 0 | 30,031 | 0 | 0 | 30,031 |
| Converter | 2,400 | 0 | 469 | 0 | -108 | 2,760 |
| System | 17,540 | 0 | 32,843 | 0 | -1,646 | 48,736 |

**Figure 5.15** System Total Cost

| Component | Capital ($/yr) | Replacement ($/yr | O&M ($/yr) | Fuel ($/yr) | Salvage ($/yr) | Total ($/yr) |
|---|---|---|---|---|---|---|
| PV | 775 | 0 | 120 | 0 | -79 | 817 |
| Grid | 0 | 0 | 1,538 | 0 | 0 | 1,538 |
| Converter | 123 | 0 | 24 | 0 | -6 | 141 |
| System | 898 | 0 | 1,682 | 0 | -84 | 2,496 |

**Figure 5.16** System Annualised Cost

Table 5.4 shows a detail of all other sizes of the PV system. Obviously, the initial capital of any of these systems is considered as the main drawback. In addition, the life cycle cost of the system is increased as system size increase. Thus, there is neither saving nor profit from installing such a system. On the other hand, PV insight, i.e. penetration reaches up to 44% in a rooftop of a house, and that consider being efficient. Hence, GRPV system is sufficient to reduce house load up to 44% with up to 49% savings in electricity bill, but has a remarkably high capital cost that makes GRPV system not cost effective.

**Table 5.4** HOMER Method Results

| **PV size (kWp)** | **2000** | **3000** | **4000** | **6000** | **7000** | **8000** | **9000** | **11000** | **14000** | **15000** | **17000** | **18000** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Inverter Size (kW)** | 2 | **2** | 3 | **5** | 5 | **6** | 6 | **8** | 9 | **9** | 10 | **11** |
| **Initial Capital** | 7,656 | 10,684 | 14,512 | 22,168 | 25,196 | 29,024 | 32,052 | 39,708 | 49,592 | 52,620 | 59,476 | 63,304 |
| **Total Cost $** | 40,961 | 43,210 | 46,301 | 52,554 | 54,786 | 57,897 | 60,221 | 66,379 | 74,213 | 76,806 | 82,331 | 85,081 |
| **PV LCOE $/kWh** | 0.0981 | | | | | | | | | | | |
| **System LCOE S/kWh** | 0.031 | 0.033 | 0.035 | 0.04 | 0.042 | 0.044 | 0.045 | 0.049 | 0.054 | 0.055 | 0.058 | 0.059 |
| **PV rate %** | 4.9 | 7.4 | 9.87 | 14.8 | 17.3 | 19.7 | 22.2 | 27.1 | 34.5 | 37 | 41.9 | 44.4 |
| **Electricity Bill Saving %** | 5.68 | 8.38 | 11.3 | 17 | 19.74 | 22.61 | 25.08 | 31.05 | 38.7 | 40.38 | 45.5 | 49.44 |

#### *5.1.2.3.2 Economic Method Result*

Tables 5.5 to 5.9 show a full description of the 5kW$_p$ solar home system that was described in HOMER software.

Table 5.5 shows the main constant of the system. The project life is assumed to be 25 years. The photovoltaic panels and the inverter have the same operating lifetime as the project lifetime. Hence, there will be no replacement for the entire project life. Thus, the renewal year is zero.

The PV size, PV cost, inverter size, and inverter cost are shown in Table 5.6. There are 20 panels that are connected together to give a total output of 5kW. The inverter size has been chosen same as the one in HOMER software because it is the optimum solution.

One of the main differences between the economic method and HOMER method is illustrated in Table 5.7. HOMER software does not have the option of including wiring system cost, i.e. balance of system (BOS), engineering cost, and installation cost. Thus, those costs provide the details that aid PV future owners in making their decision.

**Table 5.5** System Constant

| | |
|---|---|
| Real Interest rate % | **2** |
| General escalation % | **5.3** |
| Replacement year | **0.00** |
| Project Life | **25** |

**Table 5.6** SHS Size and Cost

| | |
|---|---|
| Number of PV Panels | 20.0 |
| **PV System size in Wp** | **5000.0** |
| **Inverter size kW** | **3.0** |
| Output of each PV Panel Wp | 250 |

| | |
|---|---|
| Cost $/Wp | 2.150 |
| PV Total Cost $ | 10750 |
| Inverter Cost $/kW | 800 |
| Inverter Total Cost  $ | 2400 |

**Table 5.7** SHS Installation and Operating Cost

| | |
|---|---|
| PV Maintenance $/kW | 21 |
| PV Maintenance Percentage % | 0.0100 |
| Annual Maintenance $/year | 131.500 |
| Maintenance Total Cost $ | 2,567.335 |
| Balance of System $/Wp | 0.200 |
| Balance of System (BOS) Cost $ | 1000 |
| Engineering Percent % | 10 |
| Engineering Cost $ | 1,315 |
| Installation Percent % | 13 |
| Installation Cost | 1,709.5 |
| Salvage Percent % | -10 |
| Salvage cost | -1,315. |

Table 5.8 shows the three parts of the GRPV system economic results. Part (a), includes system initial cost (IC) and total system cost. The real watt peak cost is the exact cost of the PV panels that include the parameters in Table 5.7. Part b, has the solar system total output in a year, provided by HOMER software. The calculated life cycle cost (LCC) of the PV system alone is 0.089 $/kWh. Finally, part c deals with the grid system output and cost. The life cycle cost of the entire grid tie residential PV system (GRPV) is calculated to be 0.029 $/kWh. This cost is slightly less than the one in HOMER software, 0.037 $/kWh, and this is because of increasing the total cost by including installation costs, engineering cost, and BOS cost. Still, however, the GRPV has a higher

cost than the grid only system.

**Table 5.8** System Economic Results

| | | |
|---|---|---|
| a. | Initial Capital Cost $ | 17175 |
| | ***TOTAL 25 years LCC $*** | *18427* |
| | **Real Watt Peak Cost $/kW** | 2.9549 |
| b. | Annual PV output kW/year | 8328 |
| | Total PV output project life kW/25yr | 208200 |
| | **PV LCC $/kWh** | 0.089 |
| c. | Grid Operating Cost | 1,598 |
| | Grid Cost in 25 years (Operating Cost) $ | 31,198 |
| | Total Grid Output kWh/year | 59,928 |
| | Total Grid Output (25 years) kW | 1498200 |
| | GRPV LCC $/kWh | 0.029 |

Table 5.9 shows system saving in the number of oil barrel used to produce electricity, and the reduction in $CO_2$ emission. Fossil fuel is not a sustainable source; hence governments around the world are searching for solutions. One of the solutions is to preserve fossil fuel. Thus, each house owner installs a 5kW GRPV system will save 128 barrels of oil with a rate of 5 barrels each year. The rooftop PV system not only saves the fossil fuel but also reduce the $CO_2$ emission on the air. The utilization of a 5kW PV system prevents the release of 4664 kg of $CO_2$ every year. Hence, GRPV system saves fuel and help to provide a clean environment.

**Table 5.9** System Saving

| | |
|---|---|
| 1 Oil Barrel Produce (kWh) | 1628 |
| Number of Saved Barrels | 128 |
| 1kWh Production Release $CO_2$ (Kg) | 0.5600 |

| | |
|---|---|
| $CO_2$ emission saving Kg/year | 4664 |

Table 5.10 shows the economic summary for each GRPV system that was optimized by HOMER software. As shown in Table 5.10, the life cycle cost (LCC), i.e. the levelized cost of energy (LCOE), of the solar home system is not constant and change as PV system size change. Still the initial capital cost of the solar home system SHS is higher than the grid. However, the saving in oil barrels could be the motivation for the Saudi government to utilize solar systems.

**Table 5.10** Economic Method Result

| **PV size (kW)** | **2** | **3** | **4** | **6** | **7** | **8** | **9** | **11** | **14** | **15** | **17** | **18** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Inverter Size (kW)** | 2 | 2 | 3 | 5 | 5 | 6 | 6 | 8 | 9 | 9 | 10 | 11 |
| **Initial Capital** | 7,657 | 10,502 | 14,330 | 21,987 | 24,832 | 28,660 | 31,505 | 39,162 | 48,679 | 51,524 | 58,197 | 62,025 |
| **PV LCC $/kWh** | 0.098 | 0.090 | 0.092 | 0.094 | 0.091 | 0.092 | 0.092 | 0.090 | 0.090 | 0.089 | 0.088 | 0.089 |
| **System LCC S/kWh** | 0.025 | 0.026 | 0.028 | 0.032 | 0.033 | 0.035 | 0.036 | 0.040 | 0.045 | 0.046 | 0.049 | 0.051 |
| **Barrel Saving (25 years)** | **51** | **77** | **102** | **153** | **179** | **205** | **230** | **281** | **358** | **384** | **435** | **460** |
| **$CO_2$ Unreleased kg/year** | 1,865 | 2,798 | 3,731 | 5,596 | 6,528 | 7,461 | 8,394 | 10,260 | 13,058 | 13,990 | 15,856 | 16,788 |

### 5.1.3 Second Scenario:

Since the cost of GRPV system is high in the current situation, this part investigates the factors that might help to make GRPV more cost effective. Thus, the price per watt peak of PV panels ($/$W_p$), and the sell back rate of electricity were investigated in order to search for a feasible solution.

#### *5.1.3.1 PV Price $/Wp Effect:*

The deterioration of fossil fuel reserve has made the utilization of the solar-based system as a source of energy inevitable. However, future solar system owners are appealing for the benefit of utilizing solar system. In other words, future solar system owners are wondering if the cost $/kWh of utilizing GRPV system compared with the cost $/kWh charged by the utility companies, is profitable or not? Hence, PV panel price is investigated.

According to Ref. [9], as the production of PV increase as the price per watt peak is decreased. To clarify, in the last two decades the price of PV panels has decreased by 20% as the production of PV doubled. What's more, in the next two decades, the price of solar panels is expected to reach up to half a dollar per watt peak. Hence, the objective here is to test the price of PV panels at 1$/$W_p$, & 0.5$/$W_p$.

Table 5.11 shows four models: grid only system, and the other three are GRPV system. The size of the PV system here was chosen to be 18kW with a 12kW inverter. This model was the only optimum solution that provided by the HOMER software. In the GRPV models, the sell back rate is assumed to be 0.069 $/kWh, which is the highest rate charged by the Saudi Electric Company (SEC) at residential area. The only change is in the price per watt peak of the PV panel. Obviously, the grid only option is the best option with a net present cost (NPC) of 34,705$ for the entire project life (25 years), and a life cycle cost of 0.026 dollar per kilowatt-hour. Model 3 is the nearest one to the grid system with an LCC of 0.028. However, still the GRPV system has a high capital cost and it is not profitable. Hence, even if the PV cost dropped to half dollar, GRPV system is not cost effective alternative in SA.

**Table 5.11** Prices Comparison between Grid System and GRPV System

| | Price $/W_p$ | Initial Capital ($) | NPC ($) | LCC ($/kWh) |
|---|---|---|---|---|
| **Grid Only** | Eight Tier | 0 | 34,705 | 0.026 |
| **Model 1, 18kW** | 2.15 | 64,904 | 59,969 | 0.041 |
| **Model 2, 18kW** | 1 | 38,120 | 51,774 | 0.035 |
| **Model 3, 18kW** | 0.5 | 27,050 | 40,423 | 0.028 |

#### *5.1.3.2 Electricity Sell Back Rate Effect:*

Electricity charges are rapidly increasing every year. This increase depends on the country's fossil fuel reserve and their economy. For example, Germany does not have any fossil fuel reserves and they depend on importing fuel all the time. Thus, the electrical charges in Germany considered being the highest among Europe countries [20]. The highest rate of electricity charge has made Germany one of the first leaders in PV installation. Moreover, the German government policy is to require utility companies to pay GRPV system owners, five times their electrical charge for each kWh transferred to the grid [20]. This policy is an incentive to encourage people to install the GRPV system in their homes. Thus, government incentives make GRPV system cost effective and grab peoples' attention. This is not in Germany only. There are other governments in different countries offering incentives and rebate program for PV owners. Table 5.12 shows the leader countries in PV installation. All these countries are offering different types of incentive, in order to encourage people to install GRPV system. [20]

**Table 5.12** Ranked Countries in PV installation [21]

| Country | Total PV Installation till Feb. 2012 |
|---|---|
| Germany | 17,200 MW |
| Spain | 3800 MW |
| Japan | 3600 MW |
| Italy | 3500 MW |

| **Country** | **Total PV Installation till Feb. 2012** |
|---|---|
| USA | 2500 MW |

In comparison, an oil rich country, such as Saudi Arabia, has the lowest electricity rate compared with other countries. Saudi electric company (SEC) has eight tier of electricity charge for residential areas. The tier depends on the usage of electricity by the consumer, i.e. the charge increases as electricity usage increase. Table 5.13 shows the eight tier system of Saudi Electricity Company (SEC).

**Table 5.13** SEC Electricity Charge [51]

| Tier No | KWh usage | Rates Saudi Riyal/ kWh | Rates $/kWh |
|---|---|---|---|
| 1 | **1-2000** | 0.05 | 0.013 |
| 2 | **2001-4000** | 0.1 | 0.027 |
| 3 | **4001-6000** | 0.12 | 0.032 |
| 4 | **6001-7000** | 0.15 | 0.040 |
| 5 | **7001-8000** | 0.20 | 0.053 |
| 6 | **8001-9000** | 0.22 | 0.059 |
| 7 | **9001-10000** | 0.24 | 0.064 |
| 8 | **10000 and up** | 0.26 | 0.069 |

According to Table 5.13, the GRPV system is considered to be non- cost effective solution. Hence, this makes the utilization of GRPV system not likely to happen with the current situation of PV cost in Saudi Arabia. Yet with appropriate changes in SA policy regarding renewable energy, a cost effective solution could be existed. Table 5.14 shows the same three models in Table 5.11 with different energy sell back rates. Part (a) has the grid only system with a total cost of 34,705$ for the entire project life (25 years). Part (b) has the current price of PV panels using three price categories: 0.069$/kWh, 0.15 $/kWh, and 0.2$/kWh. Part (c) & (d), have two future prices of the PV panels, 1$/$W_p$ and 0.5$/$W_p$, with four categories of sell back rate for each part. Furthermore, the saving in electricity bill is shown in Table 5.13 as well.

According to the results in Table 5.14, a cost effective results are existed. There are four costs effective solutions available, marked with a star sign in Table 5.14. Also, the solutions have a high sellback rate of electricity, and they depend on the expected price of the PV panels (i.e. future price). Moreover, the cost effective GRPV systems shown in Table 5.14 have a high capital price and a low net total price. This makes these solutions feasible. The rest of the solutions have a high capital cost and a high overall total price. However, the existence of cost effective solutions do not make them feasible to apply.

**Table 5.14** Prices Comparison between Grid System and GRPV system

| Part | System Type | Energy Sellback rate ($/kWh) | Initial Capital ($) | NPC ($) | PV-LCC ($/kWh) | LCC $/kWh | Saving in Bill (%) |
|---|---|---|---|---|---|---|---|
| **a.** | ***Grid Only*** | 0 | 0 | 34,705 | 0 | 0.026 | 0 |
| **b.** | ***GRPV Model-1 2.15$/$W_p$*** | 0.069 | 64,104 | 76,831 | 0.0975 | 0.052 | 69 |
| | | 0.15 | | 67,611 | | 0.046 | 101 |
| | | 0.2 | | 60,422 | | 0.041 | 122 |
| **c.** | ***GRPV Model-2 1$/$W_p$*** | 0.069 | 37,320 | 51,327 | 0.0498 | 0.035 | 68 |
| | | 0.1 | | 46,871 | | 0.032 | 80 |
| | | ****0.15*** | | ***32,494*** | | ***0.022*** | ***122*** |
| | | ****0.28*** | | ***20,992*** | | ***0.014*** | ***155*** |
| **d.** | ***GRPV Model-3 0.5$/$W_p$*** | 0.069 | 26,250 | 39,976 | 0.0304 | 0.027 | 69 |
| | | 0.1 | | 35,568 | | 0.024 | 80 |
| | | ****0.15*** | | ***28.331*** | | ***0.019*** | ***101*** |
| | | ****0.28*** | | ***9,641*** | | ***0.007*** | ***155*** |

## 5.2 Artificial Neural Network (ANN) Results:

ANN was used to obtain a model to predict the oil barrel price (OBP). This model was then used to predict prices until 2022. In order to validate this model, six other models were created to predict the factors that affect the OBP. Furthermore, the results were used to discuss the feasibility of the GRPV system in Saudi Arabia.

This section is divided into two subsections: the first part discusses the three training algorithms that were used in forecasting, and the second section provides the proposed models with their results.

### 5.2.1 Back Propagation (BP):

In this thesis, the multilayer feed-forward neural network with back propagation (MFFNNBP) will be used for finding the gradient of non-linear networks. A three layer neural network composed of an input layer, a hidden layer and an output layer were used in the BP algorithm. The BP has two phases: forward pass, and backward pass.

#### *5.2.1.1 Phase One: Forward Pass :*

In this phase, each input is multiplied by a weight, and, then, it is distributed to the neuron in the hidden layer. The weights are summed in each neuron. The sum of all the inputs in each neuron is a non-linear mathematical function. After this step, the output of each neuron in the hidden layer is propagated to each neuron in the output layer where it is summed again. The results from the output layer are also non-linear mathematical functions. The results from the output layer should match or be slightly different from the actual output (target). [52]

#### *5.2.1.2 Phase Two: Backward Pass:*

In the backward phase, the error between the actual target and the result from the output layer is calculated. Then, the error is propagated backward to update the weight matrices between the input & hidden layer and between hidden & output layer. [52]

### 5.2.2 Training Algorithm:

The back-propagation (BP) algorithm uses different techniques to train the data and update the weight matrices between input and output. Some techniques are faster but complex, such as the Newton methods. Others are slower and easier to implement, such as the conjugate gradient methods. This study was interested in examining the three faster techniques (three faster training algorithms) that based on the Quasi-Newton methods: the Levenberg Marquardt (LM) algorithm, the Bayesian regularization (BR) algorithm, and BFGS algorithm.

Quasi-Newton algorithms are designed to approach Hessian matrices. Hessian matrices are used for nonlinear functions and complicated optimization methods. The calculation of Hessian matrices is complex because it contains the second order derivative of the error. Thus, the Jacobian matrix, which contains the first derivative of the error function, is utilized. Hence, the LM, BR, and BFGS algorithms were formulated to approach the Hessian matrices without the need of calculating it [54].

#### *5.2.2.1 Levenberg Marquardt Algorithm (LM):*

The Levenberg-Marquardt algorithm [54] can be illustrated as:

$$H = J^T J + \mu I \qquad (5\text{-}1)$$

μ = a positive combination coefficient,

I = the identity matrix.

The weights are updated using the following equation:

$$w_{k+1} = w_k - (J_k^T + \mu \mathrm{I})^{-1} J_k e_k \qquad (5\text{-}2)$$

The LM algorithm is implemented in MATLAB as ***trainlm***.

#### *5.2.2.2 Bayesian Regularization Back-Propagation (BRBP):*

The main objective of the Bayesian regularization is to provide a network with a substantial generalization quality. This means introducing supplementary information to prevent overfitting by minimizing and modifying the linear combination of squared errors and weights. Thus, BRBP is considered insensitive to over-fitting and overtraining. This algorithm is implemented in MATLAB as ***trainbr***.

#### *5.2.2.3 BFGS Quasi-Newton Back Propagation:*

This method is based on calculating the inverse of the Hessian matrix rather than computing the exact Hessian matrix. Computing the Hessian is complex and time consuming. However, the BFGS algorithm turns this complex calculation into simple matrix multiplication. This algorithm is implemented in MATLAB environment as the ***trainbfg*** command in the neural network toolbox [53].

### 5.2.3 Proposed Models:

In this thesis, seven neural network models were implemented using MFFNNBP for forecasting. The models are shown in Figure 5.17. Each model consists of inputs, hidden layers and the output layer. Thus, each neural model is composed of three layer networks.

The first step for designing any neural network is to collect the required data. Thus, the data that were used in all the seven models are from the years 1980 to 2011. The seven neural networks shown here were connected to each other, i.e. the prediction from the first model was used in the prediction for the second model, and so on. For instance, the prediction from the population model was used to predict the net electricity generation, the prediction from the net electricity generation was used to predict the annual oil barrel consumption, and so on. The description of each model is discussed next.

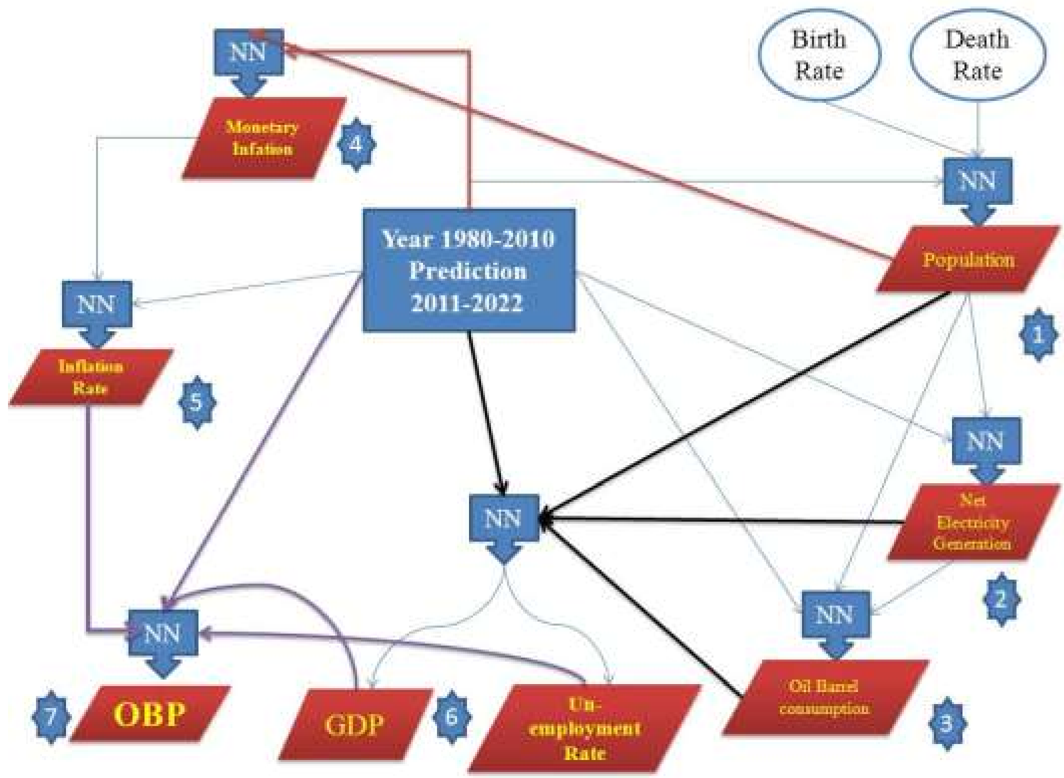



**Figure 5.17** Proposed Model

#### *5.2.3.1 Population Model:*

The population of Saudi Arabia from 1980 to 2010 were utilized to validate the proposed neural model, and then to predict the population from 2012 to 2022. Birth rate and mortality rate have been used as the input to the neural network [33]. The population was the output (i.e. target). Log-sigmoid transfer function was used in the hidden layer, and the *trainbr* was the training algorithm for the network. The data are collected from reference 58.

The provided model has 30 observations that used in the neural model. The data were divided in two parts: 20 observations used in the training set and 10 observations used in the validation and test set. Number of neurons in the hidden layer was chosen after applying trial and error method. The best number of neurons was seven neurons. The RMSE is 0.00202, and the performance function was $1.23e^{-4}$. The three layer neural network is shown in Figure 5.18, and the training performance in Figure 5.19. Figure

5.18, shows three inputs used in the neural network: mortality rate, birth rate, and year code. The third input is a code used for the year. This code was calculated using the Microsoft Excel function DATE. The root mean square error (RMSE) is considered small and hence, the model is valid. Figure 5.20, shows the population actual data verses the predicted one.

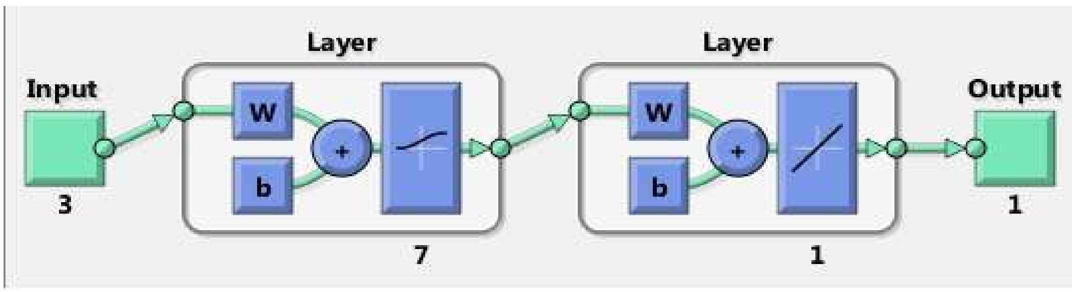



**Figure 5.18** Population Neural Model

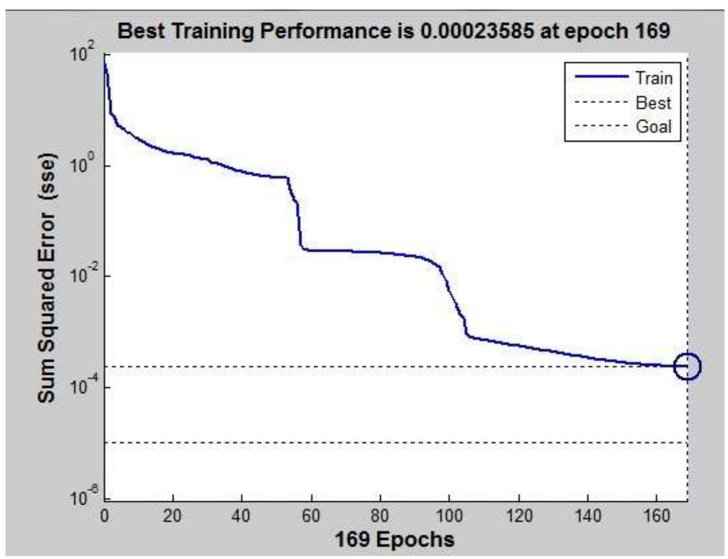



**Figure 5.19** Population Training Performance

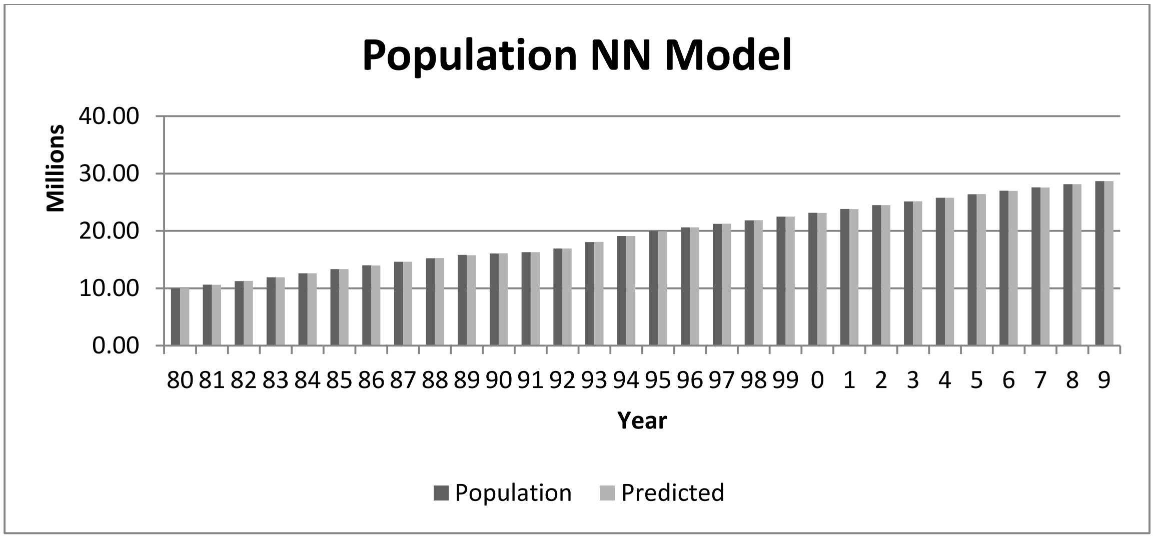



**Figure 5.20** Population Actual Vs. Predicted

After validating the model, a prediction for the population for the next 10 years was conducted. To do that we assume that the birth rate and death rate of Saudi Arabia to be constant for the next 10 years (i.e. from 2012-2022), the network is simulated to predict the population for this period. The results are shown in Figure 5.21.

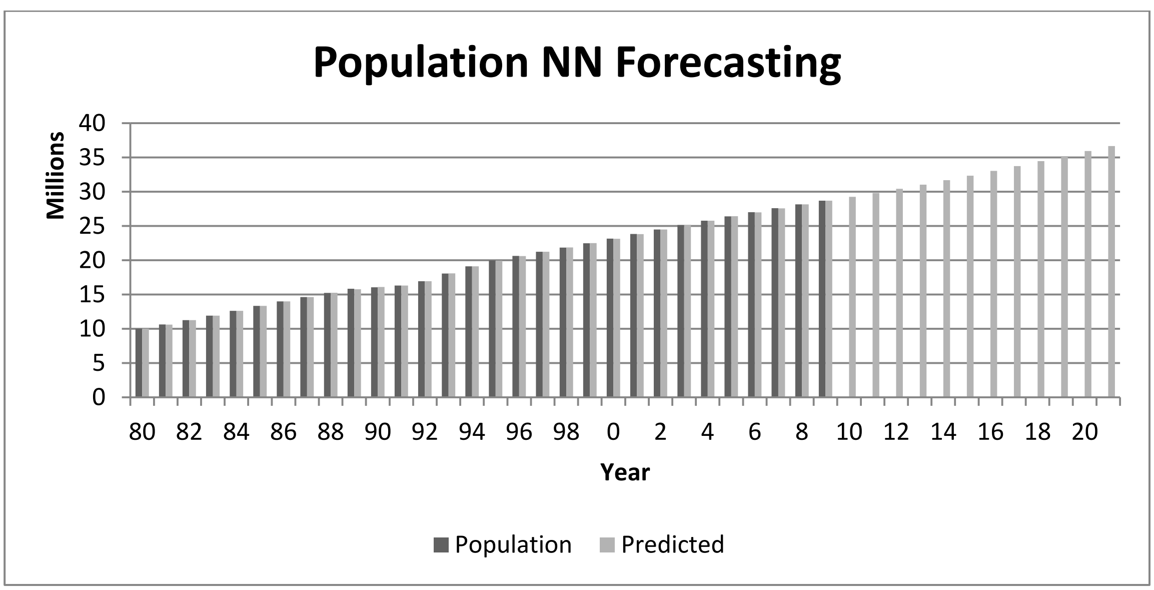



**Figure 5.21** Predicted Population from 2012 to 2022

Apparently, the predicted data coincides with this assumption. The RMSE is small, and that means the use of birth rate and mortality as inputs to the system was correct.

#### *5.2.3.2 Net Electricity Generation (NEG) Model*

This model depends on the population model, i.e. the population of Saudi Arabia has been used as input. BFGS algorithm (trainbfg) was used to train the network. The data [58] has 30 observations with 22 observations in the training set, 8 observations for the validation set, and 8 observations in the test set. Tangent transfer function (tan-sigmoid) was applied at the hidden layer with fifteen artificial neurons, and a linear transfer function (purelin) with one neuron at the output layer. The system has 0.0799 root mean square error (RMSE), and 0.185 performance error. The neural model, error performance, and the predicted data are shown in Figures 5.22, 5.23, and 5.24 respectively.

Once the neural network provides a better fitting, the predicted population from 2012 to 2022 were used to predict the NEG for the same period. The result is shown in Figure 5.24.

According to these results, the RMSE of the model is considered slightly high. This is due to using the population as the only input to the system. However, from Figures 5.23 and 5.24 as the population increased, the net electricity generation is increased. Hence, the model is valid.

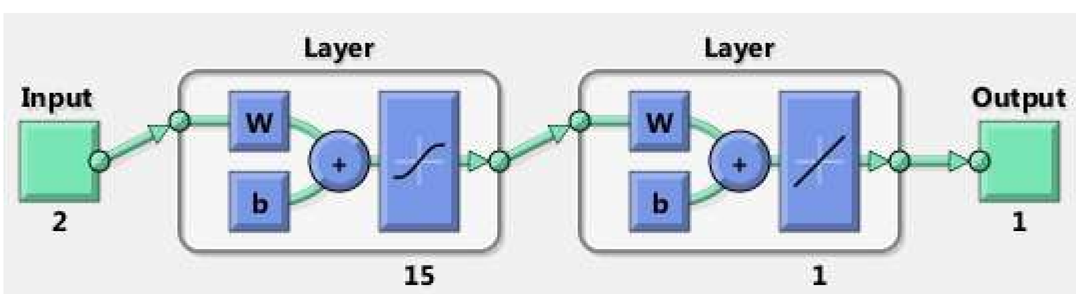



**Figure 5.22** Net Electricity Generation Neural Model

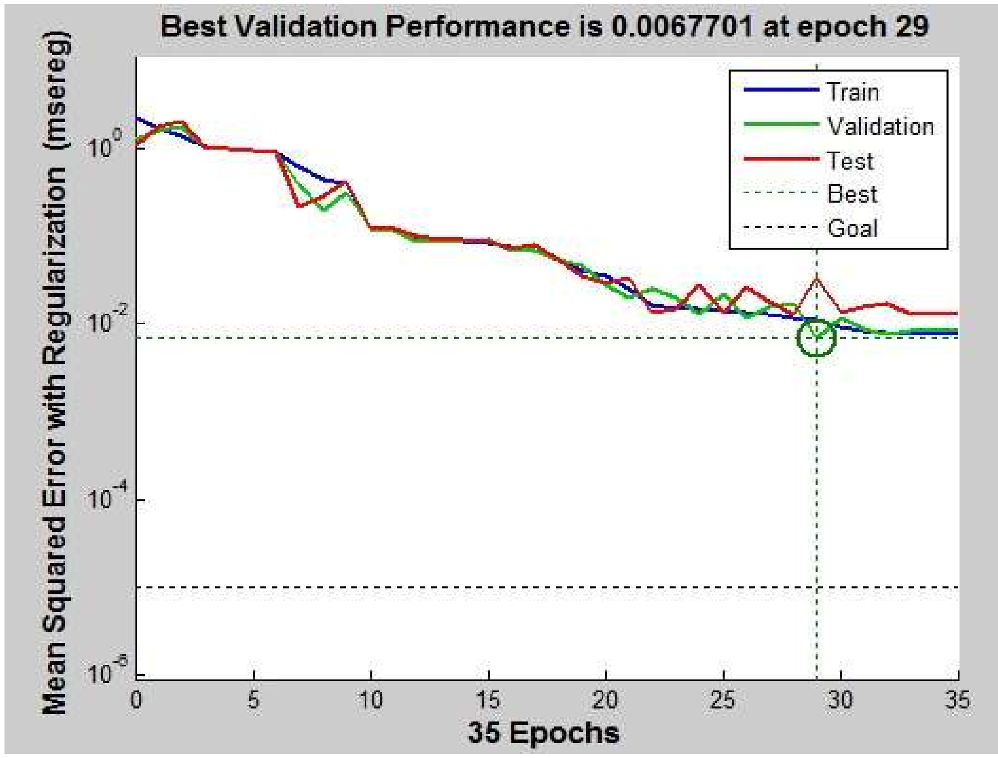



**Figure 5.23** NEG Neural Model Error Performance

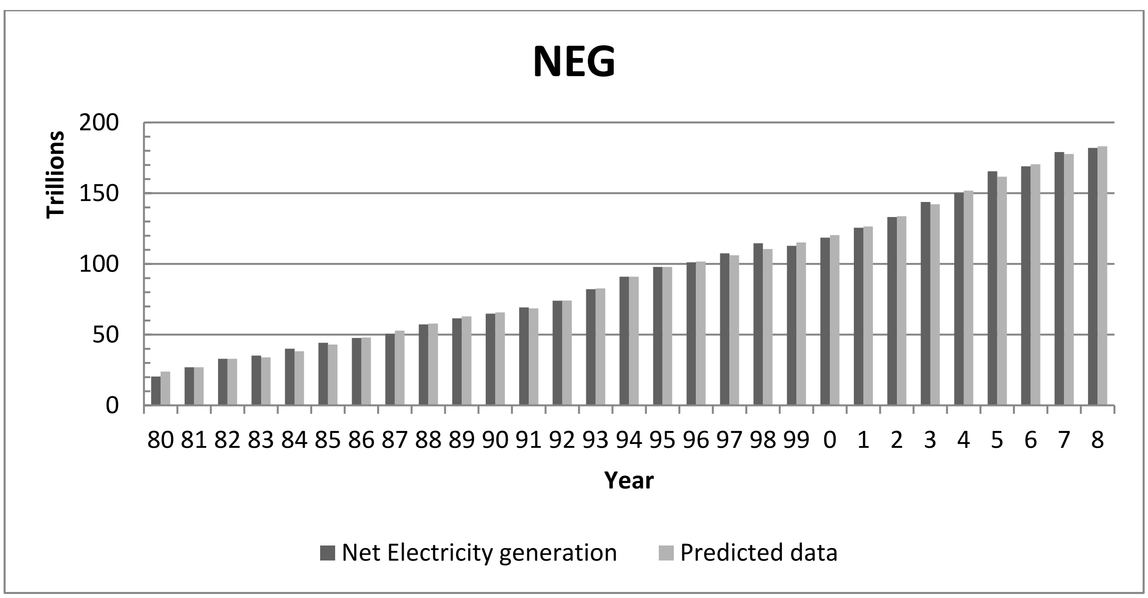



**Figure 5.24** NEG Actual Vs. Predicted

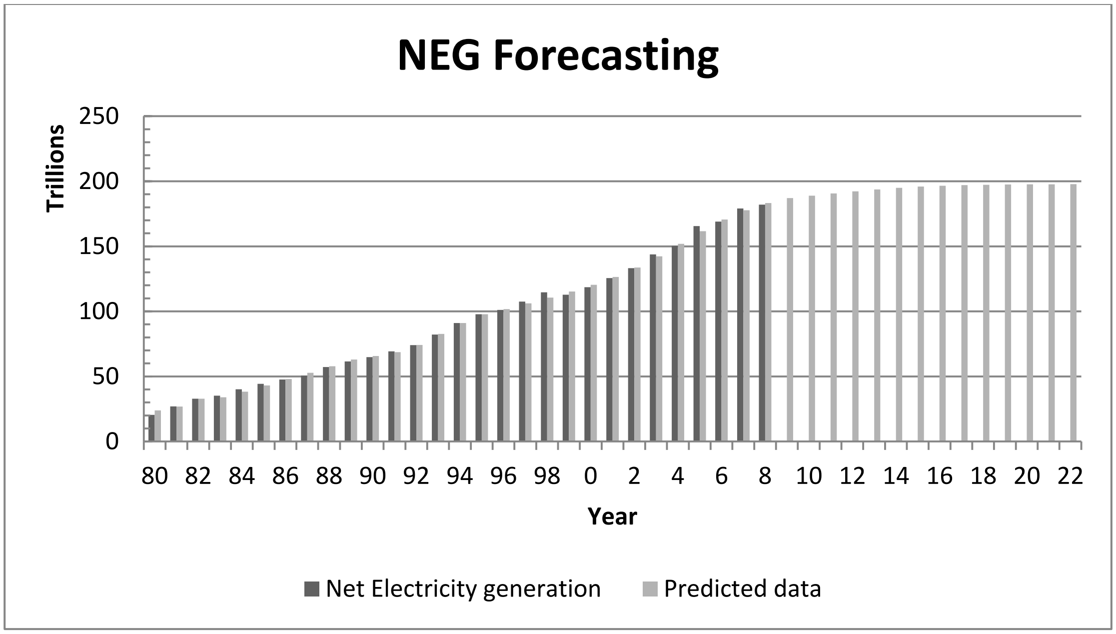



**Figure 5.25** NEG Prediction Results

#### *5.2.3.3 Oil Barrel consumption (OBC) Model:*

The challenge in this thesis, is to find out if the Kingdom of Saudi Arabia is going to utilize renewable energy sources (in our case here solar system), or not. Thus, since Saudi Arabia is an oil rich country, a prediction of annual oil barrel consumption is considered. Indeed, this part helps to understand how the reserve of oil is deteriorating.

The neural model inputs here were the population, NEG, and the year code with 33 observations. The training set consists of 23 observations; while the validation set and the test set, were consisted of eight observations. The target in this model was the annual oil barrel consumption. Tangent transfer function (tan-sigmoid) was applied at the hidden layer with four neurons, and a linear transfer function (purelin) at the output layer with one neuron, as shown in Figure 5.26. The system error performance is $8.975e^{-7}$ illustrated in Figure 5.27, and 0.0005489 RMSE. Since, the root mean square is extremely small, the model is valid. It worth to mention that the error performance in Figure 5.27 is for the training set only and the one in this result ($8.975e^{-7}$) is for the whole data. The actual verses predicted result is shown in Figure 5.28. After that, the network was used to predict the annual oil barrel consumption from 2012 to 2022, Figure

5.29. As shown from Figure 5.29 the oil barrel consumption is increasing every year. Hence, the oil is deteriorating very fast, unless some changes happen to prevent this. Thus, the need of utilizing renewable energy is inevitable. The data calculated from reference [58].

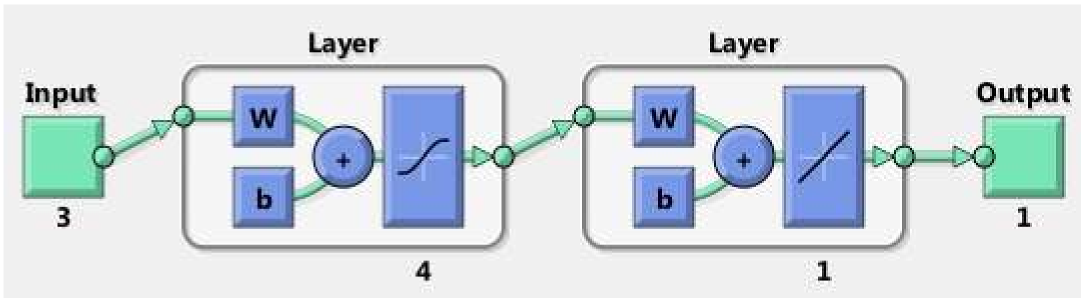



**Figure 5.26** Oil Barrel Consumption Neural Network

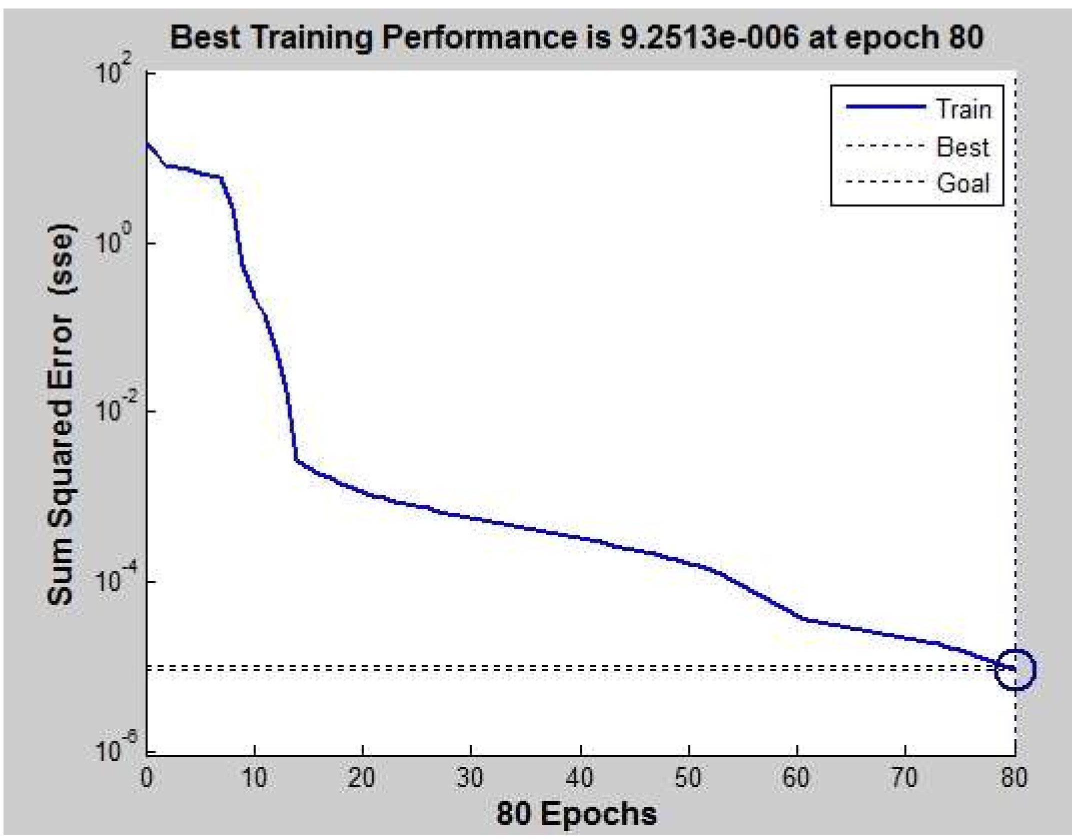



**Figure 5.27** OBC Error Performance

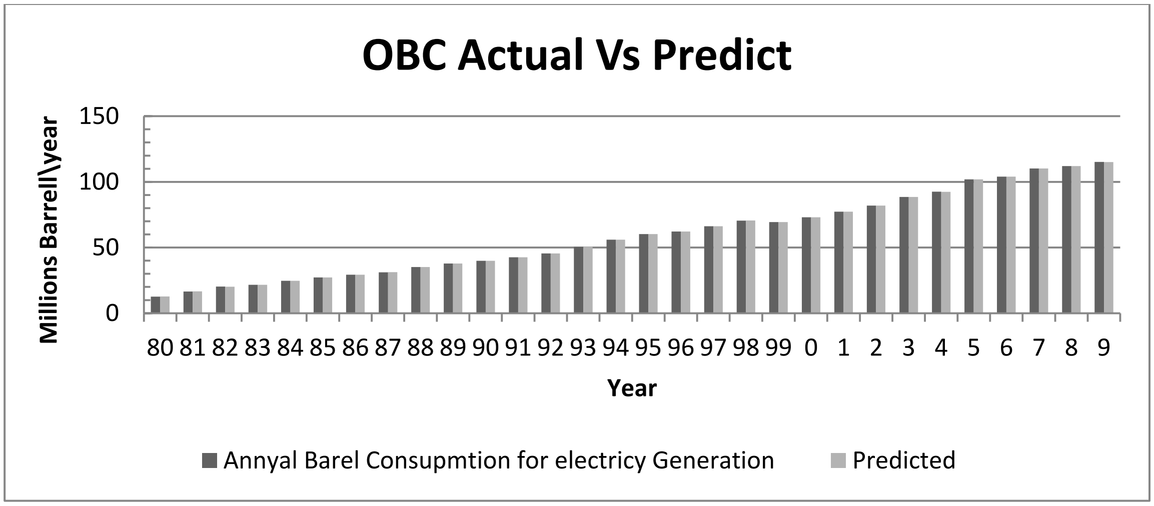



**Figure 5.28** OBC Actual Vs. Predicted

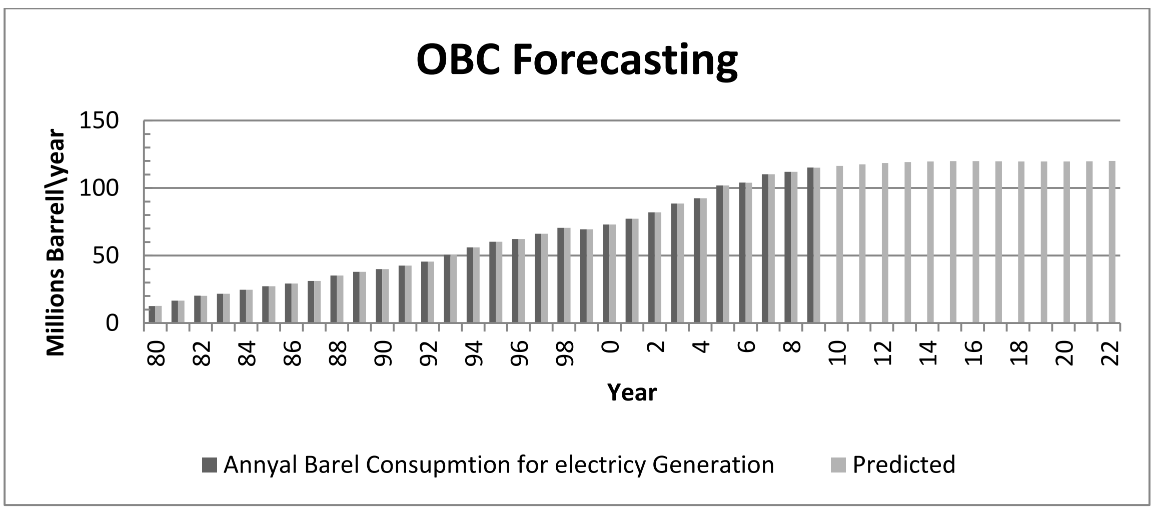



**Figure 5.29** OBC Actual Vs. Predicted from 2012 to 2022

#### *5.2.3.4 Monetary Inflation:*

The monetary inflation is related to the amount of money that has been printed by the country, i.e. monetary money is the annual budget [59]. This element has a direct effect on the inflation rate, which has a direct effect on the oil barrel price. Hence, a neural network model was implemented to predict Saudi Arabia budget for the next ten years using the population as input to the neural network. The model uses three inputs: year code, population, and remarkable occasion. The special occasions input is dealing with wars and economic recession. To clarify, the year with war, such as the Iraq war in 1990 and 1991, is marked with one, and years with no occasions are marked with zero. The model hidden layer has 6 neurons with tangent function in each neuron, and one neuron in the output layer with *purelin* function as shown in Figure 5.30. Furthermore, there are 33 observations divided into three parts: 29 observations for the training set and four observations in the validation set and test set. Neural model root mean square (RMSE) is 0.06312, and the performance error was 0.1275. The performance error behaviour of the training set is shown in Figure 5.31.

Obviously, forecasting the monetary money using population, and special occasion as inputs were not enough to get an accurate result, because the RMSE and the error performance were slightly high. However, the model is still valid.

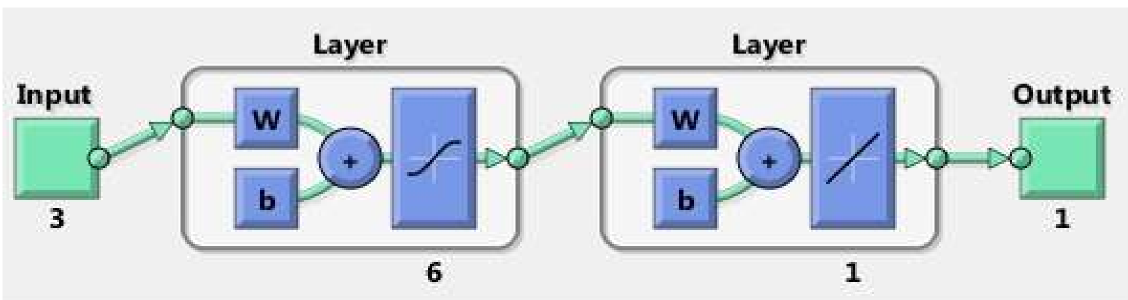



**Figure 5.30** Monetary Money Neural Network

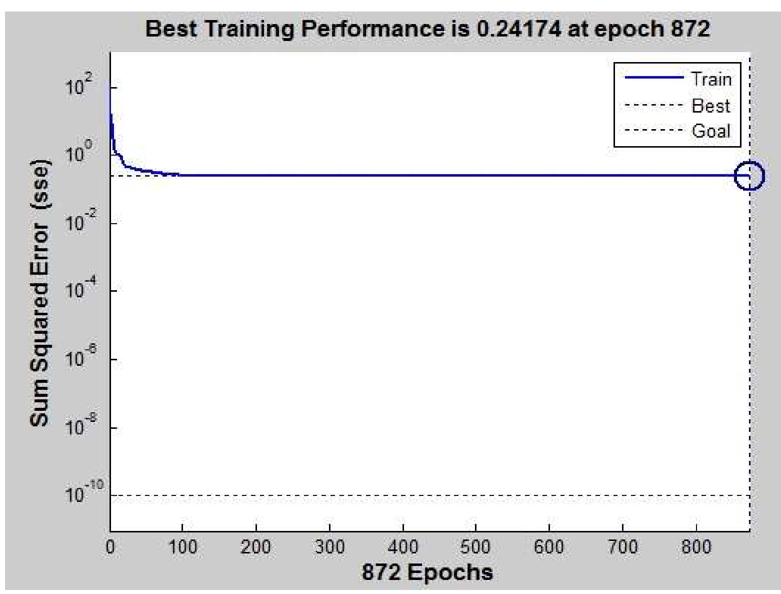



**Figure 5.31** Monetary Inflation Performance Error

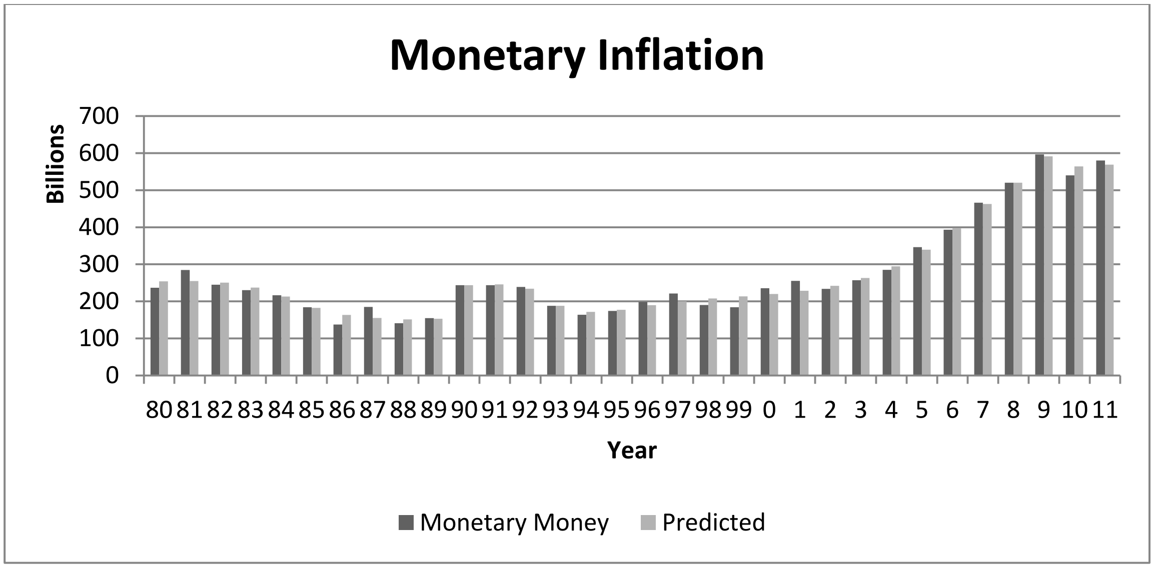



**Figure 5.32** Monetary Money Actual Vs. Predicted

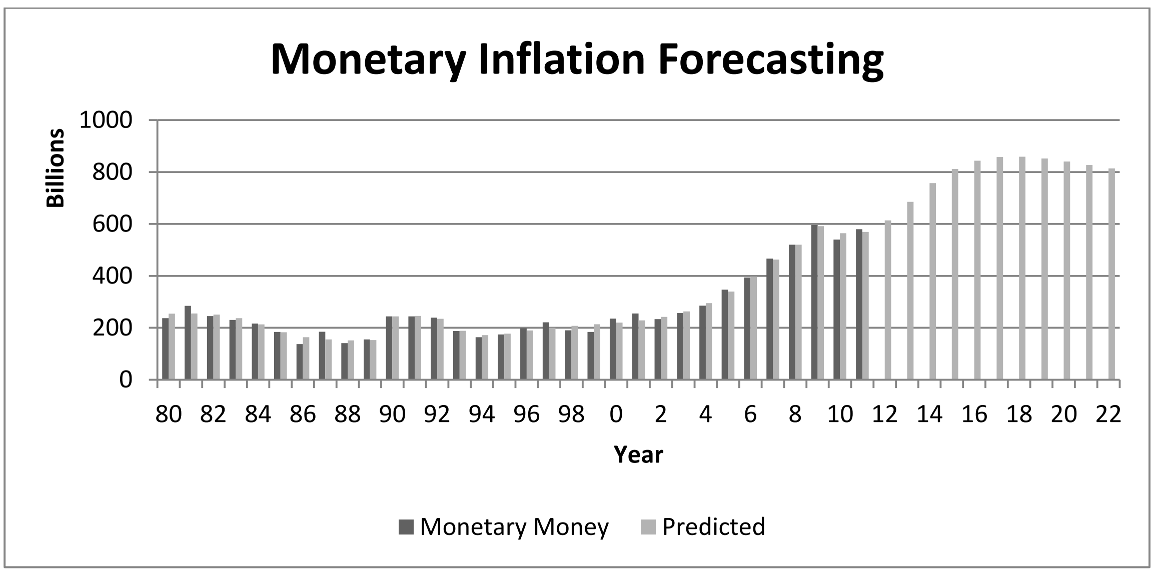



**Figure 5.33** Monetary Inflation Forecasting

#### *5.2.3.5 Inflation Rate Model:*

In general, inflation is the rate that causes an increase in the price of goods and services. In other words, it is a rate that defines wither life expenses increased or decreased. High inflation rate means high economy and hard life, low inflation rate means better economy and a better life.

The oil barrel price and inflation rate connected together in a relationship that based on movement and consequences. The price of oil has an effect on the consumer price index (CPI), i.e. an increase in the oil barrel price causes an increase in electricity, car fuel, transportation services, and other oil substitute (natural gas). Thus, any increase (decrease) in the oil barrel price (OBP), lead to an increase (decrease) in the CPI. Consequently, this causes for an increase (decrease) in the inflation rate. [55]

There are different factors affecting the inflation, though the majority of the articles [60-62] agree on one factor namely: the monetary inflation. Hence, the monetary inflation of Saudi Arabia from 1980 to 2011 used as the input to the neural network and the inflation rate is the target. The model has 21 observations in the training set, and 10 observations in the validation and test set. Logistic function (log-sigmoid) was applied at the hidden layer with 80 neurons, Figure 5.34, and a linear transfer function (purelin) at the output layer with one neuron. Finally, the prediction from 2012 to 2022 was obtained. After simulating the neural network, RMSE was 0.000356 and the error performance (Figure 5.35) was 3.68 $e^{-6}$. The results are shown in Figure 5.36 and 5.37.

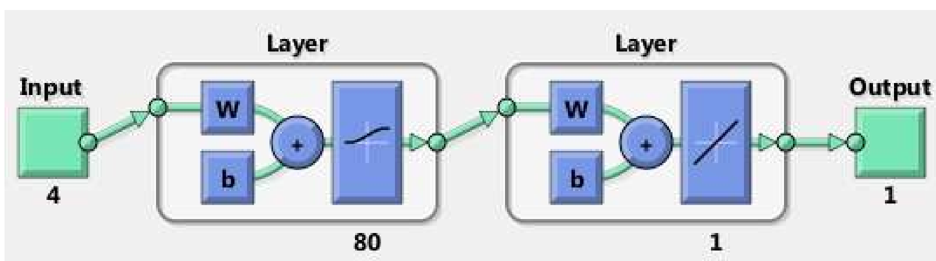



**Figure 5.34** Inflation Neural Network

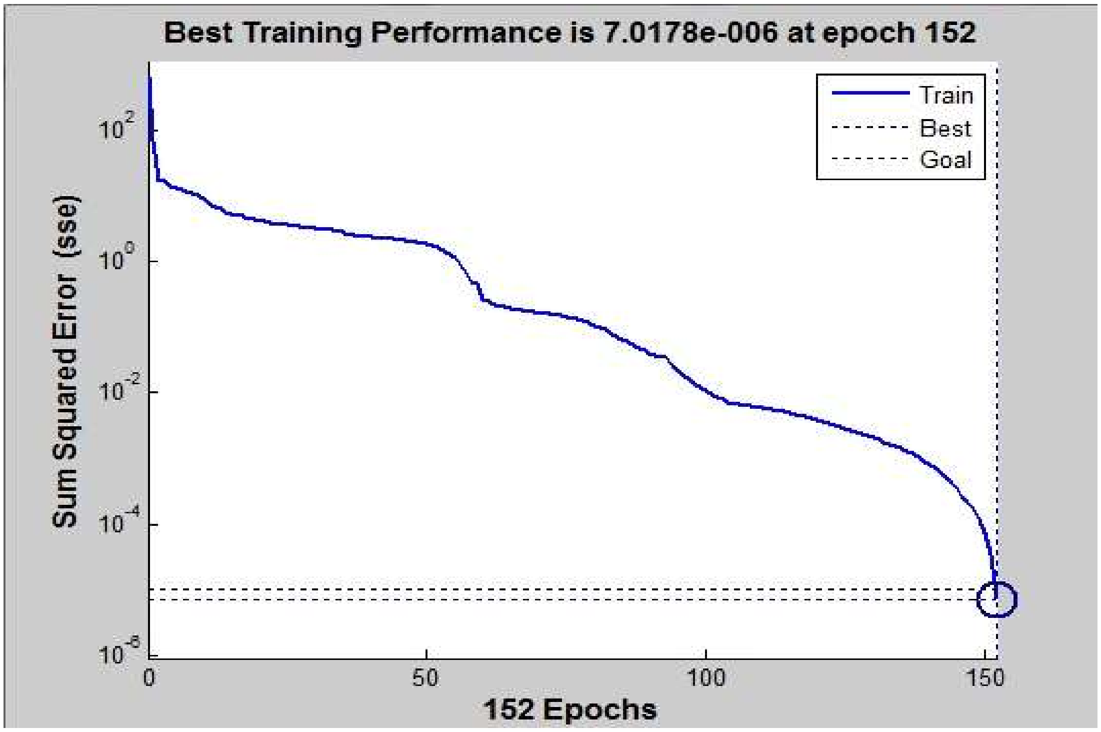



**Figure 5.35** Inflation Error Performance

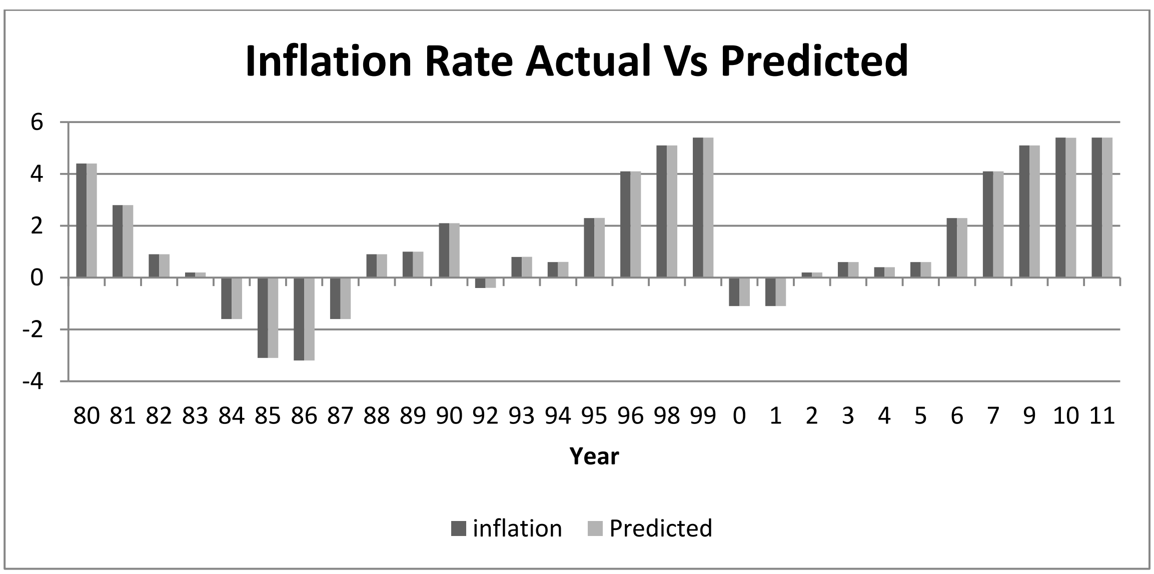



**Figure 5.36** Inflation Actual Vs. Predicted

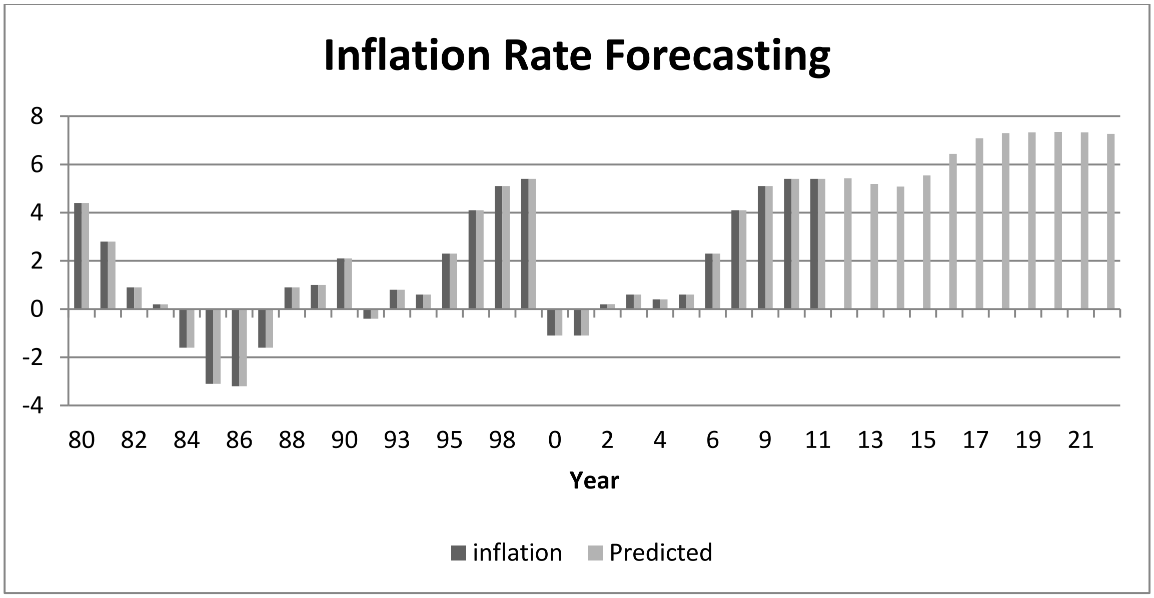



**Figure 5.37** Predicted Inflation from 2012 to 2022

#### *5.2.3.6 Unemployment Rate and GDP Model:*

Gross Domestic Product (GDP) rate is a measure of living standard for each country. Thus, country with high GDP has high economy and life expenses are high, and vice versa. GDP is one of the factors that affect the oil barrel price.

Since, Saudi Arabia is heavily dependent on oil, any changes in the oil price have a consequence in the country's economy. The unemployment rate is one of these economic effects. The unemployment rate has a massive impact on the economy of the country. An increase in the unemployment rate causes an increase in crime rates, and vice versa [55].

In this model, there were five inputs: year code, special occasion, population, NEG, and OBC. The hidden layer has 13 neurons with a logistic function used at each neuron. The output has two neurons for two targets: gross domestic product and unemployment rate. Each neuron in the output layer uses a linear transfer function (purelin). There were 21 observations used in the training process and 10 observations used in the validation and test process. After simulation, system results were 0.0003516 RMSE, and $7.17e^{-6}$ performance function. Then, the prediction from 2012 to 2022 was obtained. The data were collected from reference [35]. Results are in Figures 5.38 to 5.43.

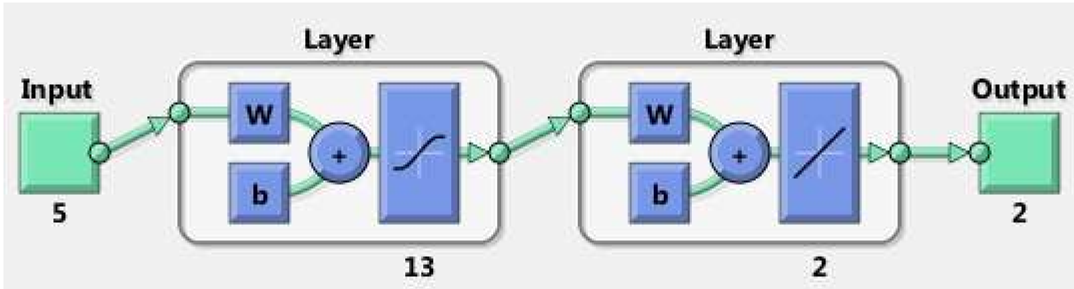



**Figure 5.38** GDP and Unemployment Neural Network

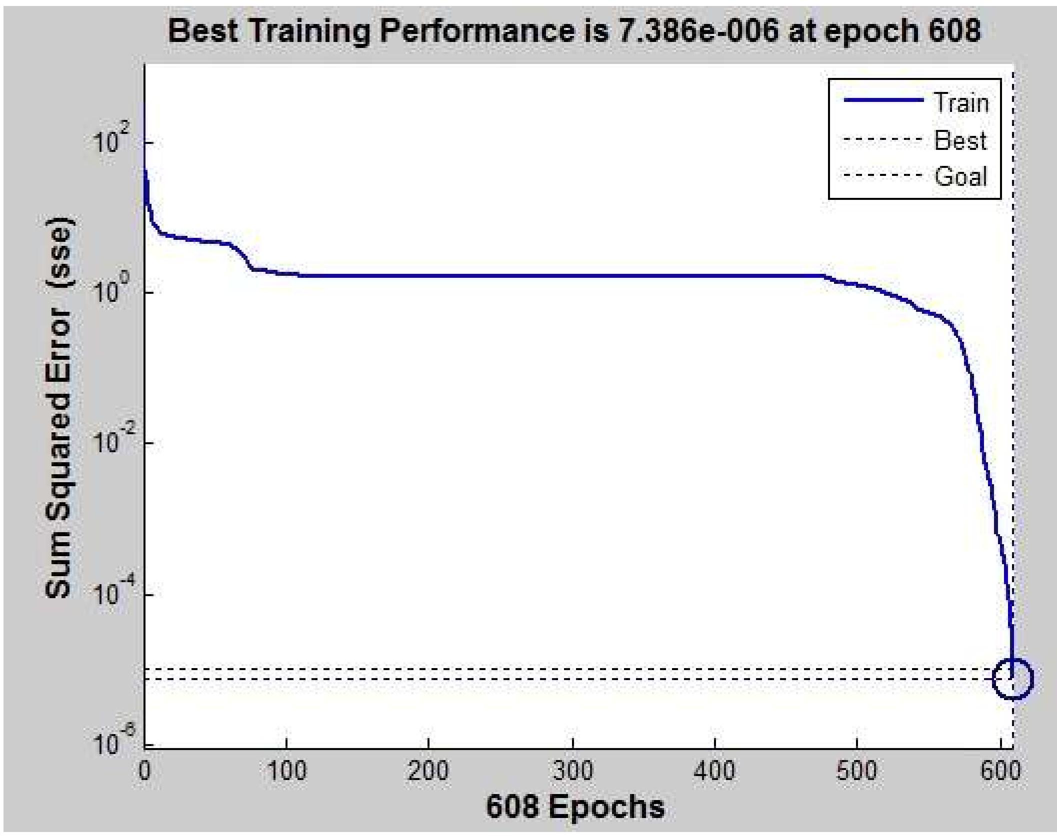



**Figure 5.39** GDP and Unemployment Error Performance

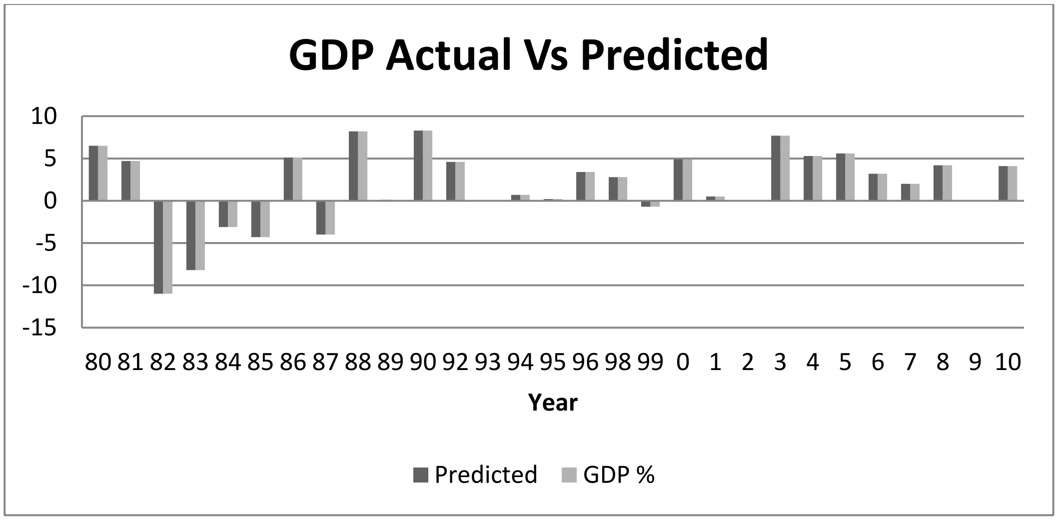



**Figure 5.40** GDP Actual Vs. Predicted

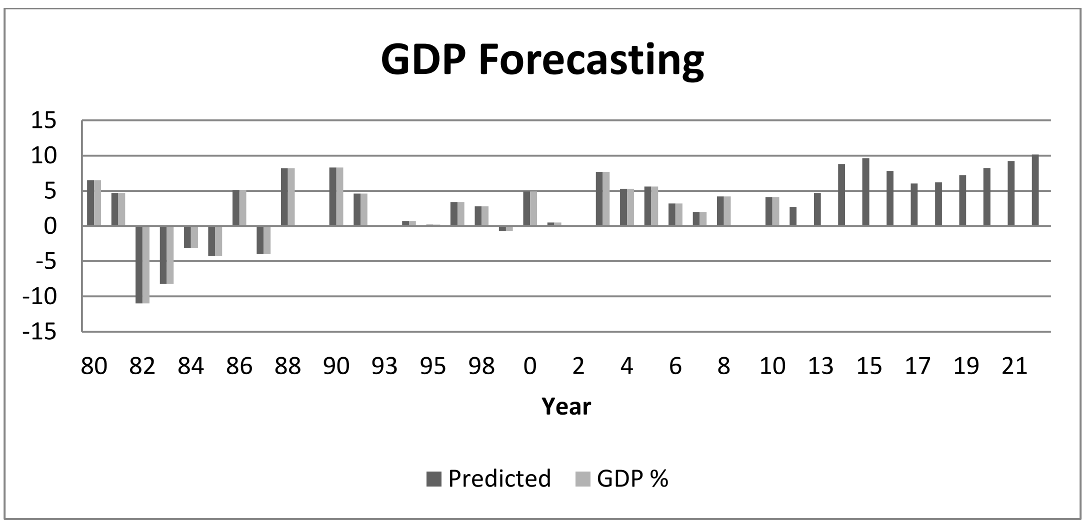



**Figure 5.41** GDP Forecasting

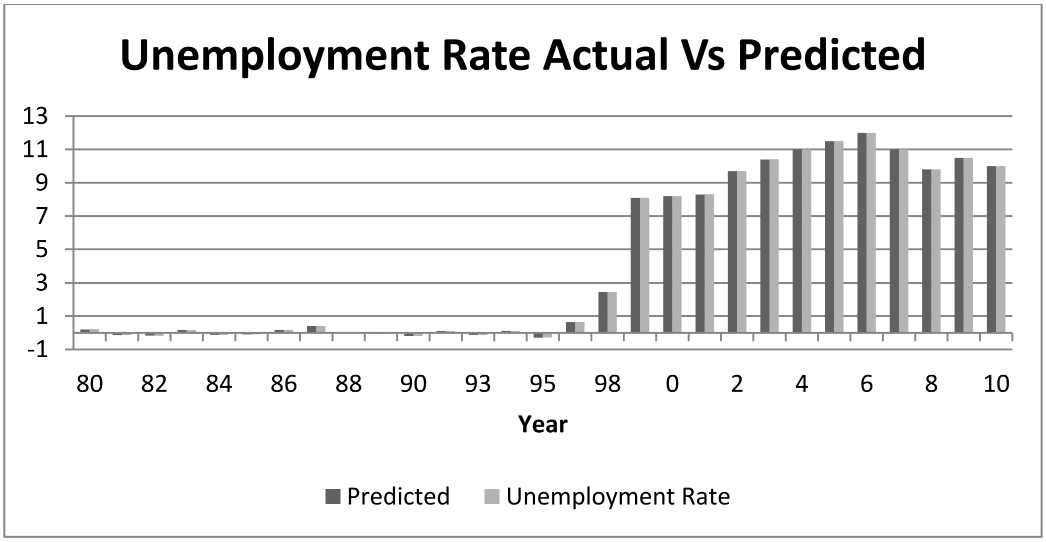



**Figure 5.42** Unemployment Rate Actual Vs. Predicted

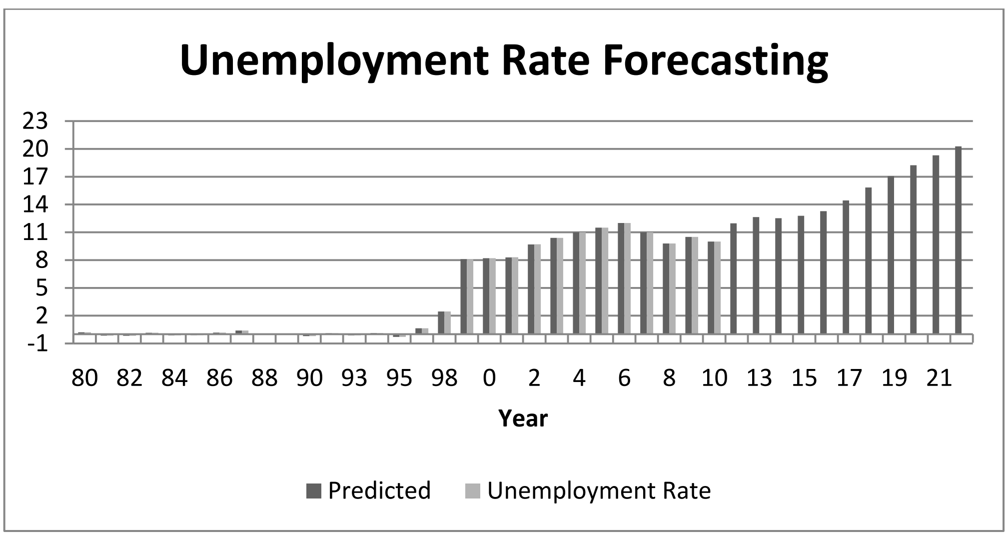



**Figure 5.43** Unemployment Rate Forecasting

***5.2.3.7 Oil Barrel Price (OBP) Model:***

This is the main model where oil barrel price was acquired. The idea here is to show the saving in oil barrel and consequently in money when utilizing solar system. The oil price that considered here is the West Taxes Intermediate (WTI) crude oil.

Oil has an enormous impact on the majority of life product. It controls the electricity prices. It is the blood supply of transportation. The change in oil price cannot express mathematically, and has a high degree of uncertainty. [44]. Moreover, oil price volatility cannot be solved using traditional statistic and economic models, because most of these models were based on linear assumption. On the contrary, artificial neural networks have the ability to detect the nonlinear patterns in the crude oil price.

##### *5.2.3.7.1 Models*

Earlier in this chapter, we mentioned that there are different elements that have influence in the oil barrel price (OBP). In this neural model, three elements were chosen as inputs to the network: the inflation rate, the GDP rate, and the unemployment rate of Saudi Arabia. The target was the WTI crude oil barrels price. WTI prices from January 1980 to June 2012 were used in the neural model. In addition, five more inputs were used in order to facilitate the search for a solution to the neural model. The inputs were the year code, special occasions, inflation factors, standard deviation, and unemployment factor. The inflation factor assigns 2 for the observation with positive inflation and 1 value for the negative inflation. Likewise, the unemployment factor assigns 1 for positive rate and -1 for negative rate. Finally, the last factor is the standard deviation of GDP, inflation rate, & unemployment rate. There were 390 observations divided in three parts: 300 observations for the training sets, and 90 observations to the validation and test sets.

The search for a model with a low error in this case was hard. Not only its time consuming, but also it was hard to find the perfect number of neurons and a perfect prediction. This is due to the nonlinearity in the oil price, and the diversity of the factors that have either direct or indirect influence of the oil prices. Thus, two algorithms have been used to find the best prediction: the Bayesian back-propagation (BRBB) algorithm and the BFGS quasi Newton back-propagation algorithm. The former provides a valid model with low RMSE and low performance error, but the predicted from July 2012 to December 2022 data was unacceptable. The latter provides a valid model with high RMSE, and high performance error but has an adequate prediction. Thus, both methods were used as shown in Figures 5.44 to 5.47. Table 5.15 shows the root mean square error and the performance error of both algorithms. The results are shown in Figures 5.48, and

5.49. Note that Figure 5.45 and 5.47 both show a low performance error. This error is only for the training sets not the whole data.

As shown in figure 5.49, the BFGS algorithm had a high error, and high fluctuations in the prices The predicted prices were reasonable because they are close to the one predicted by the U.S. Energy Information Administration (EIA) [63]. In Figure 5.49, the green and blue lines are regarding the validation and the training set. Both lines are converging together, i.e. the training set and validation set have an adequate result. The red line is for the test set. On the other hand, the results of the Bayesian back propagation have no fluctuation, and it is almost the same as the actual result. The lines in Figure 5.48 are shown above each other because they are identical. The predicted results of the BRBB algorithm were not shown because it was unreasonable.

As shown in Figure 5.44, the BRBB algorithm has eight inputs:

1. Year codes using Microsoft Excel.
2. GDP rates.
3. Inflation rates.
4. Unemployment rates.
5. Inflation factors.
6. Unemployment actors.
7. Special Occasions.
8. Standard deviation.

The BFGS, Figure 5.46, has seven inputs, which are the same inputs as in the BRPP algorithm excluding the unemployment rate. The reason behind using those factors is to make the neural network converge faster. It is worth mentioning, that the neural model was tested with different number of inputs and different number of neurons until best convergence was found.

It is worth to mention that a single neural network to predict the oil barrel price based on all inputs was attempted, but the results were disappointing.

**Table 5.15** OBP Algorithms Results

| Algorithm | Number of Neurons | RMSE | Performance Error |
|---|---|---|---|
| ***Trainbr*** | 51 | 0.0035 | 0.0043 |
| ***Trainbfg*** | 75 | 0.1118 | 4.57 |

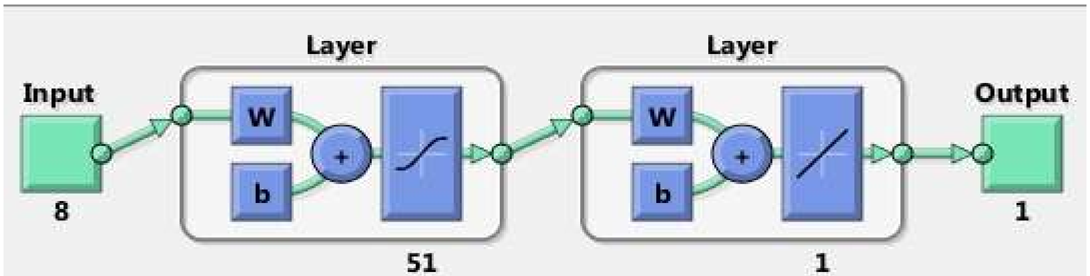



**Figure 5.44** OBP Neural Network Using BRBB

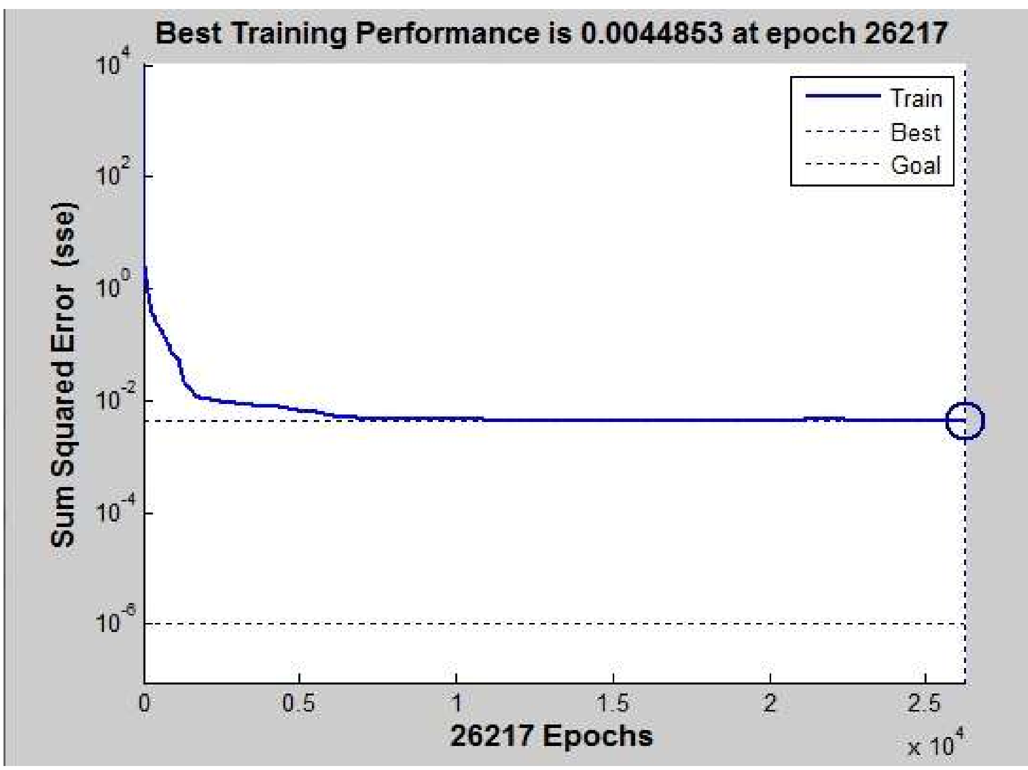



**Figure 5.45** OBP Error Performance for BRBB

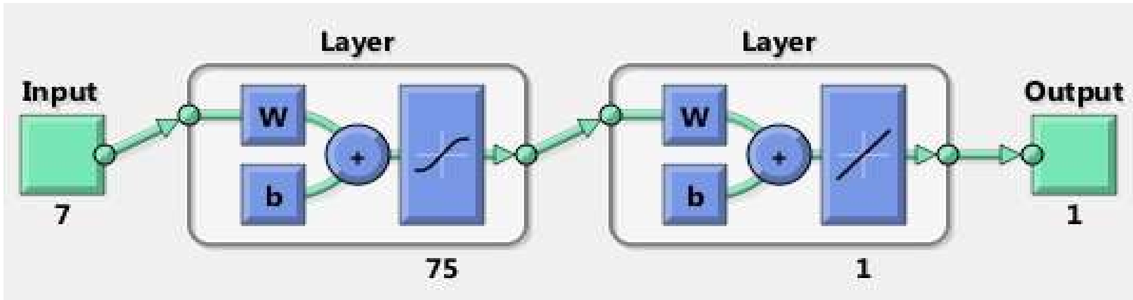



**Figure 5.46** OBP Neural Network Using BFGS algorithm

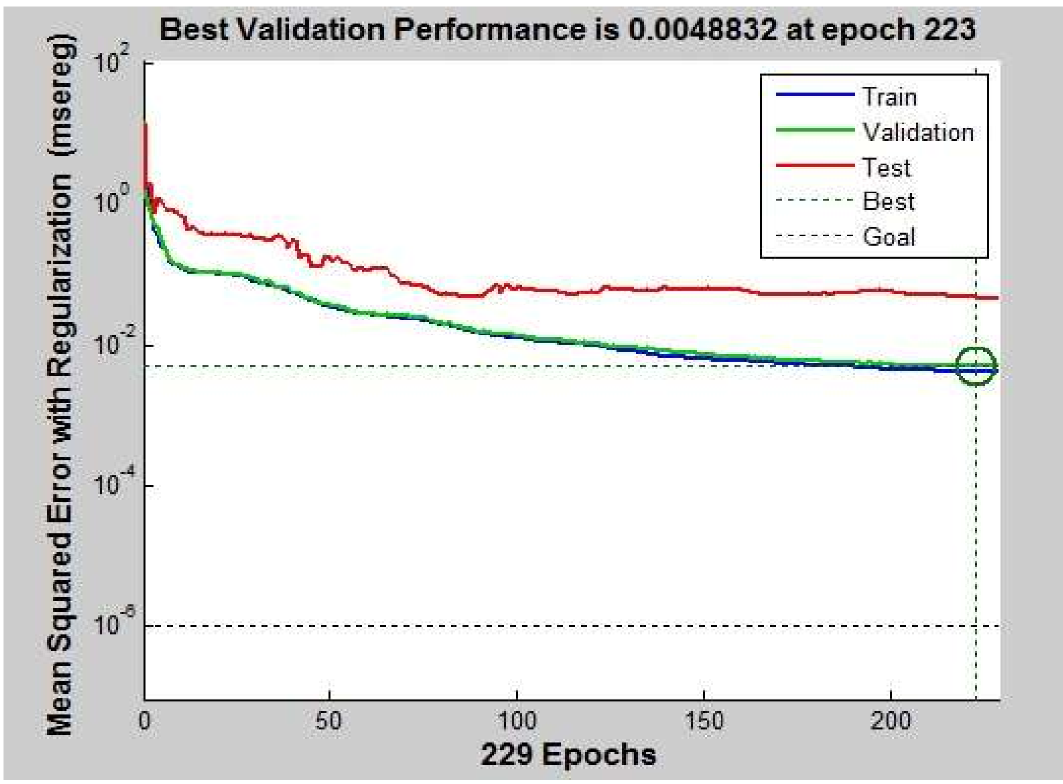



**Figure 5.47** OBP Error Performance for BFGS

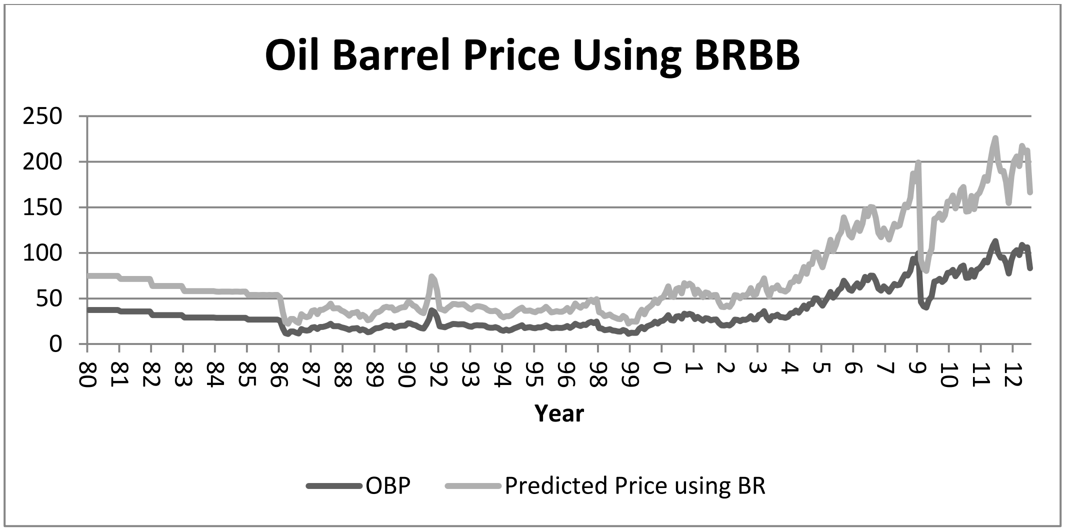



**Figure 5.48** OBP Actual Vs. Predicted Using BRBB Algorithm

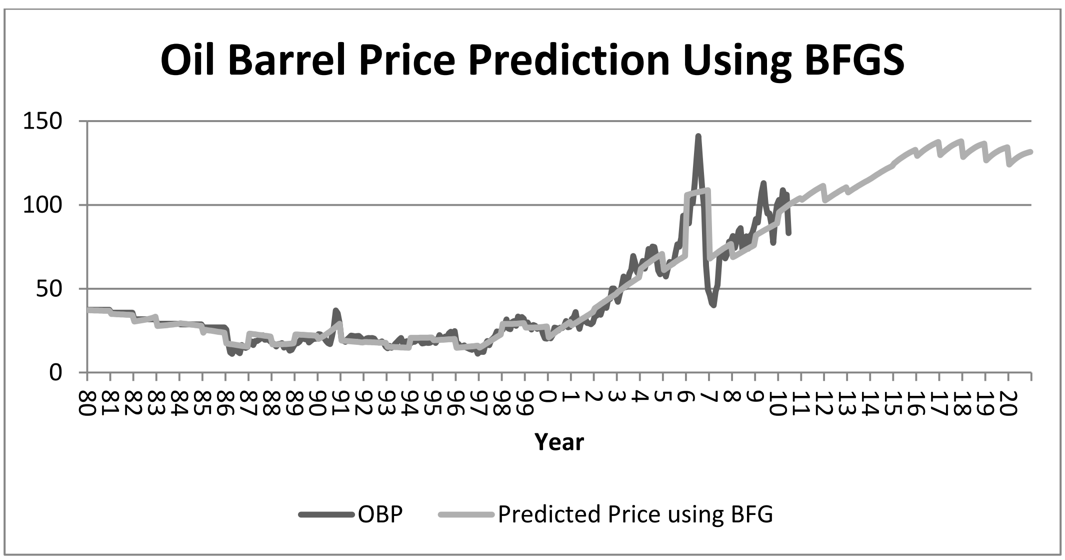



**Figure 5.49** OBP Forecasting Using BFGS Algorithm

Based on the results in Figures 5.48, and 5.49, there are many information were released. The prediction of oil price has never stayed stable for a long time, and that makes the prediction is hard to get. Furthermore, the relationship between the oil barrels price and its factors is not only complicated, but also far away from linearity. Another fact is that oil barrels price is increasing every year and it never settles on an exact price. What's more, the oil barrel price could increase more than expected during wars or economic recession. As a result, the utilization of oil in power production, transportation, and industrial production could increase as well. Hence, this increase in the oil price will lead to an increase in life expense, and hence, life becomes harder. All these facts conclude to one important issue: the need for an alternative & sustainable source of energy, and the need to save fossil fuel for the next generation.

## 5.3 Discussion:

In this section, the connection between the HOMER software calculation and artificial neural network (ANN) is provided.

An oil rich country (i.e. Saudi Arabia) is not likely to utilize solar powered systems unless the Saudi government is encouraged to utilize them. Thus, two motivating reasons have been provided here: the depletion of fossil fuels and the increasing oil barrel prices (OBP). Oil reserves as limited sources became known in 1973 when oil producing countries decided to increase oil prices [14]. Increasing oil barrel prices can be shown in two parts. The GRPV system shows the savings on oil barrels and oil barrels price can be predicted using artificial neural networks (ANN). Utilizing any GRPV system for one home could save from 51 to 460 barrels for the next 25 years with an average of 3 to 18 barrels every year. This implies that if the Saudi government initiates a one thousand 5k$W_p$-GRPV system project for each province in the next ten years, ***i.e. 100 houses/province/year with a total of 1400 GRPV system each yea*****r**, large savings in money and oil barrels are attainable. Hence, if this project was initiated, it will not only lead to preserving oil for the next generation and save money, but it will also assist in reducing $CO_2$ emissions. Table 5.16 shows the savings in oil barrel prices from the GRPV system in the current situation, i.e. 2.15 \$/$W_p$ and capital cost of 17,540 \$/SHS. On the other hand, Table 5.17 shows savings that are dependent on the future prices of PV panel (1\$/$W_p$). The GRPV system's capital cost of the one dollar per watt peak PV panel is 10,100 \$/SHS. In the present situation, the Saudi government has no savings in terms of money, but there are savings in the number of oil barrels produced. However, the total cost of the 1400 GRPV system each year is less than the cost of 50MWh generator with significant differences in energy and emissions. In other words, while a

1400 GRPV system produces 7 MWh/year pollution-free and zero-oil barrels, a 50MWh generator releases 240-terra kg of $CO_2$ and uses 268 million oil barrels every year. Conversely, when the PV panel prices drop to reach one dollar per watt peak, there will be savings in the number of oil barrels as well as in terms of money. Hence, even though a GRPV system has a high initial capital cost, it helps to reduce pollution, and, in the future, it will save money as well.

**Table 5.16** SA Saving Using 2.15$/Wp PV Panels for the 1400 GRPV System Project

| Year | System Cost $ | Barrel saving | OBP Predicted $/Barrel | SA Government Save $ | Surplus | Total Production kWh |
|---|---|---|---|---|---|---|
| **2013** | 25,548,062 | 179200 | 108 | 19,353,600 | -6,194,462 | 7,000 |
| **2014** | 26,059,024 | 179200 | 107 | 19,174,400 | -6,884,624 | 7,000 |
| **2015** | 26,580,204 | 179200 | 112 | 20,070,400 | -6,509,804 | 7,000 |
| **2016** | 27,111,808 | 179200 | 121 | 21,683,200 | -5,428,608 | 7,000 |
| **2017** | 27,654,044 | 179200 | 133 | 23,833,600 | -3,820,444 | 7,000 |
| **2018** | 28,207,125 | 179200 | 139 | 24,908,800 | -3,298,325 | 7,000 |
| **2019** | 28,771,268 | 179200 | 141 | 25,267,200 | -3,504,068 | 7,000 |
| **2020** | 29,346,693 | 179200 | 141 | 25,267,200 | -4,079,493 | 7,000 |
| **2021** | 29,933,627 | 179200 | 139 | 24,908,800 | -5,024,827 | 7,000 |
| **2022** | 30,532,300 | 179200 | 137 | 24,550,400 | -5,981,900 | 7,000 |
| **Total** | **279,744,155** | **1,792,000** | **1,278** | **229,017,600** | **50,726,555** | **70,000** |

**Table 5.17** SA Saving Using 1$/Wp PV Panels for 1400 GRPV System Project

| Year | System Cost $ | Barrel saving | Average Predicted price $/Barrel | SA Government Save $ | Surplus | Total Production kWh |
|---|---|---|---|---|---|---|
| **2013** | 14,711,256 | 179200 | 108 | 19,353,600 | 4,642,344 | 7,000 |
| **2014** | 15,005,481 | 179200 | 107 | 19,174,400 | 4,168,919 | 7,000 |
| **2015** | 15,305,591 | 179200 | 112 | 20,070,400 | 4,764,809 | 7,000 |
| **2016** | 15,611,703 | 179200 | 121 | 21,683,200 | 6,071,497 | 7,000 |
| **2017** | 15,923,937 | 179200 | 133 | 23,833,600 | 7,909,663 | 7,000 |
| **2018** | 16,242,415 | 179200 | 139 | 24,908,800 | 8,666,385 | 7,000 |
| **2019** | 16,567,264 | 179200 | 141 | 25,267,200 | 8,699,936 | 7,000 |
| **2020** | 16,898,609 | 179200 | 141 | 25,267,200 | 8,368,591 | 7,000 |
| **2021** | 17,236,581 | 179200 | 139 | 24,908,800 | 7,672,219 | 7,000 |
| **2022** | 17,581,313 | 179200 | 137 | 24,550,400 | 6,969,087 | 7,000 |
| **Total** | **161,084,149** | **1,792,000** | **1,278** | **229,017,600** | **67,933,451** | **70,000** |

# 6 Chapter 6: Conclusion

In this thesis, two different methods have been investigated which aim to answer a straightforward question: can Saudi Arabia utilize renewable energy sources instead of being totally dependent on oil? While this was a difficult question to answer, this thesis provides analysis which might redirect the Saudi government towards prospective renewable energy sources. Recommendations for the program's implementation are provided in this thesis.

## 6.1 Conclusions:

The goal of this work was to design a residential grid tie photovoltaic system that meets the residential demand in Saudi Arabia and be as efficient and cost effective as possible to maximize financial return on the system. The study of grid-tie residential photovoltaic system (GRPV) in Saudi Arabia has been conducted here using HOMER software, and Microsoft excel.

The results show that GRPV systems have a long way to go before they are utilised in Saudi Arabia due to a number of issues. Due to the fact that this solar powered system has a high capital cost, its use in Saudi Arabia has been delayed. In addition, Saudi Arabia currently lacks the policies that are needed for this to work. For example, there is no regulated way to pay solar system owners for the electricity transferred to the SEC grid. Conversely, the low cost of electricity charge from the Saudi Electric Company is another issue. Public education is needed to inform the stakeholders about the advantages of utilizing renewable energy. Another issue is that the Saudi government provides subsidies for the production of energy from fossils fuel production and not for renewable energy sources. With this current situation, GRPV system is not socially and economically feasible.

Utilizing a solar powered system as an energy source has many advantages. It can reduce $CO_2$ emissions and the number of oil barrels that are used to produce energy. GRPV system also supplies power to the grid [36]. According to Shalwala in Ref. [5], this reduces the peak load and supplies from the power plant generators while maintaining a constant voltage profile. Hence, GRPV systems are an environmentally friendly source of energy.

Artificial neural networks (ANN) were useful in predicting the West Taxes Intermediate (WTI) crude oil barrel prices. Seven models were used in this thesis. All models were dependent on each other. In other words, to obtain accurate results, the prediction of the first model was used in the second model, and so on. Table 5.18 summarizes the results of the seven models and the root mean square error (RMSE) and performance error are provided. Although all of these models have a non-linear relationship between the input(s) and the target(s), the differences in the RMSE depends on the model accuracy and how close it is to linearity.

Combining between HOMER software and ANN models has shown that using a grid-tie photovoltaic (GRPV) system aid to maintain fossil fuel for the next generation, reduce emission, reduce load demand, and reduce electricity bills.

To sum up, this thesis has shown the challenges that Saudi Arabia is facing to utilize the solar system as an energy source. Also, it answers the question of when Saudi Arabia can utilize GRPV system

**Table 6.1** Artificial Neural Network Results

| Model | RMSE | Performance Error | Transfer Function | Algorithm | Hidden Neurons |
|---|---|---|---|---|---|
| **Population** | 0.00202 | $1.23e^{-4}$ | Log | trainbr | 7 |
| **NEG** | 0.0799 | 0.185 | Tan | trainbfg | 2 |
| **OBC** | 0.000548 | $8,975e^{-7}$ | Tan | trainbr | 4 |
| **Monetary Money** | 0.06312 | 0.1275 | Tan | trainbr | 6 |
| **Inflation Rate** | 0.000356 | $3.68\ e^{-6}$ | Log | trainbr | 80 |
| **GDP and Unemployment rate** | 0.000351 | $7.16e^{-6}$ | Tan | trainbr | 13 |
| **OBP** | 0.0035 | 0.0043 | Tan | Trainbr trainbfg | 51 & 75 |

## 6.2 Contributions:

This work provides some answers to the position of Saudi Arabia towards renewable energy solar system. It contributes the following:

1. A description of Saudi Arabia's current stance towards solar energy systems.
2. An analysis of the factors that affect the utilization of the solar energy system in Saudi Arabia.
3. Possible solutions, which will assist Saudi Arabia in utilizing GRPV systems within residential areas.
4. Generating a residential load profile.
5. Population forecasting, net electricity generation forecasting, oil barrel consumption forecasting, Monetary Money forecasting, inflation rate forecasting, and oil barrel price forecasting.

In fact, the monetary value of oil is escalating and the capital cost of a PV system is decreasing. Hence, one of the main contribution of this work is to give a basis for assigning a *present worth* of the renewable energy to compare it with oil.

## 6.3 Recommendation and Future work

### 6.3.1 Recommendations:

- At the current situation, Saudi Arabia should wait until the price of the PV panels drop to one dollar per watt peak.
- Saudi Arabia needs an energy policy that enforces the utilization of renewable energy sources, such as, the solar system.
- Lack of knowledge regarding renewable energy sources particularly solar powered system is one of the obstacles that slow down the growth of the solar system. Thus, Saudi government need to establish programs that educate the public regarding the benefit of utilizing the GRPV system in both economically and environmentally. They also need to know about fossil fuel demolishing.

- Saudi Electric Company (SEC) should include renewable energy sources as a part of their power supplies.
- The need of an incentive program to encourage people to use GRPV system.
- With Saudi government support, Saudi's banks need to provide a low rate loan especially for future owners of GRPV system.

### 6.3.2 Future Work:

Future work will include:

1. Studying another forecasting system, such as swarm system, fuzzy, and extreme learning machine, then combine them with ANN.
2. Analysing and investigating the economic feasibility between two renewable energy sources.
3. Studying system stability with respect to the solar system.

In fact, People purchase grid tie PV systems to help reduce $CO_2$ emission and do their part towards a clean environment. By installing GRPV system people generate their own electricity and clean their environment.

# Appendix A: Data Sheets

## A.1 Sharp Panel

SHARP

solar electricity

245 WATT

MULTI-PURPOSE MODULE

NEC 2008 Compliant
New Triple Tab Technology

NU-U245P1

MULTI-PURPOSE 245 WATT MODULE FROM THE WORLD'S TRUSTED SOURCE FOR SOLAR.

Using breakthrough technology, made possible by nearly 50 years of proprietary research and development, Sharp's NU-U245P1 solar module incorporates an advanced cell surface texturing process to increase light absorption and improve efficiency. Common applications include commercial and residential grid-tied roof systems as well as ground mounted arrays. Designed to withstand rigorous operating conditions, this module offers high power output per square foot of solar array.

Sharp's most powerful commercial module manufactured today.

**ENGINEERING EXCELLENCE**
High module efficiency for an outstanding balance of size and weight to power and performance.

**DURABLE**
Tempered glass, EVA lamination and weatherproof backskin provide long-life and enhanced cell performance.

**RELIABLE**
25-year limited warranty on power output.

**HIGH PERFORMANCE**
This module uses an advanced solar cell surface texturing process to increase light absorption and improve efficiency.

**INNOVATIVE**
156 mm pseudo-square monocrystalline solar cells provide high power output. Ideal for large commercial rooftops where space is a premium.

The NU-U245P1 offers industry-leading performance for a variety of applications.

Improved Frame Technology

**SHARP: THE NAME TO TRUST**
When you choose Sharp, you get more than well-engineered products. You also get Sharp's proven reliability, outstanding customer service and the assurance of our 25-year limited warranty on power output. A global leader in solar electricity, Sharp powers more homes and businesses than any other solar manufacturer worldwide.

BECOME POWERFUL

# 245 WATT

## NU-U245P1

**NEC 2008 Compliant**
**Module output cables: 12 AWG with locking connectors**

| ELECTRICAL CHARACTERISTICS | |
|---|---|
| Maximum Power (Pmax)* | 245 W |
| Tolerance of Pmax | +10%/-5% |
| Type of Cell | Monocrystalline silicon |
| Cell Configuration | 60 in series |
| Open Circuit Voltage (Voc) | 37.3 V |
| Maximum Power Voltage (Vpm) | 30.4 V |
| Short Circuit Current (Isc) | 8.7 A |
| Maximum Power Current (Ipm) | 8.08 A |
| Module Efficiency (%) | 15.0% |
| Maximum System (DC) Voltage | 600 V |
| Series Fuse Rating | 15 A |
| NOCT | 47.5°C |
| Temperature Coefficient (Pmax) | -0.485%/°C |
| Temperature Coefficient (Voc) | -0.351%/°C |
| Temperature Coefficient (Isc) | 0.053%/°C |

*Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (ASTM E892 global spectral irradiance) at a cell temperature of 25°C.

| MECHANICAL CHARACTERISTICS | |
|---|---|
| Dimensions (A x B x C below) | 39.1" x 64.6" x 1.8"/994 x 1640 x 46 mm |
| Cable Length (I) | 43.3"/1100 mm |
| Output Interconnect Cable** | 12 AWG with MC4 Locking Connector |
| Weight | 44.1 lbs / 20.0 kg |
| Max Load | 50 psf (2400 Pascals) |
| Operating Temperature (cell) | -40 to 194°F / -40 to 90°C |

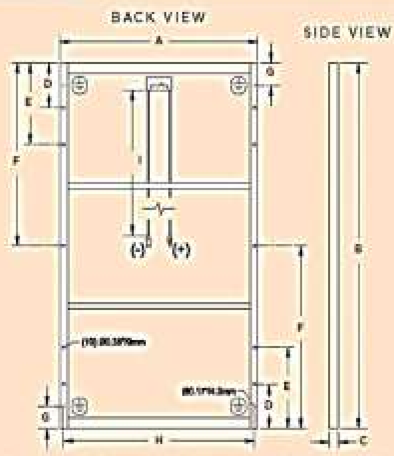
**A safety lock clip (Multi Contact part number PV-SSH4) may be required in readily accessible locations per NEC 2008 690.33 (C)

| QUALIFICATIONS | |
|---|---|
| UL Listed | UL 1703 |
| Fire Rating | Class C |

| WARRANTY |
|---|
| 25-year limited warranty on power output |
| Contact Sharp for complete warranty information |

Design and specifications are subject to change without notice.
Sharp is a registered trademark of Sharp Corporation. All other trademarks are property of their respective owners. Contact Sharp to obtain the latest product manuals before using any Sharp device. Cover photo: Solar Installation by SPG Solar.

### DIMENSIONS




| A | B | C | D | E |
|---|---|---|---|---|
| 39.1"/994 mm | 64.6"/1640 mm | 1.8"/46 mm | 7.9"/200 mm | 14.4"/366 mm |

| F | G | H | I |
|---|---|---|---|
| 32.3"/820 mm | 3.9"/100 mm | 37.7"/958 mm | 43.3"/1100 mm |

Contact Sharp for tolerance specifications

### "BUY AMERICAN"

Sharp solar modules are manufactured in the United States and Japan, and qualify as "American" goods under the "Buy American" clause of the American Recovery and Reinvestment Act (ARRA).

SHARP

SHARP ELECTRONICS CORPORATION
5901 Bolsa Avenue, Huntington Beach, CA 92847
1-800-SOLAR-06 • Email: sharpsolar@sharpusa.com
www.sharpusa.com/solar



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## A.2 Sunny Boy Inverter

SUNNY BOY 3000TL / 4000TL / 5000TL


**High Yields**

- Maximum efficiency of 97 %
- MultiString technology*
- Transformerless, with H5 topology
- Shade management with OptiTrac Global Peak

**Safe**

- Integrated ESS DC switch-disconnector

**Simple**

- Easily accessible connection area
- Cable connection without tools
- DC plug system SUNCLIX

**Communicative**

- Bluetooth technology as standard
- Multilingual graphic display
- Multi-function relay as standard

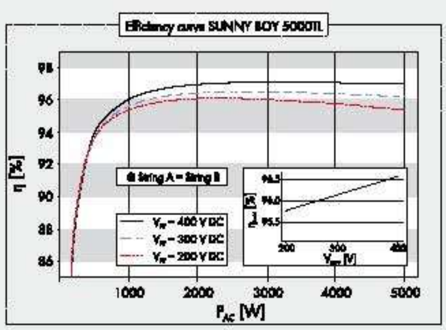
### SUNNY BOY 3000TL / 4000TL / 5000TL

Perfection Plus. Usability. The transformerless Sunny Boy generation

More communicative, easier to use and more efficient than ever: this Sunny Boy is setting new standards in inverter technology. A modern graphic display, readout of daily values even after sunset, simplified installation concept and wireless communication via *Bluetooth*: The new Sunny Boys fulfill every wish. With the new OptiTrac Global Peak shade management and an optimal efficiency of 97 %, the inverters ensure optimum solar yield. As transformerless, multi-string devices, the Sunny Boy 4000TL and 5000TL provide maximum flexibility for plant design, and are the first choice for demanding generator designs.

* Sunny Boy 4000TL / 5000TL

| Technical data | Sunny Boy 3000TL | Sunny Boy 4000TL | Sunny Boy 4000TL/V | Sunny Boy 5000TL |
|---|---|---|---|---|
| **Input (DC)** | | | | |
| Max. DC power (@ cos φ = 1) | 3200 W | 4200 W | 4200 W | 5300 W |
| Max. DC voltage | 550 V | 550 V | 550 V | 550 V |
| MPP voltage range | 188 V – 440 V | 175 V – 440 V | 175 V – 440 V | 175 V – 440 V |
| DC nominal voltage | 400 V | 400 V | 400 V | 400 V |
| Min. DC voltage / start voltage | 125 V / 150 V | 125 V / 150 V | 125 V / 150 V | 125 V / 150 V |
| Max. input current / per string | 17 A / 17 A | 2 x 15 A / 15 A | 2 x 15 A / 15 A | 2 x 15 A / 15 A |
| Number of MPP trackers / strings per MPP tracker | 1 / 2 | 2 / A: 2, B: 2 | 2 / A: 2, B: 2 | 2 / A: 2, B: 2 |
| **Output (AC)** | | | | |
| AC nominal power (@ 230 V, 50 Hz) | 3000 W | 4000 W | 3680 W | 4600 W |
| Max. AC apparent power | 3000 VA | 4000 VA | 4000 VA | 5000 VA |
| Nominal AC voltage; range | 220, 230, 240 V; 180 – 280 V | 220, 230, 240 V; 180 – 280 V | 220, 230, 240 V; 180 – 280 V | 220, 230, 240 V; 180 – 280 V |
| AC grid frequency; range | 50, 60 Hz; ± 5 Hz | 50, 60 Hz; ± 5 Hz | 50, 60 Hz; ± 5 Hz | 50, 60 Hz; ± 5 Hz |
| Max. output current | 16 A | 22 A | 22 A | 22 A |
| Power factor (cos φ) | 1 | 1 | 1 | 1 |
| Phase conductors / connection phases | 1 / 1 | 1 / 1 | 1 / 1 | 1 / 1 |
| **Efficiency** | | | | |
| Max. efficiency / Euro-eta | 97.0 % / 96.3 % | 97.0 % / 96.4 % | 97.0 % / 96.4 % | 97.0 % / 96.5 % |
| **Protection devices** | | | | |
| DC reverse-polarity protection | ● | ● | ● | ● |
| ESS switch-disconnector | ● | ● | ● | ● |
| AC short circuit protection | ● | ● | ● | ● |
| Ground fault monitoring | ● | ● | ● | ● |
| Grid monitoring (SMA Grid Guard) | ● | ● | ● | ● |
| Galvanically isolated / all-pole sensitive fault current monitoring unit | –/● | –/● | –/● | –/● |
| Protection class / overvoltage category | I / III | I / III | I / III | I / III |
| **General data** | | | | |
| Dimensions (W / H / D) in mm | 470 / 445 / 180 | 470 / 445 / 180 | 470 / 445 / 180 | 470 / 445 / 180 |
| Weight | 22 kg | 25 kg | 25 kg | 25 kg |
| Operating temperature range | -25 °C ... +60 °C | -25 °C ... +60 °C | -25 °C ... +60 °C | -25 °C ... +60 °C |
| Noise emission (typical) | ≤ 25 dB(A) | ≤ 29 dB(A) | ≤ 29 dB(A) | ≤ 29 dB(A) |
| Internal consumption: (night) | < 0.5 W | < 0.5 W | < 0.5 W | < 0.5 W |
| Topology | transformerless | transformerless | transformerless | transformerless |
| Cooling concept | Convection | OptiCool | OptiCool | OptiCool |
| Electronics protection rating / connection area (as per IEC 60529) | IP65 / IP54 | IP65 / IP54 | IP65 / IP54 | IP65 / IP54 |
| Climatic category (per IEC 60721-3-4) | 4K4H | 4K4H | 4K4H | 4K4H |
| **Features** | | | | |
| DC connection: SUNCLIX | ● | ● | ● | ● |
| AC connection: screw terminal / plug connector / spring-type terminal | –/–/● | –/–/● | –/–/● | –/–/● |
| Display: text line / graphic | –/● | –/● | –/● | –/● |
| Interfaces: RS485 / Bluetooth | ○/● | ○/● | ○/● | ○/● |
| Warranty: 5 / 10 / 15 / 20 / 25 years | ●/○/○/○/○ | ●/○/○/○/○ | ●/○/○/○/○ | ●/○/○/○/○ |
| Certificates and permits (more available on request) | CE, VDE 0126-1-1, DK 5940, RD 1663, G83/1-1, PPC, AS4777, EN 50438*, C10/C11, PPDS | | | |
| * Does not apply to all national deviations of EN 50438 | | | | |
| ● Standard features ○ Optional features – not available | | | | |
| Data at nominal conditions | | | | |
| Type designation | SB 3000TL-20 | SB 4000TL-20 | SB 4000TL-20/V 0159 | SB 5000TL-20 |




## Accessories

RS485 interface
DM-485CB-10

# Appendix B: SEC Breaker Sizes

*Dear Bandar*
*Sorry for the delay. Please find enclosed an attachment where you will find all you need. However, you can contact me to discuss any items that need to be clarified and please don't hesitate.*

*Best Regards.*

***Mohammed Hamid Al Zaki***
***SEC Project Manager, for***
***The Operational Performance***
***Improvement Project***
***Cellular: 0503204229***
***Off. 01-4032222 / 23709***

الشركة السعودية للكهرباء
Saudi Electricity Company
طاقة مثمرة

**From:** Bandar Mutwali [mailto:bandar.h.a.m@gmail.com]
**Sent:** Saturday, December 10, 2011 12:57 PM
**To:** Mohammed H. Al zaki
**Subject:** Assistance Request (Bandar Mutwali)

Dear Abu Sami,
I hope you get my message in good health, and thank you for answering my call today.
Regarding to our phone call, I needed some information about the load in residential area.
I need to know how much is load for an average house in Summer, winter, Spring, and Fall.
You told me now one can get you the hourly data of any residential. I am afraid that not right. I think it is possible. Anyway, if you could not get an hourly date. Let us say the monthly load will do the job. Is energy consuming in Riyadh, same as energy consuming in the Eastern region? If not can you get their energy consuming for a house?
Also, I need to know how is our electric bill system work? i.e. the way SEC charge customer for electric used.
One last thing, does the Saudi Electric Company has any regulations regarding the Solar System?
I know you are busy all the time, and I know I am bothering you with this questions.
However, you are the only one who can give a reliable data no one else.
Thank you for your time.
Sincerely

---

The past cannot be changed; the future is still in your power.
Eng. B Mutwali
Halifax, NS
Canada
902-456-5187

## B.1 Breaker Sizes from the Saudi Electricity Company (SEC)

Saudi Electricity Co. — الشركة السعودية للكهرباء

| ضوابط إيصال التيار الكهربائي<br>حساب أحمال المشتركين | التاريخ: /٠٨/١٤٢٣هـ<br>رقم الاصدار : (١) |
|---|---|

Customers Load Determination depending on the area → حساب أحمال المشتركين عن طريق المساحة المشيّدة للمبنى

Breaker Size (Amps) — Total Connected Electricity KVA — Area in square meter

| سعة القاطع (أمبير) | مجموع الأحمال الموصلة (ك.ف.أ) | المساحة المشيّدة للمبنى (م٢) |
|---|---|---|
| ٣٠ | ٤، ٨، ١٢ | ٢٥، ٥٠، ٧٥ |
| ٦٠ (60) | 13, 16, 20, 24, 27 | 76, 100, 125, 150, 174 |
| ١٠٠ (100) | 28, 32, 36, 40, 43, 46 | 175, 200, 225, 250, 275, 300 |
| ١٥٠ (150) | 47, 50, 53, 56, 60, 63, 66, 68 | 301, 325, 350, 375, 400, 425, 475, 465 |
| ٢٠٠ (200) | 69, 70, 73, 75, 76, 80, 83, 86, 90, 91 | 466, 475, 500, 524, 525, 550, 575, 600, 625, 630 |
| ٣٠٠ (300) | 92, 93, 96, 100, 103, 106, 110, 113, 116, 120, 123, 126, 130, 133, 136, 137 | 631, 650, 675, 700, 725, 750, 775, 800, 825, 850, 875, 900, 935, 950, 975, 980 |
| ٤٠٠ | ١٣٨، ١٤٠، ١٤٣، ١٤٦، ١٥٠، ١٥٢ | ٩٨١، ١٠٠٠، ١٠٢٥، ١٠٥٠، ١٠٧٥، ١١٠٠ |
| ٥٠٠ | ١٥٣، ١٥٦، ١٦٠، ١٦٣، ١٦٦، ١٨٠، ١٩٣، ٢٠٦، ٢٢٠، ٢٢٨ | ١١٠١، ١١٢٥، ١١٥٠، ١١٧٥، ١٢٠٠، ١٣٠٠، ١٤٠٠، ١٥٠٠، ١٦٠٠، ١٦٦٠ |
| ٦٠٠ | ٢٢٩، ٢٣٣، ٢٤٦، ٢٦٠، ٢٧٣، ٢٧٤ | ١٦٦١، ١٧٠٠، ١٨٠٠، ١٩٠٠، ٢٠٠٠، ٢٠٢٠ |
| ٧٠٠ | ٢٧٥، ٢٨٦، ٣٠٠، ٣١٣، ٣٢٠ | ٢٠٢١، ٢١٠٠، ٢٢٠٠، ٢٣٠٠، ٢٣٥٠ |
| ٨٠٠ | ٣٢١، ٣٢٦، ٣٤٠، ٣٥٤، ٣٦٦ | ٢٣٥١، ٢٤٠٠، ٢٥٠٠، ٢٦٠٠، ٢٧٠٠ |

صفحة ٨ من ١١

# Appendix C: Project in Saudi Arabia

## C.1 Solar Future Project in Saudi Arabia

Reference Project | On-Grid, Roof-Top

### 2 MW: King Abdullah University, Saudi Arabia

CONERGY

The roof top of the King Abdullah University of Science and Technology is certainly unique. It bears the first and largest solar installation of Saudi Arabia. The 2 MW Conergy power plant is a record breaking project for the entire Middle East.

**6,000 times around the world in a car**

The roof top solar installation is installed on the north and south laboratories of the university. The power system features premium components, combining over 9,300 high-efficiency solar modules with Conergy Suntop III mounting systems and Conergy 280K central inverters. The photovoltaic plant occupies 11,577 square meters of roof space and produces 3,332 megawatt hours of clean energy annually, while also saving up to 33,320 tons of carbon emissions. This equates to carbon offsets of approximately 6,000 circumnavigations of the world by car.

**A secret formula**

Conergy partnered up with Saudi Arabia's leading solar system integrator, National Solar Systems (NSS). The Hamburg based solar experts designed the park and were responsible for the engineering, supervision and commissioning while installation works and operational management were implemented by National Solar Systems. Managing Director of NSS, Abdulhadi Al-Mureeh says: "For the first time, clean power is flowing into the national grid. This is a historical event for us in Saudi Arabia. The strong collaboration and mutual cooperation between National Solar and Conergy was the secret formula behind this success."

**Oil-rich Middle East goes green**

Saudi Arabia, the largest oil producer of the Organization of Petroleum Exporting Countries (OPEC) with approximately one-fifth of the world's proven oil reserves, is planning to make solar power a major contributor to its energy supply. With its favourable insolation levels and extensive areas featuring very low population densities it shows ideal characteristics for the deployment of solar energy.

"We are extremely pleased to be part of this ground-breaking project", says Marc Lohoff, Head of Conergy Asia Pacific and the Middle East. "We support the future of renewable energy in the Middle East with our solar know how and the latest technology. This project demonstrates that the development of alternatives to traditional fossil fuel has taken on a new urgency, even in oil-rich countries like Saudi Arabia."

| Project Highlights | |
|---|---|
| Date | December 2009 |
| Location | KAUST, Saudi Arabia |
| Output | 2 MWp |
| Produced MW/h annually | 3,332 MWh annually |
| Modules | 9,306 Monocrystalline modules |
| Inverters | Conergy 280K central inverters |
| Mounting System | Conergy Suntop III mounting systems |
| Size of Plant | 11,577 square meters |
| $CO_2$ Emissions Saved | 3,320 tons / year |

CERTIFIED CONERGY QUALITY

KAUS THO-RP-ENG-02 2011

www.conergy-group.com

## Press Release

### Saudi Arabia: New financial centre going for solar "Made in Germany" with Conergy

***First rooftop plant in the metropolis of Riyadh reflects increasing importance of sustainability***

**Hamburg/Singapore/Riyadh, 10 January 2012** – The latest financial centre of Saudi Arabia, the King Abdullah Financial District (KAFD), will be reducing its dependence on the kingdom's oil reserves and will be relying on solar technology from Conergy for a portion of its energy requirements. By installing a solar system on the roofs of parcels 5.07 and 5.08 – the first solar rooftop plant in Riyadh – the KAFD is choosing sustainable architecture with the aim of achieving one of the most significant eco certifications in the world: the "LEED Gold" certification awarded by the US Green Building Council.

At close to 200 kilowatts, the solar plant will not only be the first but also the largest rooftop plant in Riyadh. In collaboration with its local partner Modern Times Technical Systems (MTTS), Conergy will be installing over 800 Conergy PowerPlus 230M modules on some 1.7 kilometres of Conergy SunTop III mounting systems over a surface of 1,300 sqm. The 330 megawatt hours of clean energy generated each year – which could supply 1,500 computers in the financial centre – will be fed into the power grid of the metropolis via 14 string inverters. The solar plant will prevent the emission of 180 tons of the damaging greenhouse gas $CO_2$ annually once it is connected to the grid by the first quarter of this year.

Conergy is providing support to companies in the Middle East on this new path towards sustainability. "The KAFD is no doubt an ecological pioneer, who we commend for playing this role," says Alexander Lenz, Conergy President of South East Asia and the Middle East. "With its environmentally friendly architecture, the KAFD demonstrates how the Saudi financial sector can reduce its dependence on fossil fuels. With the first rooftop plant in Riyadh, the KAFD is setting an example – and simultaneously encouraging more green awareness and action in the Middle East."

Currently, there are more solar plants under construction in Saudi Arabia with a total capacity of some 15 megawatts. Conergy has been contributing for many years now to the expansion of solar energy in the country: in 2010, the solar energy company erected the first, and at 2 megawatts also then the largest, solar plant of the kingdom on the roof of the "King Abdullah University of Science and Technology" (KAUST) in Thuwal. With its expansion into solar energy, Saudi Arabia is pursuing its goal of reducing its consumption of its oil and gas reserves that are intended for the export market. The Gulf state is instead planning to build their domestic infrastructure for renewable energy production. In June, the Saudi Minister of Petroleum and Mineral Resources Ali Al-Naimi commented on the situation by giving the following statement to

O U R  W O R L D  I S  F U L L  O F  E N E R G Y news agency Bloomberg: "Saudi Arabia plans to generate solar electricity equalling the amount of its energy from crude exports."

According to Green Alpha Advisors, Saudi Arabia exports approximately 2.7 billion barrels of oil a year. With one barrel of crude corresponding to around 1,700 kilowatt hours of electricity, the entire oil exports of the kingdom is equivalent to 4,590 billion kilowatt hours per year, a quarter of the world's energy demand. To produce this amount of energy would require close to a quarter of a million solar PV plants with an installed capacity of 10 megawatts each. Compared to the solar capacity installed in Saudi Arabia and its neighbouring countries of approximately 100 MW, these targets appear rather ambitious. But they also show that sustainability is now on the agenda in the sun-bathed Gulf state – and that solar energy is part of their solution to create a sustainable future.

**About Conergy**

The Hamburg-based Conergy AG is a leading solar company, with 1,600 employees in 14 countries on four different continents. As a system supplier, the Conergy Group develops and produces crystalline solar modules, inverters and mounting systems at three locations in Germany. Conergy can therefore provide customers not only with "Made in Germany" quality standards but also with all the components required for a photovoltaic facility from a single manufacturer, thanks to its in-house production. With its own components and systems, the solar company develops, finances and implements solar facilities, plants and entire solar parks up to the megawatt class. Furthermore, Conergy distributes its product portfolio through a large network of partners and wholesalers.

Since it was founded in 1998 Conergy has sold more than 1.6 gigawatts of solar energy. Conergy AG has been listed on the Frankfurt Stock Exchange (ISIN: DE 00060 40025) since 2005 and pursues a strategy of growth into the renewable energy markets of the future.

For more information, please visit www.conergy.com

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