# Yarmouk University

## Hijjawi Faculty for Engineering Technology

# Feasibility Study Of A Hybrid Wind/PV System Connected To The Jordanian Grid

A Thesis Presented to
The Department of Electrical Power Engineering

In fulfillment
of the requirements for the degree of
Master of Science
In Electrical Power Engineering

**By**

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July, 2012

# APPROVAL

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# DEDICATION

I would like to thank my mother for her encouragement, love and sacrifices and to my father for his patience, advise, love and support. To my mother and to my father I dedicate this work.

Hussein Al-Masri

# ACKNOWLEDGMENT

At the outset, I would like to offer a word of thanks to my parents, sisters and brother who deserve more than words of gratitude. I don't know how to thank them, but it was their ever-present inspiration, encouragement and support, both emotional and spiritual, that have seen me through this very critical period. Their prayers have instilled in me the strength to patiently succeed, as I feel I have today.

I would like to thank Dr. Fathi Amoura for his supervision and for his helpful advice and practical assistance. He has not only enlightened me, but also put me up with my shortcomings very patiently indeed.

Finally, I like also to extend my thanks to the Department of Electrical Power Engineering at the Yarmouk University for providing me with the suitable needs and requirements.

Eng.Hussein Al-Masri

# ABSTRACT

**Al-Masri, Hussein Mohammad Khalaf, feasibility study of hybrid wind/PV system connected to the Jordanian grid.**

**A MATLAB software and Hybrid Optimization Model for Electric Renewables (HOMER) software are used to investigate the feasibility of connecting wind/PV hybrid system to the Jordanian grid.**

**The data collected from formal organizations (Royal Scientific Society, National Center for Research and Development and Ministry of Energy and Mineral Resources) indicates that Ras Elnaqab (located south of Jordan) is an optimal location. This is because it enjoys to be one of the highest yearly average of both wind speed and solar radiation. It is interesting to know that it is rarely to locate a site that enjoys both high wind speed and high solar radiation. Normally, locations with high speed are deprived from high solar radiation and vice versa.**

**From the daily load data for a whole year, an average daily load curve for each month of the year has been calculated.**

**These data has been supplied to HOMER software and from the interaction with MATLAB software; two important results are calculated. The first is sharing percent between the wind energy (77.62%) and the PV energy (22.38%).**

**The second result is sizing the units. i.e. size of each wind turbine and their numbers (38 wind turbines each of 1.5MW) and size of PV panels and their numbers (76,124 each of 280 Watt).**

**The study indicates that wind/PV hybrid system sells to and purchases kWhr from the national grid given that the local load is satisfied at any time. The net result (for the whole year of 2011) is 2,254,382 kWhr to be sold to the national grid.**

**In conclusion, the application is feasible.**

***Keywords***— HOMER, Hybrid wind/PV power system, feasibility study.

# LIST OF SYMBOLS

*PV* : Photo-voltaic.

*HAWT* : Horizontal Axis Wind Turbine.

*VAWT* : Vertical Axis Wind Turbine.

*BTU* : British Thermal Unit.

*HOMER* : Hybrid Optimization Model for Electric Renewables.

*DC* : Direct Current.

*AC* : Alternating Current.

*NPC* : Net Present Cost in $.

*COE* : Cost Of Energy in $/KWh.

$C_P$ : Power Coefficient.

$V_{mp}$ & $I_{mp}$ : Voltage and Current at maximum power extracted from PV module.

*RSS* : Royal Scientific Society.

*NCRD* : National Centre for Research and Development.

EC : Energy Centre.

*EP* : Energy Purchase.

*JD* : Jordanian Dinar.

*RF* : Renewable Fraction.

*RPM* : Revolutions Per Minute.

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# CHAPTER ONE

## *INTRODUCTION*

### 1.1 Renewable Energy

Energy can be defined as the ability to do a work. It is an integral part of our daily life, it is used in agriculture, industry, health and social services. In other words, energy is the backbone of our life.

The current population growth rate is about 1.14% per year. Jordan population growth rate is estimated to be 0.984% in 2011. Energy usage increases with continuity in the population growth. The US Energy Information Administration (EIA) predicts 50% increase in the world energy consumption from 2005 and 2030 (See Figure 1.1) [2,21] (In order to sense Quadrillion BTU unit, it equals the energy of 170 million barrels of crude oil, or it equals to 293 terawatt-hours [22]).

Moreover, World Energy Consumption (WEC) survey predicts that the global energy demand will increase by 1.5 to 3 times in 2050 and by 2 to 5 times in 2100 [1]. The population grows upwards and the world's energy demand increases proportionally.

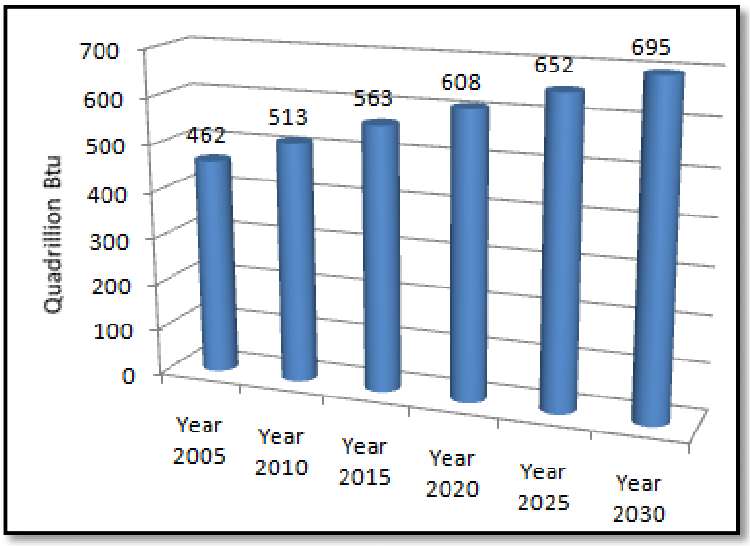



**Figure 1.1: World Energy Consumption**

Approximately 80 % of the energy consumed on the earth comes from fossil fuels (i.e. oil, coal and natural gas) (See Figure 1.2) that will run out sooner or later. Although they might last more than expected, they cause the greenhouse effect, acid rains and air pollution [2].

An alternative to the fossil fuel power is renewable energy technologies (solar, wind,…etc), they are non-polluting, efficient and help to reduce Carbon Dioxide emissions.

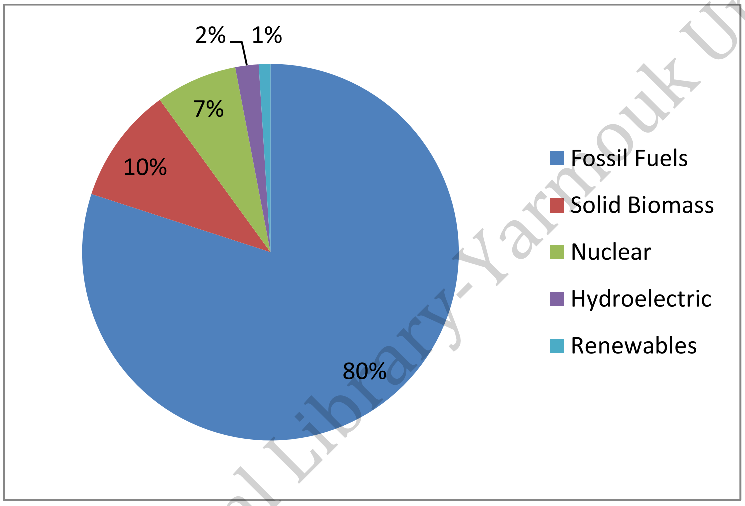



**Figure 2.2: Fuels supply the world's energy in 2005**

Although there is a great concern and virtual progress accomplished in renewable technologies, many fields are still at an early stage of development and not technically mature. If an effective research is applied in a modern way, renewable energy sources are considered highly responsive to overall energy policy guidelines, environmental, social, and economic goals[4]. One of the renewable energy critical issues is the degree of matching between renewable energy production and load patterns. Therefore, electrical energy storage is one of the most important methods advocated by the renewable energy community[7]. The interaction with the grid is bi-directional, so that the excess power generated by the hybrid renewable system is supplied to the grid, while the lack of generated energy is made by the national grid in order to satisfy the local energy demand[6].

Jordan is a non-oil producing country. Subsequently, most of fuel needs are imported. This constitutes financial burden on the national economy [8]. Therefore, great efforts and considerable researches are done on renewable energy. Exploitation of renewable energy resources such as wind and solar are environmentally friendly sources and that why they highly encouraged.

Arab Renewable Energy Commission has selected Jordan as its headquarters. In addition, the National Energy Strategy calls for 7 per cent of the Jordan's energy mix to come from renewable energy sources by 2015, and 10 per cent by 2020[5]. As a result, in the last few years there is an increased interest in renewable energy resources, this is because they are characterized by low operation costs compared with non-renewable resources, pollution free, inexhaustible and available all over the world, waste less, low emission and reliable resources. For these reasons renewable energy resources are suitable for many applications. Comparing with other renewable energy resources, wind and photo-voltaic are the most two available resources on earth and enjoy rapid growth around the world.

## 1.2 Wind Power

The first use of wind power was to sail ships in the Nile some 5000 years ago [4]. Wind can be simply defined as an air motion that results from earth rotation and atmosphere heating by sun. The amount of heat on the surface of the earth is not equal because earth is not flat, this will lead to pressure and temperature differences that force the air to move from one place to another. In this case, some locations will have higher wind speed than others [9].

Global wind power development is expected to keep its rapid growth (See Figure 1.3), the average growth rate is assumed to be 21%, this means that the global installed wind capacity will reach 409 GW in 2014. Technology of wind energy generation becomes the choice for many countries around the world in order to face the global recession and financial crisis, wind energy is inexpensive and easy to install [10].

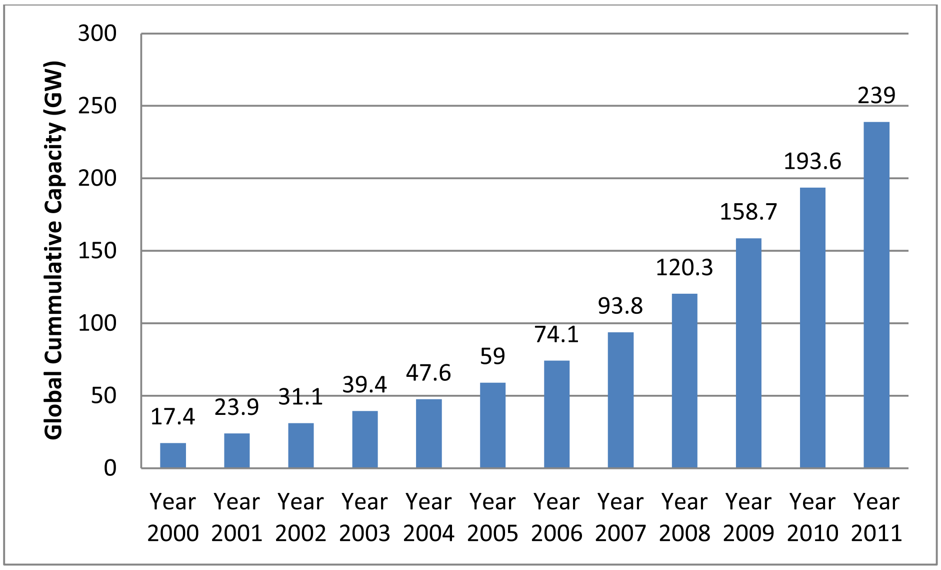



**Figure 1.3: Global Wind Power Cumulative Capacity**

The worldwide installed wind energy percent distribution according to the five continents is shown in Figure 1.4.

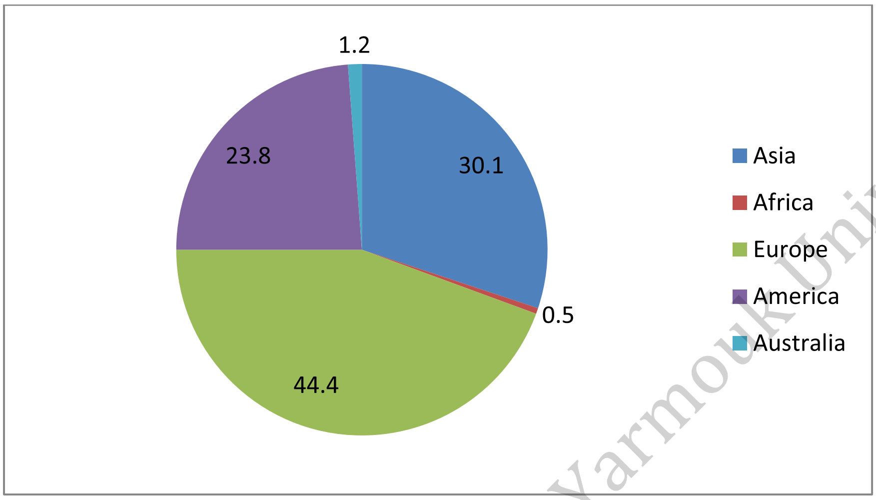



**Figure 1.4: Continental wind energy installed capacity distribution in 2010**

Exact continental wind energy installed capacity in MW referring to the global wind energy capacity at the end of 2010 is represented in Table 1.1 [10].

**Table 1.1: Exact continental wind energy installed capacity in MW**

| Continent | Installed Capacity in MW |
|---|---|
| **Asia** | 58,249 |
| **Africa** | 906 |
| **Europe** | 85,983 |
| **America** | 46,090.9 |
| **Australia** | 2,386 |
| **Global wind energy capacity** | 193,614.9 |

The site for wind energy installations should be selected according to the average wind speed as an initial indicator, in practice there is a minimum wind speed to generate electrical power, the relationship between the average annual wind speed and the gained wind energy is shown in Table 1.2 [11].

Table 1.2 : Relationship between Average Annual Wind Speed and Wind Energy

| Average Annual wind speed in m/s | Wind energy |
|---|---|
| **Less than 4.5** | Poor |
| **4.5 to 5.4** | Marginal |
| **5.4 to 6.7** | Good to very good |
| **More than 6.7** | Exceptional |

There are numerous advantages of wind energy. Firstly, it is friendly to the environment since no fossil fuel is burnt to generate electrical power. Secondly, Wind farms use less space than the traditional power station and the rest of the land in the wind farms can be used for other purposes. Thirdly, Wind is free source of energy. Finally, Wind power is reliable when it is combined with other renewable energy resources such as the photovoltaic power for the purpose of balancing out the fluctuation of the power that is supplied to the load.

## 1.3 Photovoltaic Power

There is a vigorous growth of the worldwide PV cumulative installation capacity (See Figure 1.5), even during times of financial and economical crisis [42].

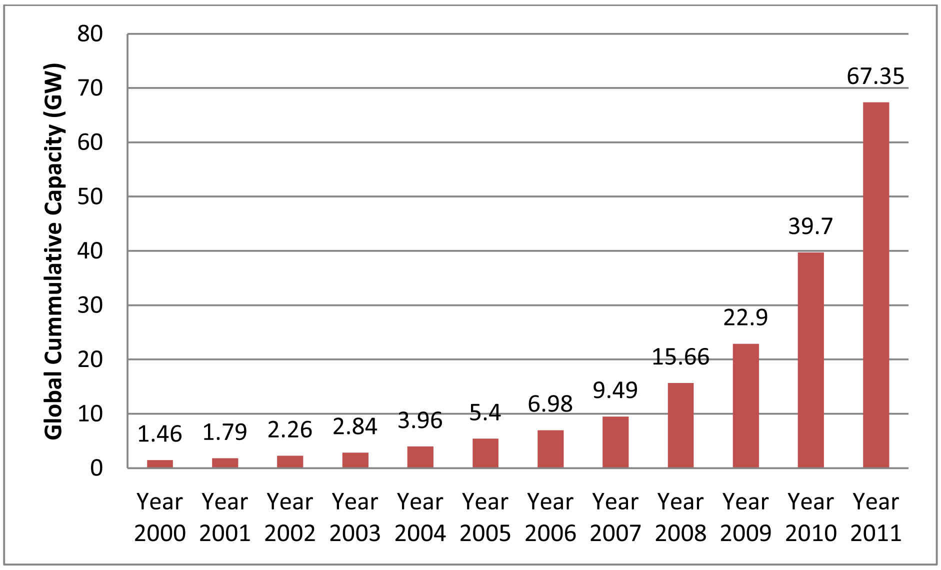



**Figure 1.5: Global Photovoltaic Power Cumulative Capacity**

Photovoltaic power results from the direct conversion of solar irradiation into electricity, this effect was firstly discovered by French physicist Becquerel in 1839 [4]. Photovoltaic array is composed from several modules, each module contains a number of photovoltaic cells (See Figure 1.6) are composed from a semi conducting material such as: monocrystalline silicon, polycrystalline silicon, amorphous silicon and others, these materials are used depending on their efficiencies. In practice several arrays are connected together in series or parallel configuration to produce any required DC voltage or current.

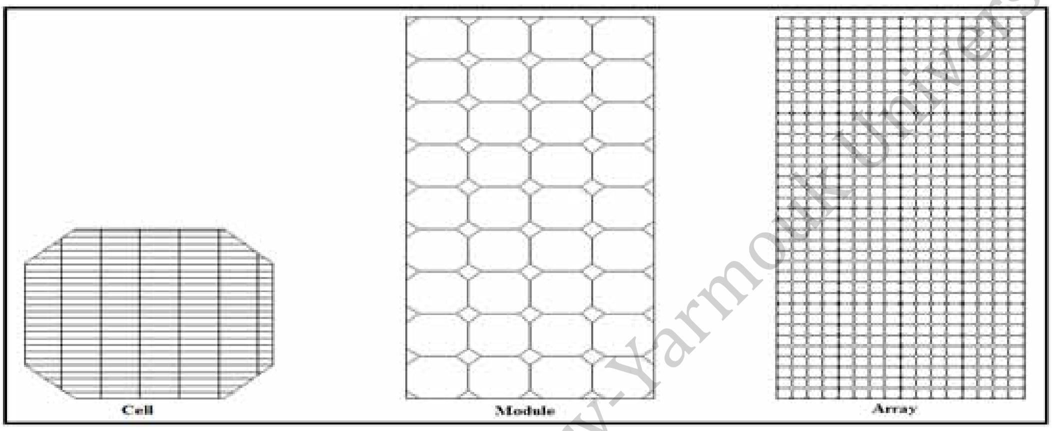



**Figure 1.6: Cell, Module and Array**

When the photovoltaic cells are exposed to the solar irradiation; the semi conducting material will absorb photons and release the electrons in order to move them from the valence band to the conduction band resulting in the build up of voltage between the electrodes. For the purpose of mechanical protection the PV cell is provided with glass cover and an applied transparent adhesive. To enhance the ability of absorbing more radiation, the PV array contains an anti-reflection coating. The operation and construction of the PV cell are shown in Figure 1.7 [4].

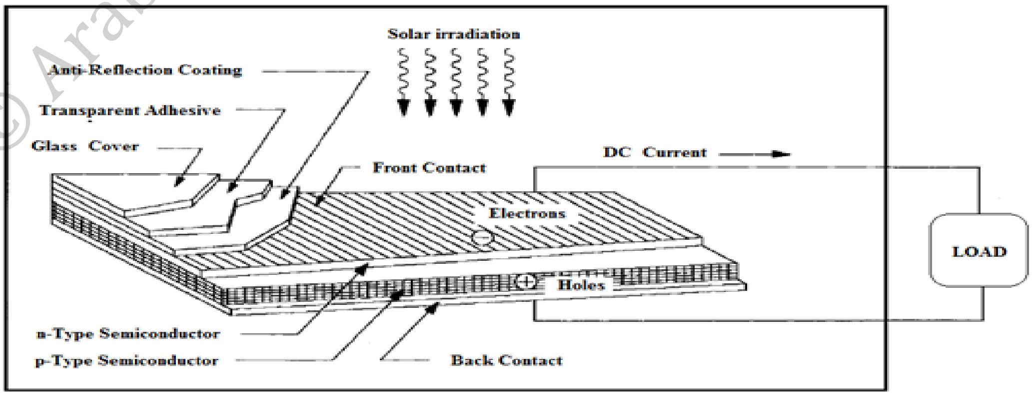



**Figure 1.7: Operation & Construction of PV cell with performance**

There are various advantages of photovoltaic energy. Firstly, it is environmental friendly, clean and silent. Secondly, Photovoltaic power resources are locally available, it does not need to be imported from other location across the world, thus, it reduces dependence on imported oil and also it reduces the environmental impacts associated with transportation. Thirdly, Photovoltaic power is reliable and operates for long period of time with actually no maintenance. Finally, photovoltaic power is recommended when it is combined with other renewable energy resources such as the wind power for the purpose of balancing out the fluctuation of the power that is supplied to the load.

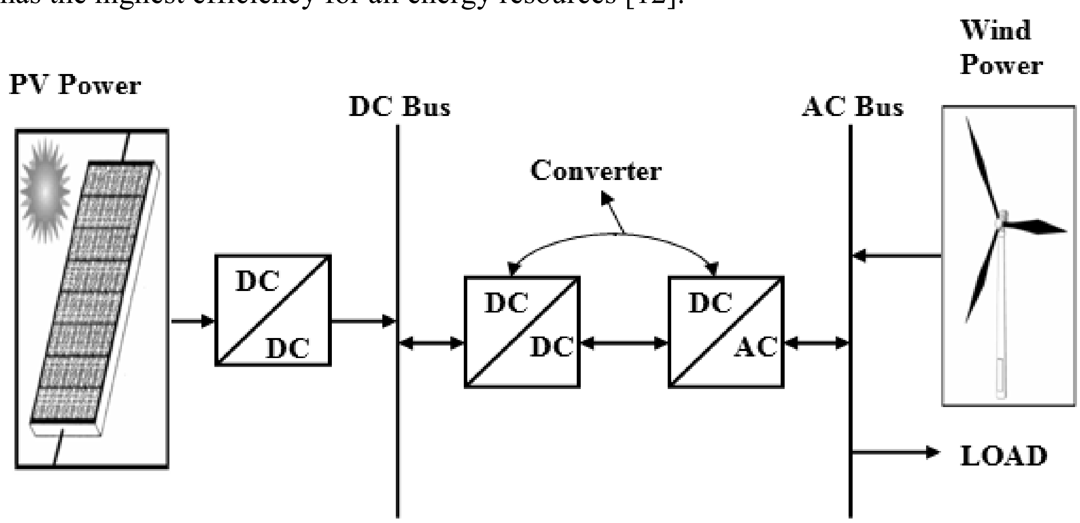
On the other hand, there are some limitations with using photovoltaic arrays such as production of PV modules that contains some toxic materials like Cadmium that cannot be recycled. Moreover, PV power is more expensive than the conventional energy resources; this is due to the high manufacturing cost of the PV devices and also the conversion efficiency of the PV panels. PV power will become at competitive price as the efficiency of the PV cell semiconducting material increases.

## 1.4 Hybrid Wind/Photovoltaic Power

A typical hybrid renewable energy system consists of two or more renewable energy resources such as PV array, wind turbine and hydro-turbine. In this thesis, a hybrid grid connected system composed of wind turbines and a photovoltaic array is considered. Wind turbines generate AC current while PV cells generate DC current. Therefore, various connection topologies are available as follows:

1- AC-coupled hybrid power systems.
2- DC-coupled hybrid power systems.
3- Mixed-coupled hybrid power systems.

The third scenario (See Figure 1.8) is the best choice based on that the mixed one has the highest efficiency for all energy resources [12].




**Figured 1.8: Mixed Coupled Hybrid Wind/PV System**

Unbalance and intermittence of renewable energy resources are the main reason for establishing hybrid electrical system. Numerous conditions should be available in the proposed site for hybrid installations. Firstly, the solar insolation and wind speed quantities should complement each other in order to enhance the desired goal of the hybrid wind photovoltaic system. For the PV arrays, an appropriate south direction without any obstacles to face the sun is necessary. For the wind farm, suitable wind speed and wind directions are needed. Secondly, flat, enough and homogeneous space are indispensable. Most of these conditions are satisfied in the southern region of the Hashemite Kingdom of Jordan. For example, Ras Elnaqab in Ma'an district which is the largest town in south Jordan; its area is $33000 km^2$ which is about one-third of the kingdom area. Ma'an has the highest values of solar radiation and sunshine hours (See Figure 1.9 [13]) worldwide; the annual solar irradiation in Ras Elnaqab is 5.93 $kWh/m^2/day$. In addition, the annual average wind speed is about $6.13 m/s$.

Moreover, Most of their lands are flat and homogeneous and they are not used for plantation. As a result, Ras Elnaqab is a suitable place for the proposed hybrid system.

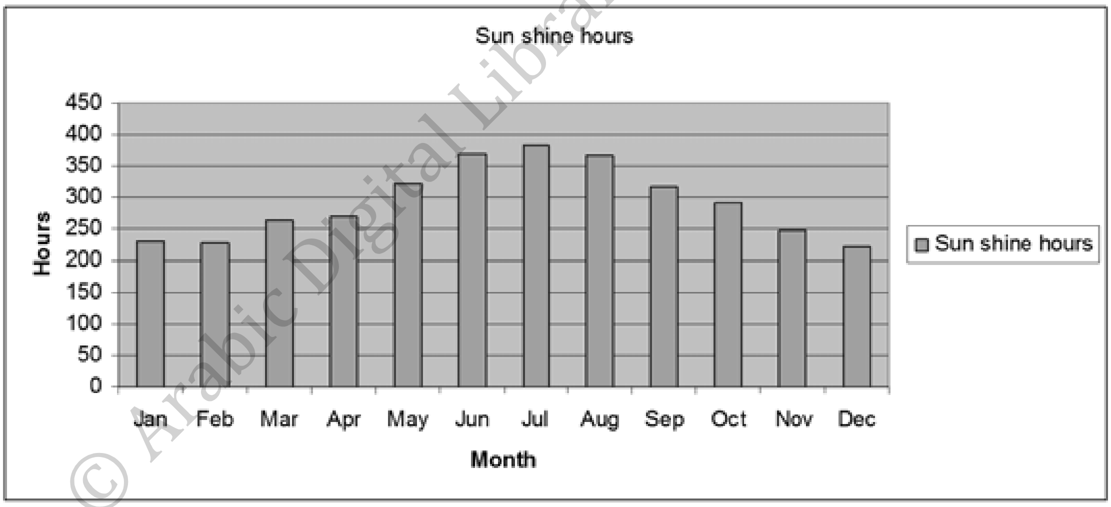



**Figure 1.9: Monthly Sunshine Hours for Ma'an, Jordan**

Hybrid grid connected wind/PV systems minimize the energy that is purchased from the utility grid since the surplus or excess energy will be returned back into the grid. Therefore, batteries are not necessary and not used in our system. Electrical utility in an on-grid renewable system performs the goal of energy storage.

## 1.5 Literature Review

The following literature survey consists of various papers that are related to the hybrid wind/PV renewable system:

G. Halasa and J. A. Asumadu [14] presented a paper about the next generation of power energy systems using solar- and wind-energy systems for the country of Jordan. Sights are chosen to produce electricity using the wind in the Mountains in Northern Jordan and the sun in the Eastern Desert. It is found that the cost of windmill farm to produce 100 - 150 MW is $290 million while solar power station to produce 100 MW costs $560 million. The electrical power costs $0.02/kWh for the wind power and $0.077/kWh for the solar power. The feasibility for using wind and solar energies is justified once the price oil reaches $100.00 per barrel.

T. Markvart [15] presented a paper about sizing of the PV array and wind turbine in a PV/wind energy hybrid system. Using measured values related to solar and wind energy at a given location, the method employs a simple graphical construction to determine the optimum configuration of the two methods that satisfies the energy demand of the user throughout the year.

K. Sopian, A. Fudholi, M. H. Ruslan, M. Y. Sulaiman, M. A. Alghoul, M. Yahya, N. Amin, L. C. Haw and A. Zaharim [16] presented a paper about utilizing a hybrid energy system to supply household demand. This paper describes design, simulation and feasibility study of a hybrid energy system for a household in Malaysia. One year recorded wind speed and solar radiation are used for the design of a hybrid energy system. In 2004 average annual wind speed in Kuala Terengganu is 3 m/s and annual average solar energy resource available is 5.2 kWh/m2/day. In the optimization process, HOMER simulates every system configuration in the search space and displays the feasible ones in a table, sorted by total net present cost (NPC). The optimization study indicates that sensitivity analysis of the HOMER is shown in the overall winner which shows that the most least cost and optimized hybrid system is a combination of the 2 kW PV, 1 units wind turbine with capacity 1 kW, 1 kW converter, and 24 unit batteries.

W.D. Kellogg, M.H. Nehrir, G. Venkataramanan and V. Gerez [17] presented a paper that uses a simple numerical algorithm for generation unit sizing. It has been used to determine the optimum generation capacity and storage needed for a stand-alone, wind, PV, and hybrid wind/PV system for an experimental site in a remote area in Montana with a typical residential load. Generation and storage units for each system are properly sized in order to meet the annual load and minimize the total annual cost to the customer. Moreover, an economic analysis has been performed for the mentioned three scenarios.

M.J. Khan and M.T. Iqbal [57] presented a paper about a pre-feasibility study of using hybrid energy systems with hydrogen as an energy carrier for applications in Newfoundland, Canada. HOMER is used as a sizing and optimization tool. Sensitivity analysis with wind speed data, solar radiation level, diesel price and fuel cell cost was done. A remote house having an energy consumption of 25 kW h/d with a 4.73 kW peak power demand was considered as the stand-alone load. It was found that, a wind–diesel–battery hybrid system is the most suitable solution at present. However, with a reduction of fuel cell cost to 15% of its current value, a wind–fuel cell system would become a superior choice. Validity of such projection and economics against conventional power sources were identified. Sizing, performance and various cost indices were also analyzed in this paper.

E. A. Al-Ammar , N. H. Malik and M. Usman [39] presented a paper about the application of hybrid power systems in Kingdom of Saudi Arabia to a remote village called Al-Qtqt. The simulation of this hybrid power system is done using HOMER software. Five case studies were designed and simulated. HOMER helps to choose the optimal case for the system and the optimal percentage of Minimum Renewable Fraction. It is shown that the optimal case is the solar and grid combination and it represent a system connected to the grid with the addition of using renewable energy.

H. Bludszuweit, J. A. Domínguez and J. L. Bernal [58] presented a paper about A simulation system using Matlab/Simulink® for battery sizing in grid-connected Renewable generation is compared with results from the optimization tool HOMER. The system is intended to reinforce remote weak distribution grids. The battery smoothes the power output and absorbs the prediction errors. As a reference, a wind – battery system is chosen. The impact of the integration of photovoltaic generation is studied. As an example for the meteorological conditions, wind data from the airport and solar irradiation mean values for Zaragoza are applied. Simulated renewable power ranges from 600 kW to 1.1 MW. The battery sizes obtained from the Matlab simulation differ substantially from HOMER results but show similarities. This is due to the difference in the battery models. Integration of solar generation can reduce battery size relative to total installed power and also reduce total cost of generated energy.

G. Liu, M. G. Rasul, M. T. O. Amanullah and M. M. K. Khan [59] presented a paper about environmental, economic analyses and the sustainability of a Hybrid Power Systems (HPS). An investigation is made on small-scale operations of 100kWh per day HPS as a grid-assisted power generation consisting of solar (photovoltaic) and wind energy. To simulate long-term continuous implementation of the HPS, the hourly mean global solar radiation and wind speed data of 2007, from Alice Spring of Australia, are used as an example of a typical hot arid climate. The monthly solar exposure between 13.31 and 21.3 $MJ/m^2/day$ and mean wind speed of 7.13 m/s in 2007 is considered for simulation. HOMER is used for simulation. It is found that, for Alice Spring arid climates, renewable fraction of the optimized system is 54%. It is also found that the HPS has benefits of cost saving. The reduced NPC and COE are only equal to about 85.3% of energy consumption from standard grid. In addition, through a set of sensitivity analysis, it is found that the wind speed has more effects on the environmental and economic performance of a HPS under the specific climate.

## 1.6 Methodology

The first step in planning any renewable energy project is the site assessment, and that is because of the high dependability of the renewable energies (solar and wind in our case) on the location. The site selection decision was carried out after intensive literature review and data collected from the Royal Scientific Society with emphases on sites with high wind speeds and solar radiation which are suitable for hybrid projects. The research resulted in a number of candidate sites for the project implementation and after a thorough evaluation, one of the locations with the best combination of wind and solar energy and enough plain land space suitable for the implementation is in Ras Elnaqab in Ma'an district. In addition it is easily reachable by the electric utility grid.

In this thesis a hybrid wind-photovoltaic power station will be investigated and a simulation model will be built using HOMER simulation program, an economic analysis for 25 years project lifetime is to be performed.

The first step is location selection, the second step is the selection of suitable components. The selection is done by studying the behavior of the wind speed distribution at Ras Elnaqab then the optimal turbine parameters to generate the maximum possible energy is obtained.

The size of the components to be used in the power station is determined by studying the energy demand of the load (Ma'an Substation-maximum demand is approximately 35 MW), and on the renewable energy available from the wind and solar resources. An iterative sizing algorithm with three main constraints namely the cost of energy, the renewable energy fraction of the system and the amount of energy purchased from the grid. By taking into consideration the load demand of Ma'an and the energy output of a single PV panel and Wind turbine under the climate condition of the region and applying the sharing ratio, the optimal number of PV panels and wind turbines will be determined.

To obtain the output of the different components with respect to the demand for a period of 25 years, a system model was built using HOMER, which is used to obtain a detailed study of the electrical behavior and economic feasibility of the hybrid power station.

# CHAPTER TWO

## *CONCEPTS OF HYBRID WIND/PHOTOVOLTAIC SYSTEM*

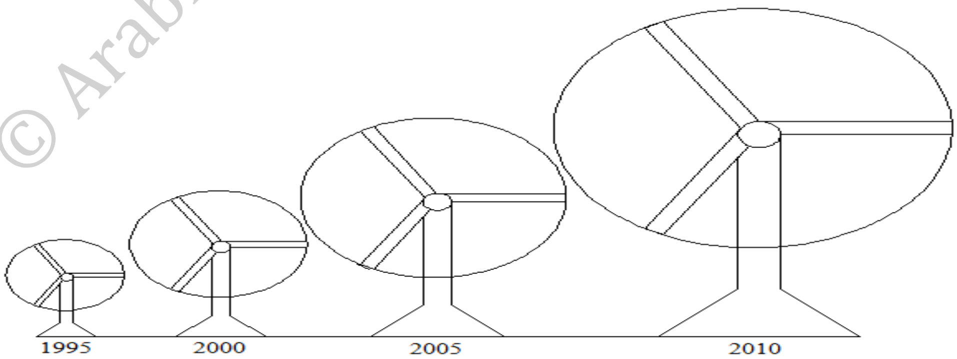
## 2.1 Wind Energy

### 2.1.1 Overview

The first use of wind power in the past was to sail ships in the Nile some 5000 years ago. A large-scale grid connected wind turbine of a 3 MW rated capacity was installed in 1988 at Berger Hill in the United Kingdom. These days, large-scale wind turbines are routinely installed in order to compete the electrical utilities with supplying an economical and clean energy to the customer. Since 1980s the availability of grid connected wind turbines has risen to 95%; the grid connected wind power station can generate electricity at a cost under 0.035JD per KWh, at this price, wind energy has become the least expensive new source of electric power in the world, less expensive than nuclear and fossil fuel plants. Hence, it has become economically attractive to utilities. Referring to Table 1.1, over 190 GW of wind capacity has been installed worldwide at the end of 2010 [3].

### 2.1.2 Wind Turbine

Technology of wind energy has grown rapidly over the last three decades, as a result of increasing rotor diameters and the use of advanced power electronics to allow operation at variable rotor speed (See Figure 2.1).




| | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|
| **Nominal Power (MW)** | 0.6 | 1.5 | 5 | 10 |
| **Rotor Diameter (m)** | 46 | 70 | 115 | 160 |
| **Hub Height (m)** | 78 | 100 | 120 | 178 |

**Figure 2.1: Progress of Wind Turbine**

Since the onset of the wind energy technology, several designs were developed. Based on the axis of rotation; wind turbines are classified into two types; horizontal-axis and vertical-axis turbines. The horizontal-axis wind turbine (HAWT, See Figure 2.2) is the most common used today, its axis of rotation is in parallel to earth surface, these turbines have yaw motors that force the blades to be moved in order to gain higher wind speed and hence higher wind power, another advantages of the HAWT are low cut-in wind speed and a relatively high power coefficient. On the other hand, it shows some disadvantages; the generator and gear box are placed over the tower which makes the design more sophisticated and expensive [18].


**Figure 2.2: Horizontal axis wind turbines**

The vertical axis wind turbine (VAWT, See Figure 2.3) is less popular than the previous type, its axis of rotation is vertical to earth surface, this type is mainly used in locations that have poor wind speed values. Since it receives the wind in any direction, it requires no yaw mechanism. The structure is simple since the gearbox and the electrical generator are placed on the ground. On the other hand, VAWT requires guy wires for support. Thus, many applications will be limited such as the offshore wind farms. Moreover VAWT output power can't be easily controlled in case of high wind speed. As a result, the horizontal-axis wind turbine has higher efficiency than vertical-axis wind turbine [3].

**Figure 2.3: Vertical axis wind turbines [34]**

### 2.1.3 Principle of Wind Turbine operation

Wind turbines are composed of three main conversion levels. It starts with the rotor that converts wind energy into mechanical energy. Then, the generator converts mechanical energy into electrical power, and finally transformer that transfers the electrical power to the grid (See Figure 2.4).

Wind turbines catch the power of the wind through their blades and transform it to rotating mechanical power. Optimal number of blades is three in order to enhance the balance of mechanical loads, the speed of rotation decreases as the radius of the swept area (length of the blade) increases. Under normal conditions, the rotational speed for megawatt turbines ranges between 10 to 15 rpm. To convert this low-speed; gearbox adjusts the low speed produced by the turbine rotor to the high speed of the generator.

By the use of a generator, mechanical energy is then converted into electrical energy fed into a grid. In this stage, a power electronic converter and a transformer with circuit breakers and electricity meters are needed. These days, Turbines are mostly connected to a medium voltage system while large wind farms are connected to high and extra high voltage systems.

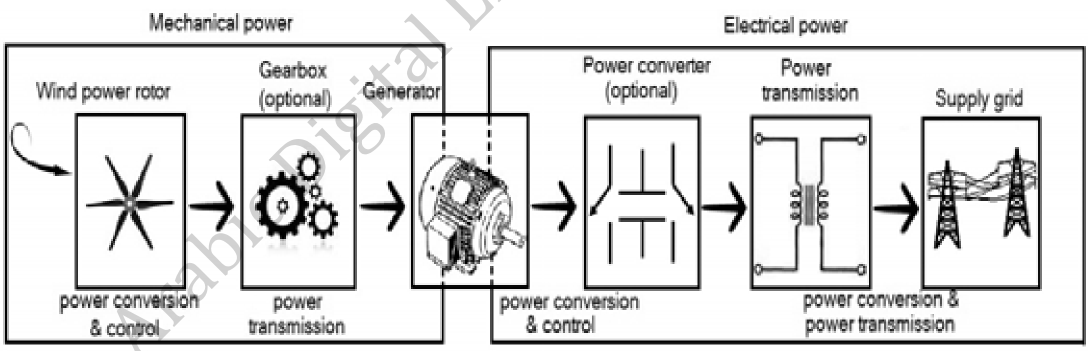



**Figure 2.4: Main components of a wind turbine system [34]**

### 2.1.4 Main Components of Wind Turbine

The main components of a wind turbine which is commercially available (See Figure 2.5 [18]) are:

1. Tower.
2. Rotor.
3. Low speed and high speed shafts.
4. Gear box.
5. Generator.
6. Yaw system.

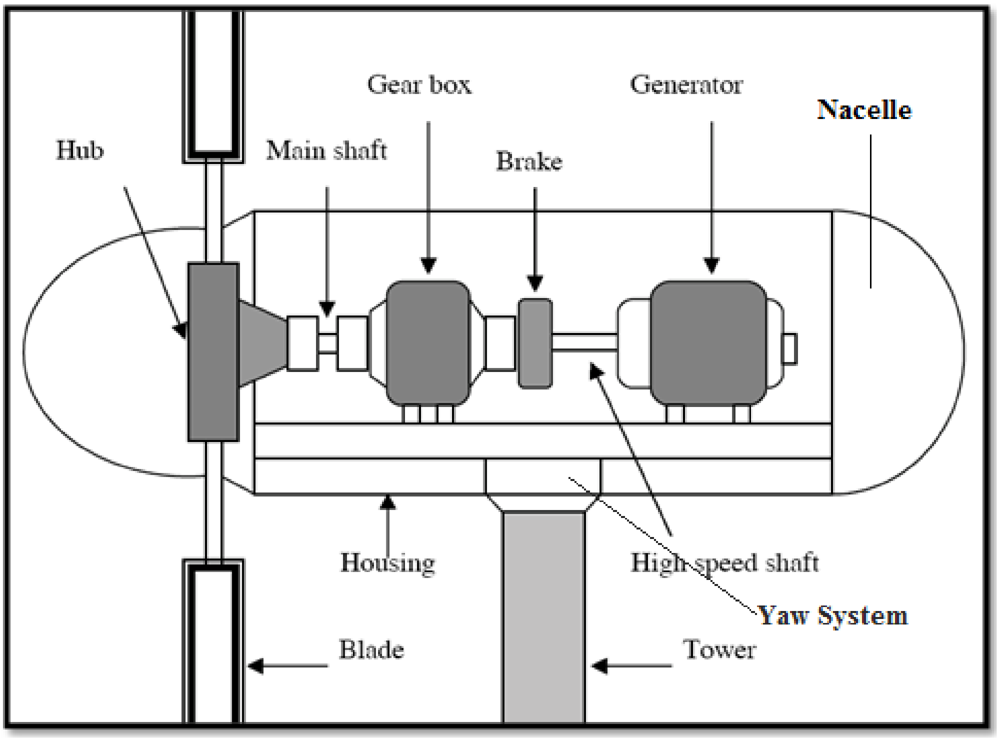



**Figure 2.5: Main Components of Wind Turbine [18]**

### 2.1.4.1 Tower

Tower supports the rotor and places it high enough for the purpose of capturing wind flow, higher the wind turbine tower means higher and steadier wind speed. Therefore, rotor will run faster in order to gain more wind energy. Various types of towers are shown below in Figure 2.6 [18].

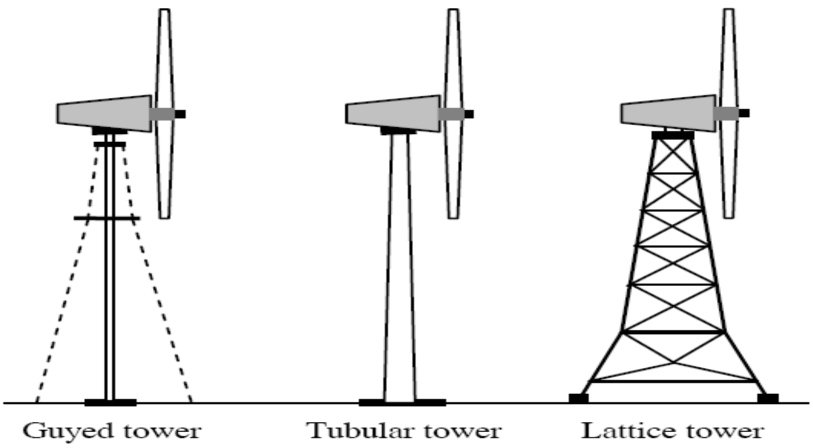



**Figure 2.6: Different types of towers [18]**

### 2.1.4.2 Rotor

Rotor transforms the kinetic energy from wind into mechanical shaft power, its components are blades, hub, shaft and bearing. Most turbine designs feature three designed blades made of fiberglass or plastic [18].

### 2.1.4.3 Low speed and high speed shafts

Low speed shaft is called the main shaft or rotor shaft, it is a rotating component that transfers the torque from the rotor to the gearbox. After that the high speed shaft transfers the torque from the gearbox to the electrical generator.

### 2.1.4.4 Gearbox

Gearbox is an important component in the wind turbine. Since the rotor speed ranges between 30 to 50 rpm while the electrical generator speed ranges between 1000 to 1500 rpm. Therefore, gearbox is used to manipulate the speed in order to fit electrical generator speed.

### 2.1.4.5 Generator

Small-scale wind turbines KW range capacities use DC generator while large-scale wind turbines with MW rated power normally use AC generators. The most common used is the induction generator since it has a burly construction, inexpensive and requires less maintenance.

### 2.1.4.6 Yaw system

The yaw system of the wind turbine rotates the overall nacelle toward the correct direction of wind in order to obtain an optimal wind flow and thus a maximum gained output power. Rotation of the nacelle is done by various electric motors that are activated by receiving signals from anemometer which is an instrument for measuring wind speed.

### 2.1.4.7 Drive Train

A complete wind turbine drive train consists of all the rotating components: rotor, main shaft, gearbox, mechanical brakes and generator.

### 2.1.5 Power in wind

The first law of Thermodynamics states that neither matter nor energy could be created or destroyed, this is because the amount of energy is constant in the universe but it can be changed from one form to another. Wind turbine converts some of the kinetic energy that is contained in the air into mechanical and then into electrical energy. The power of wind is given by equation 2.3.

$$P = \frac{1}{2}\rho A V^3 \tag{2-3}$$

Where: $P$ = Power of wind in $KW$.

$\rho$ = Air density in $Kg/m^3$= 1.225 $Kg/m^3$ for dry air at sea level.

$V$ = Wind speed in $m/s$.

$A$ = Swept or rotor area in $m^2$=$\pi l^2$.

Where: $l$ = radius of swept area or length of the blade in $m$ (See Figure 2.7).

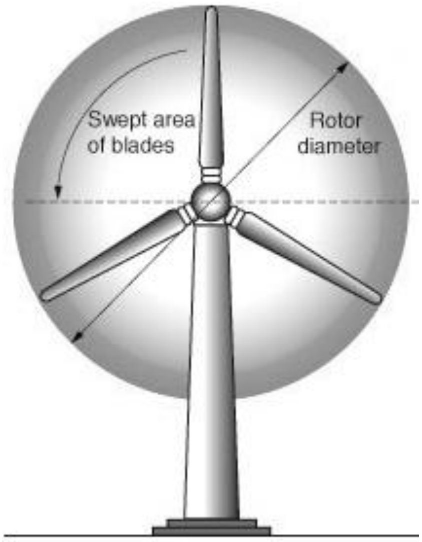



**Figure 2.7: Swept Area [34]**

### 2.1.6 Power from wind turbine

In 1962 Albert Betz, a German physicist, established the upper limit for the energy that can be captured from wind to be $\frac{16}{27}$ or 59.26% [3]. In practice, the power coefficient is less than the Betz limit. In addition, the mechanical and electrical efficiencies throughout the wind turbine should be considered. The power coefficient $C_P$

and actual output power that is extracted from wind turbine are given by the following equations [3]:

$$P = C_P \eta \frac{1}{2} \rho A V^3 \tag{2-4}$$

$$C_P = \frac{\left(1-\left(\frac{Vo}{V}\right)^2\right)\left(1+\left(\frac{Vo}{V}\right)\right)}{2} \tag{2-5}$$

Where:

$\eta$ = The wind turbine mechanical and electrical efficiencies.

$V$ = Upstream wind speed at the blade's entrance.

$V_o$ = Downstream wind speed at the blade's exit.

From equation (2-5), the value of the power coefficient depends on the ratio of $\frac{Vo}{V}$ the plot of power coefficient $C_P$ versus the ratio of downstream to upstream wind speed $\frac{Vo}{V}$ is shown in Figure 2.8. Note that, power coefficient $C_P$ has a maximum value at 0.59 when $\frac{Vo}{V} = \frac{1}{3}$.

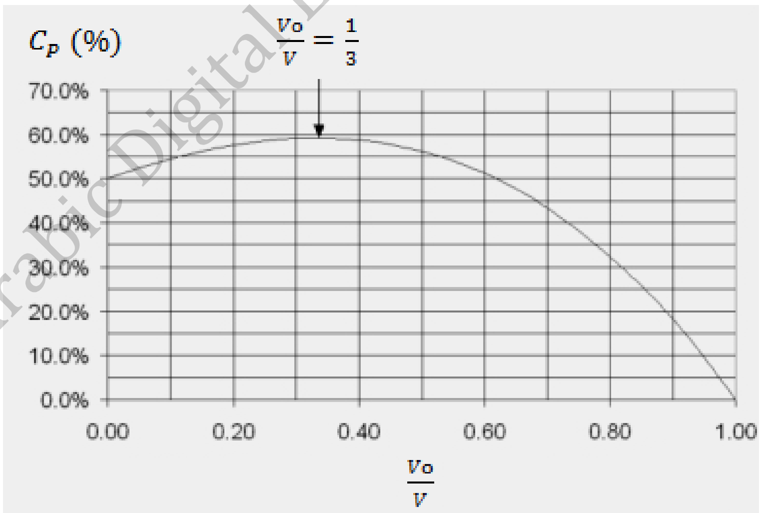



**Figure 2.8: Power coefficient $C_P$ versus $\frac{Vo}{V}$**

The maximum power that can be extracted from wind turbine referring to equation (2-4) is expressed by equation (2-6):

$$P = 0.59 \eta \frac{1}{2} \rho A V^3 \tag{2-6}$$

### 2.1.7 Wind turbine characteristic

Regarding the wind turbine characteristic, Figure 2.9 below shows the wind turbine output power variation with steady wind speed:

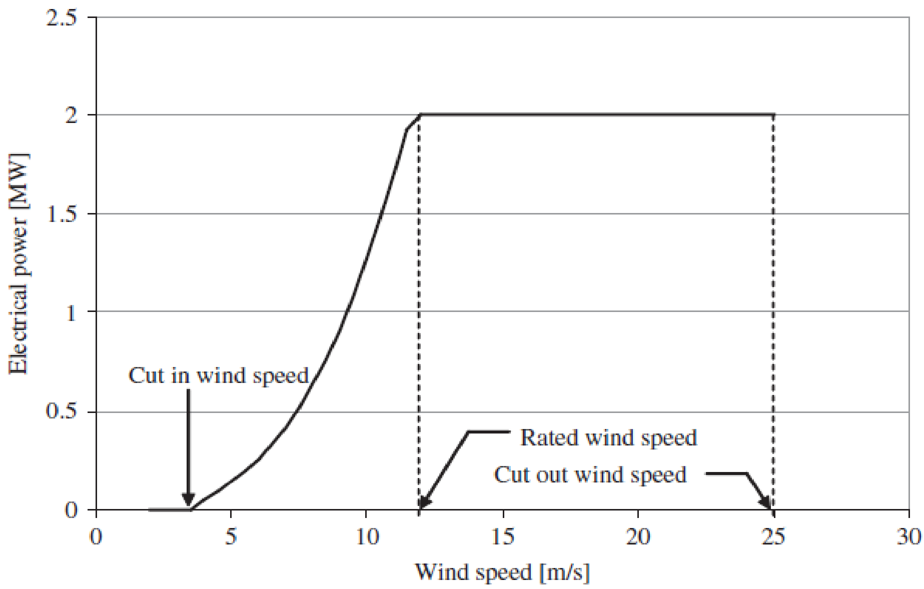



**Figure 2.9: Wind turbine characteristics**

From the wind turbine characteristics that is shown in Figure 2.9, as the wind speed increases the output power of the wind turbine start to increase at the cut-in value, this direct relationship continues until reaching the rated value of wind speed and output power. After that, a constant relationship appears; as the wind speed increases above the rated value the output power is unaffected, at the cut-out speed value there is a risk to damage the rotor. Thus, a braking system is employed to standstill the rotor.

As a result, the wind turbine converts the kinetic wind energy into mechanical power to rotate the rotor and generate electricity.

### 2.1.8 Relationship between wind speed and height

The relationship between wind speed and height is called wind profile or wind gradient, this relationship depends on the roughness of the terrain. As a result, wind speed increases with height upon a certain level. Moreover, this relationship is represented by two laws. Firstly, Logarithmic law; if the wind speed in meters per seconds is available at height $Z$ in meter and the roughness $Z_o$ that is normally measured in centimeters, then the speed at height $Z_R$ is given by equation (2-7) [18].

$$V(Z_R) = V(Z)\frac{\ln\left(\frac{Z_R}{Z_O}\right)}{\ln\left(\frac{Z}{Z_O}\right)} \qquad (2\text{-}7)$$

Secondly, Power law; if the wind speed $S_o$ that is measured by anemometer at height $H_o$, then the speed at wind turbine hub height $H$ (See Figure 2.10) [17] is:

$$S = S_o\left(\frac{H}{H_o}\right)^{\alpha} \qquad (2\text{-}8)$$

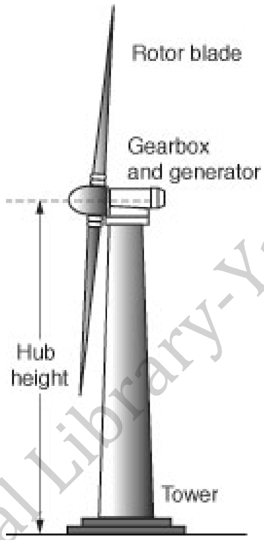



**Figure 2.10: Hub Height [34]**

The exponent $\alpha$ is a measure of the surface friction and it has an experimental accepted value of 0.13 [17].

### 2.1.9 Pitch regulated and Stall regulated wind energy conversion systems

Turbines are designed to withstand stormy wind speeds. However, there is a range of wind speeds before the cut-out wind speed where turbines use different types of control strategies in order to deal with high wind speeds that cause a risk to the turbine. These control strategies are classified into pitch- regulated and stall-regulated (See Figure 2.11).

Pitch-regulated wind energy conversion System has an active control system which change the pitch angle (turn the blade around its axis) in order to decrease the rotational speed in variable-speed turbines. Pitch-regulated control is usually used for high wind speeds only (above the rated speed), when high rotational speeds and aerodynamic torques can destroy turbine. As wind speeds exceed rated value, the blades will pitch for the purpose of slowing down the turbine's rotational speed or the torque transferred to the shaft. As a result, the speed or the torque is kept at safe below threshold value. Pitch regulated turbines behave to increase power until the rated wind speed. After that, the power is unaffected until a cut–out speed when the braking system is activated.

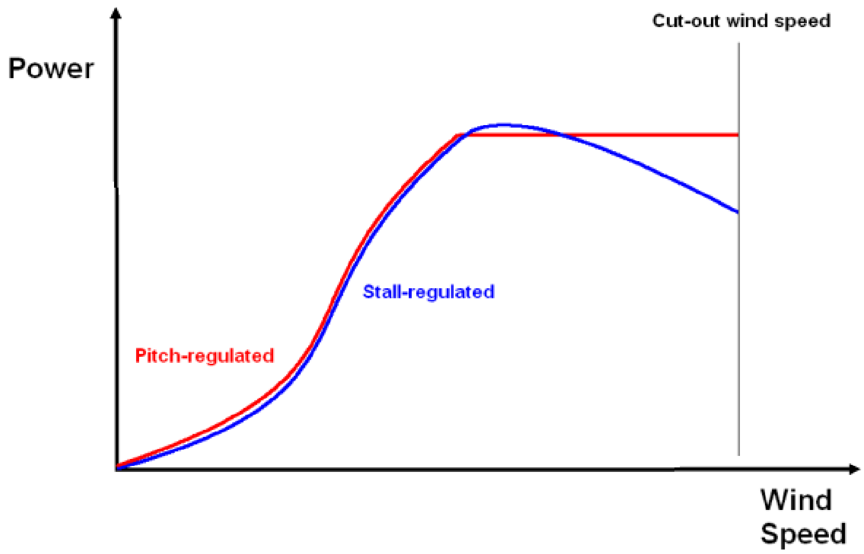



**Figure 2.11: Pitch regulated vs. stall regulated**

Stall-regulated wind energy conversion system design its blades so that the power production decreases with increasing wind speed above a certain value which is usually not equal the rated value of wind speed (See Figure 2.11). This is because the aerodynamic effects on the turbine blades (regions of the blade are stalled, propagating from the hub and outwards with increasing the wind speed). On the negative side, The blades design perform worse in high wind speeds in order to protect the wind turbine. Moreover, stall-regulation is preferred compared with pitch-regulation in case of capital cost of the turbine as well as lower maintenance associated with more moving parts.

In conclusion, stall-regulated systems depends on the blades to control the torque or the rotational speed of the turbine in high wind speeds, whereas the pitch-regulated systems have an active pitch control for the blades. This allows the pitch-regulated systems to have a constant power output above the rated wind speed, while the stall-regulated systems are not able to keep a constant power output in high winds.

## 2.2 Power Electronics

Circuits of power electronics are used as rectifiers that convert AC into DC. In addition they are used as inverters that convert DC into AC. Moreover, power electronic circuits are used to control both voltage and frequency [3].

Power electronic circuit that is shown in Figure 2.12 is used to convert both variable frequency and variable voltage into fixed 50Hz output voltage for the purpose of matching the utility requirements. This process is very important since wind turbines operate at variable speed for maximum energy production. This is because, the output frequency and voltage of the induction generator change with wind speed.

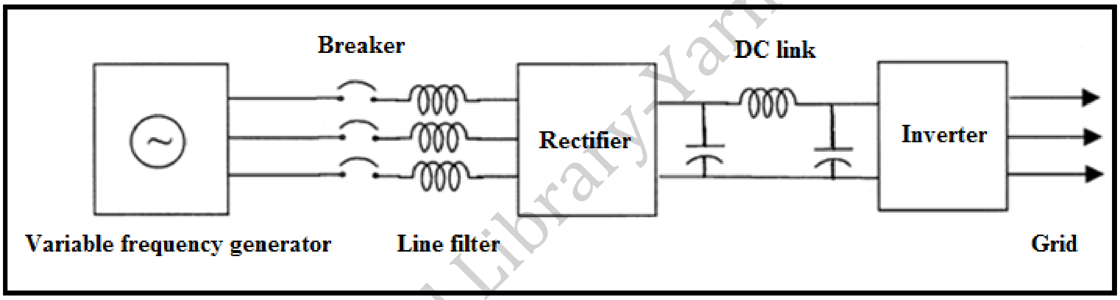



**Figure 2.12: Variable speed and constant frequency wind power system [3]**

The hybrid wind/photovoltaic system includes both inverter and rectifier power electronic circuits in order to convert the current from DC to AC and AC to DC respectively.

### 2.2.1 Rectifier

The common type of the AC to DC rectifiers is three phase fully controlled bridge rectifier with a resistive load (See Figure 2.13). The average DC output voltage is given by [20]:

$$V_{DC} = 1.35V_L \cos\alpha \qquad (2\text{-}9)$$

Where: $V_L$= Three phase line to line AC source voltage.

$\alpha$=Thyristor firing delay angle.

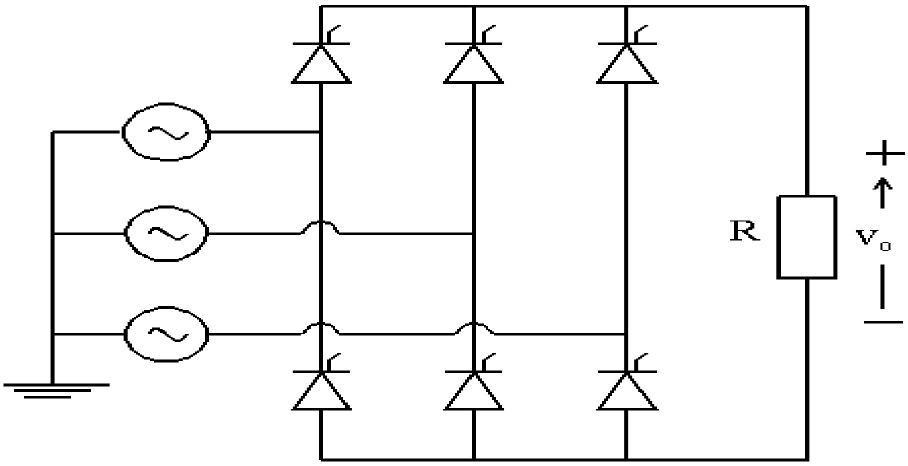



**Figure 2.13: Three phase fully controlled bridge rectifier**



### 2.2.2 Inverter

In a hybrid wind/photovoltaic renewable system inverters are used to convert the DC current that is generated by photovoltaic arrays into AC current to match the grid requirements. DC to three phase AC inverter is used for variable frequency drive applications and for high power applications. A basic three-phase inverter consists of three single phase inverter switches each connected to one of the three load terminals (See Figure 2.14). The 50 Hz fundamental frequency phase-to-neutral rms voltage is given by [3]:

$$V_{ph} = 0.7797 V_{DC} \quad (2\text{-}10)$$

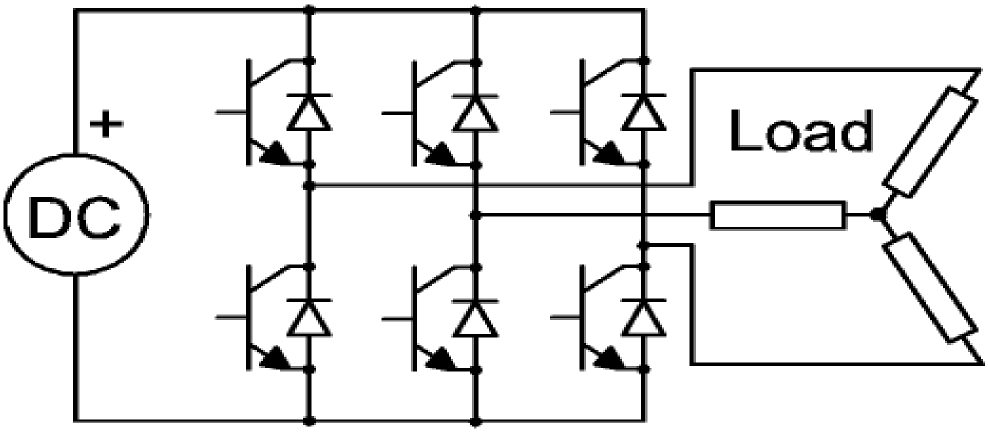



**Figure 2.14: Three phase inverter**

## 2.3 Photovoltaic Energy

### 2.3.1 Overview

The photovoltaic system can be classified into standalone and grid connected systems. In standalone systems the generated power is transferred to the load but if there is an excess generated power; a storage system is needed such as batteries. If there are more than two power sources such as PV modules and wind turbines known as hybrid wind/PV renewable system. Note that, in the grid connected system the grid performs as a storage system. Photovoltaic power results from the direct conversion of solar insolation into electricity.

### 2.3.2 PV cell

Photovoltaic cell is the basis of PV arrays that is composed from a semi conducting material such as: monocrystalline silicon, polycrystalline silicon, amorphous silicon and others, these materials are used depending on their efficiencies.

The cost per KWh in photovoltaic energy depends on two factors. First, the photovoltaic energy conversion efficiency. Second, the capital cost per watt. The conversion efficiency of the PV cell is given by [3]:

$$\eta = \frac{\textbf{Electrical Output Power}}{\textbf{Solar Power impinging the cell}} \tag{2-11}$$

Regarding semi-conducting materials, polycrystalline has lower conversion efficiency than monocrystalline but its cost is much lower this will reduce the cost per watt for the polycrystalline [3]. As a result, the polycrystalline photovoltaic cell (See Figure 2.15) is the candidate to be used in our hybrid wind/PV system.

**Figure 2.15: Polycrystalline PV Cell [34]**

### 2.3.3 Module and array

Photovoltaic array is composed from various modules; each module contains a number of photovoltaic cells. Area of the PV cell is in the range of square inch and generates (1 Watt) of power [3]. In order to gain more power from PV panels (with area is about square feet) and PV arrays are used (See Figure 2.16).

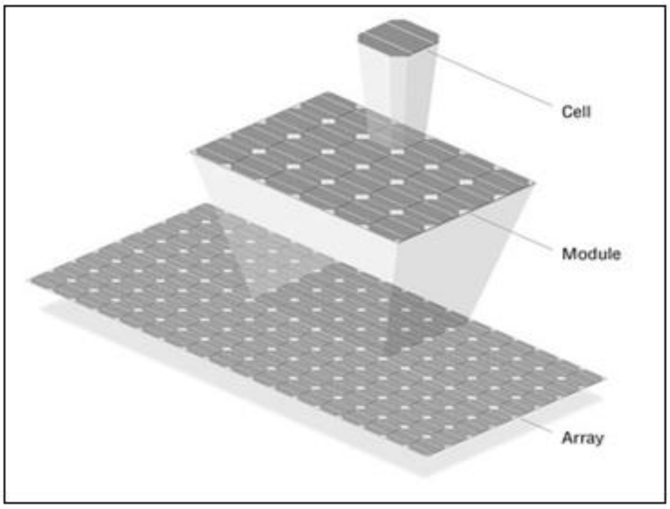



**Figure 2.16: Cell, Module and Array [34]**

### 2.3.4 PV Module Equivalent Circuit

The equivalent circuit of the PV cell is configurated by the electrical circuit shown in Figure 2.17.

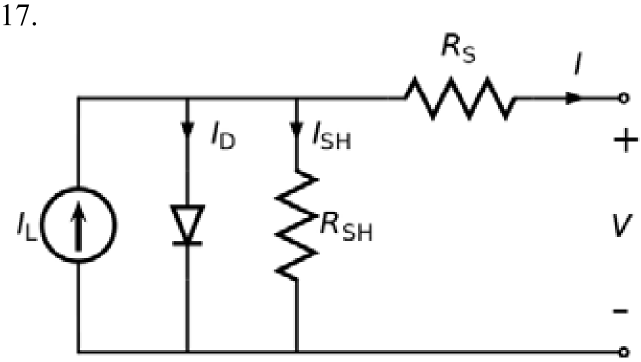



**Figure 2.17: Equivalent circuit of PV module**

Using Kirchhoff's Current Law (KCL) that is "The algebraic sum of all the currents at any node in a circuit equals zero [23]". Therefore, the output current $\boldsymbol{I}$ *is* equal to the light-generated current source $\boldsymbol{I_L}$ minus the summation of both diode current $\boldsymbol{I_D}$ and the shunt-leakage current $\boldsymbol{I_{SH}}$. The series resistance $\boldsymbol{R_s}$ represents the internal resistance. The shunt resistance $\boldsymbol{R_{SH}}$ is inversely related to the leakage current to ground.

An ideal PV cell has both $\boldsymbol{R_s}$ = 0 and $\boldsymbol{R_{SH}}$ =∞, this means that there is no series loss and no leakage to ground respectively [3]. The series resistance $\boldsymbol{R_s}$ value ranges between 0.05 to 0.10 Ω. In addition, the shunt resistance $\boldsymbol{R_{SH}}$ ranges between 200 to 300 Ω. Note that, PV conversion efficiency is sensitive to small variations of $\boldsymbol{R_s}$ but it is insensitive to the variations of $\boldsymbol{R_{SH}}$. Referring to Ohm's Law, As $\boldsymbol{R_s}$ increases the PV output current decreases noticeably [3].

With respect to the equivalent circuit, the current delivered to the external load equals:

$$I = I_L - (I_D + I_{SH}) \quad (2\text{-}12)$$

The open-circuit voltage $V_{oc}$ of the cell is obtained when the load current is zero ($I$ = 0) and is given by:

$$V_{oc} = I_{SH} \times R_{SH} \quad (2\text{-}13)$$

The diode current is given by the classical diode current expression:

$$I_D = I_o\left[e^{\frac{QVoc}{AKT}} - 1\right] \quad (2\text{-}14)$$

Where:

$\boldsymbol{I_o}$ = The saturation current of the diode.
$\boldsymbol{Q}$ = Electron charge =$1.6 \times 10^{-19}\, C$.
$\boldsymbol{A}$ = Curve-fitting constant.
$\boldsymbol{K}$ = Boltzmann constant =$1.38 \times 10^{-23}\, J/K$.
$\boldsymbol{T}$ = Temperature in Kelvin $K$.

The full expression for the load current is given by:

$$I = I_L - I_o\left[e^{\frac{QVoc}{AKT}} - 1\right] - \frac{V_{OC}}{R_{SH}} \quad (2\text{-}15)$$

In practical cells, the shunt current$\left(\frac{V_{OC}}{R_{SH}}\right)$ is negligible compared to the values of $I_L$ and $I_D$ and is generally ignored.

### 2.3.5 Short Circuit Current $I_{SC}$ & Open Circuit Voltage $V_{OC}$

There are two substantial values that describe the photovoltaic cell performance; these are Short Circuit Current (SCC) $I_{SC}$ and Open Circuit Voltage (OCV) $V_{OC}$. However, at these two operating points, the power from the solar cell is zero.

The SCC is measured by shorting the output terminal. Since the small value of series resistance $\boldsymbol{R_s}$, both shunt and diode branches are ignored and thus their currents are ignored. As a result, the Short Circuit Current (SCC) $I_{SC}$ is equivalent to the photocurrent $I_L$.

The OCV is measured by opening the output terminal. This means that the output current is zero ($I$=0). Referring to equation (2-13) the open circuit voltage is given by:

$$\boldsymbol{V_{oc} = (I_L - I_D) \times R_{SH}} \qquad (2\text{-}16)$$

### 2.3.6 The $\boldsymbol{I - V}$ and $\boldsymbol{P - V}$ characteristics

Regarding the photovoltaic characteristic, Figure 2.18 shows the PV output current and power variation with voltage, the power generated by the PV device depends on the load that varies from zero ohm at short circuit current to infinity ohm at open circuit current.

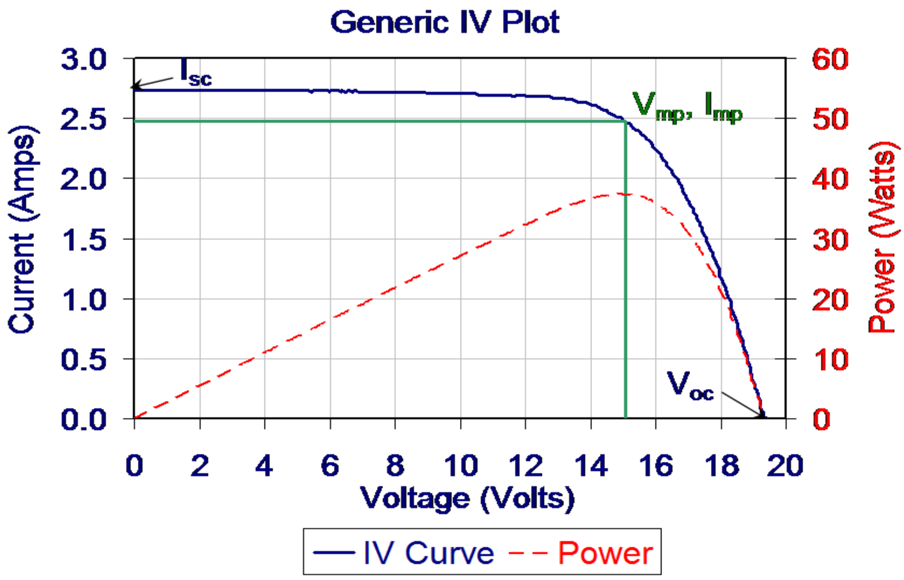



**Figure 2.18: Photovoltaic characteristic**

Maximum power in Figure 2.18 is the multiplication result of $V_{mp}$ and $I_{mp}$ (Voltage and Current at point of maximum power). To gain more power two techniques are available. Firstly, PV arrays are connected in series, thus, more voltage is achieved and as a result, higher power is obtained. Secondly, PV arrays are connected in parallel, thus, more current is achieved and as a result, higher power is obtained [24].

The load on the circuit determines the voltage and current. Depending on the position on the IV curve, an increase in load can increase or decrease the power output by the solar cells. Doubling the number of cells will generally increase the power, but the power increase will depend on the current and voltage dictated by the load. Modern inverters contain max power point trackers that adjust the perceived load to operate the facility at maximum possible output. A photovoltaic system connected to the utility grid contains an inverter that changes direct current and voltage from the solar array to alternating current that is available on the utility grid.

#### 2.3.6.1 The Fill Factor (FF)

The Fill Factor determines the maximum power from a solar cell. It is defined as the ratio of the maximum power to the product of $V_{OC}$ and $I_{SC}$. Graphically and referring to Figure 2.18, the FF is the ratio of the rectangular area ($A$) with parameters $V_{mp}$ and $I_{mp}$ to the rectangular area ($B$) with parameters $V_{OC}$ and $I_{SC}$.

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{I_{max} \times V_{max}}{V_{oc} \times I_{sc}} \qquad (2\text{-}17)$$

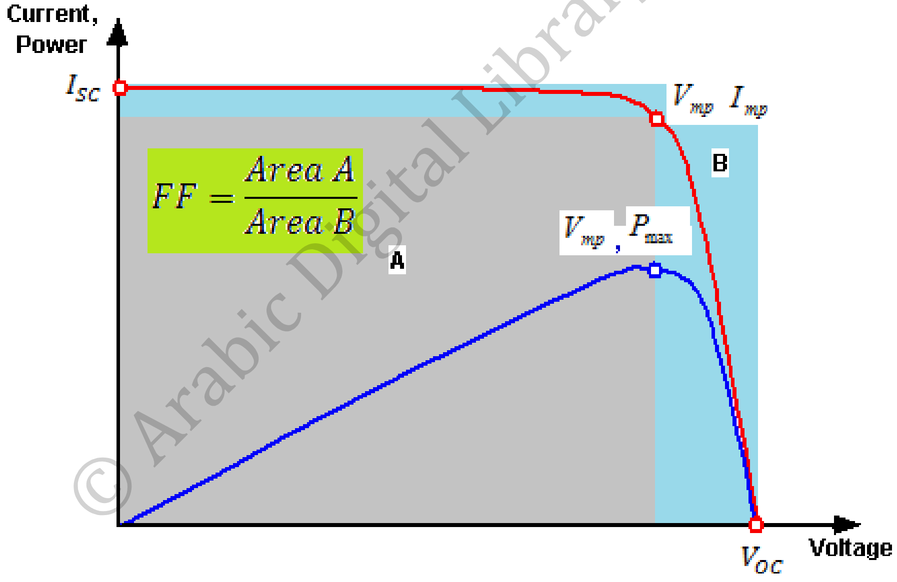



**Figure 2.19: Fill Factor (FF)**

### 2.3.6.2 Efficiency (η)

The efficiency is an important parameter to compare one solar cell with another. Equation (2-11) implies that efficiency is the ratio of the output power from the solar cell to the input power from the sun. The maximum power is:

$$P_{max} = FF \times V_{oc} \times I_{sc} \qquad (2\text{-}18)$$

Obviously, the higher efficiency η of the solar cell, the higher the output power is gained under a given illumination.

$$\eta = \frac{FF \times V_{oc} \times I_{sc}}{P_{in}} \quad (2\text{-}19)$$

Efficiencies for different types of semi-conducting materials are described in descending order as shown in the table below [19].

**Table 2.1: Efficiencies of various types of semi-conducting materials**

| Semi-Conducting Material | Efficiency |
|---|---|
| **Monocrystalline Solar Cells** | **18-24%** |
| **Polycrystalline Solar Cells** | **14-17%** |
| **Amorphous Silicon Solar Cells** | **Around 10%** |



### 2.3.7 Horizontal Coordinate System

The Horizontal Coordinate System (HCS, See Figure 2.20) partitions the sky into two parts. First, upper visible hemisphere, its pole is called Zenith. Second, lower invisible hemisphere, its pole is called Nadir [25].

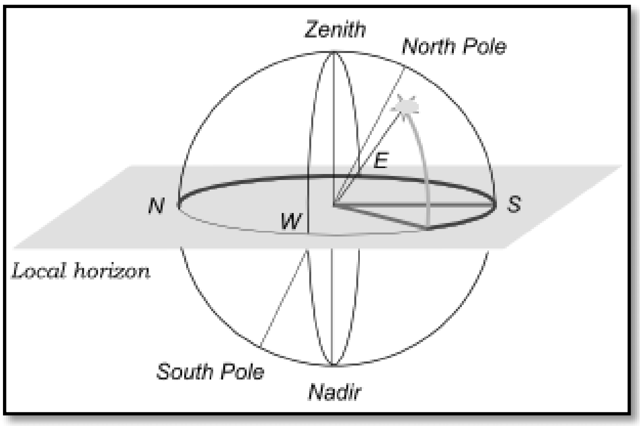



**Figure 2.20: The Horizontal Coordinate System [25]**

The Sun-Earth angles (See Figure 2.21) that are used to determine the Sun position with respect to the observer's location, these are [26]:

1) **Altitude Angle ($\alpha$):** It is sometimes called elevation, it is the angle between the sun and the observer's local horizon. Elevation angle ranges between 0 to 90°. In

addition, solar altitude angle is the angle between the rays of the Sun and the horizontal plane under consideration.

2) **Azimuth Angle ($\gamma_{sun}$):** It is the angle of the sun around the horizon, usually measured from the north. It is the angle between the north direction and the projection of the Sun rays.

3) **Zenith Angle ($\theta_z$):** It is sometimes used instead of altitude in some calculations. The zenith angle is the complement of altitude angle. Moreover, the zenith angle is the angle of the Sun's ray away from the zenith direction.

$$Zenith\ Angle = 90° - Altitude\ Angle \quad (2\text{-}20)$$

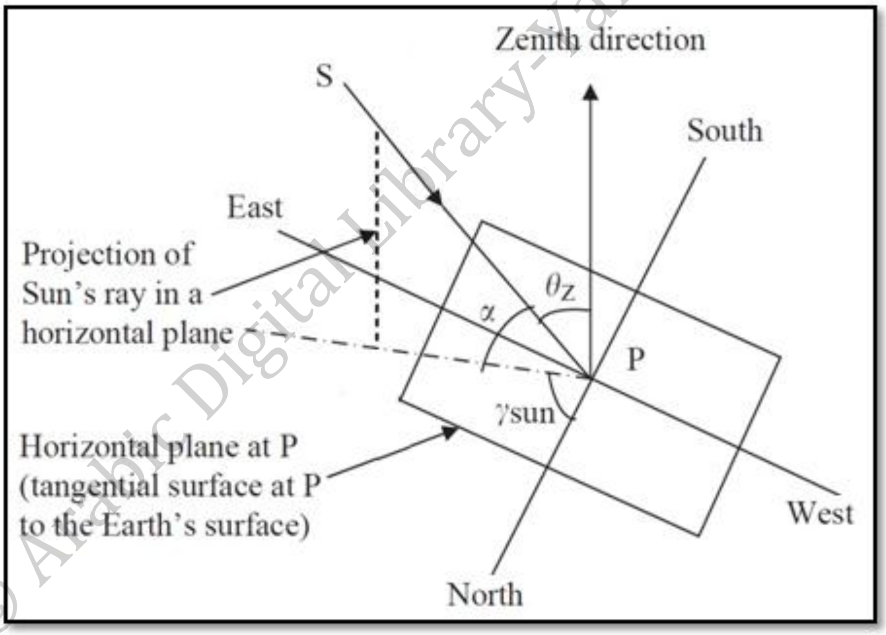



**Figure 2.21: Altitude, Azimuth and solar Zenith angles**

## 2.4 Hybrid Wind/PV System

The hybrid wind-photovoltaic renewable energy system combines the features of two individual systems. Therefore, such systems present lower cost and higher reliability that will balance out the fluctuations in the generated energy. In general, hybrid wind-photovoltaic systems can be classified into two types [33].

Firstly, standalone or off-grid system that is isolated from the utility grid. Moreover, main uses of this type are to electrify remote areas where the connection to the grid is expensive. In some locations, extending a 138 KV transmission line to the electric grid will cost approximately 390,000 $ per mile (170,000 JD per km) [55].

Secondly, grid connected or on-grid system (See Figure 2.22) that is connected to the utility grid. It allows the continuity of supplying the load even if the sun is not shining or the wind is not blowing or when the hybrid wind/PV system cannot provide enough power. In addition, excess generated renewable energy could be sold to the grid. Note that, on-grid systems eliminate the need for storages or batteries, this will reduce the hybrid system components' costs.

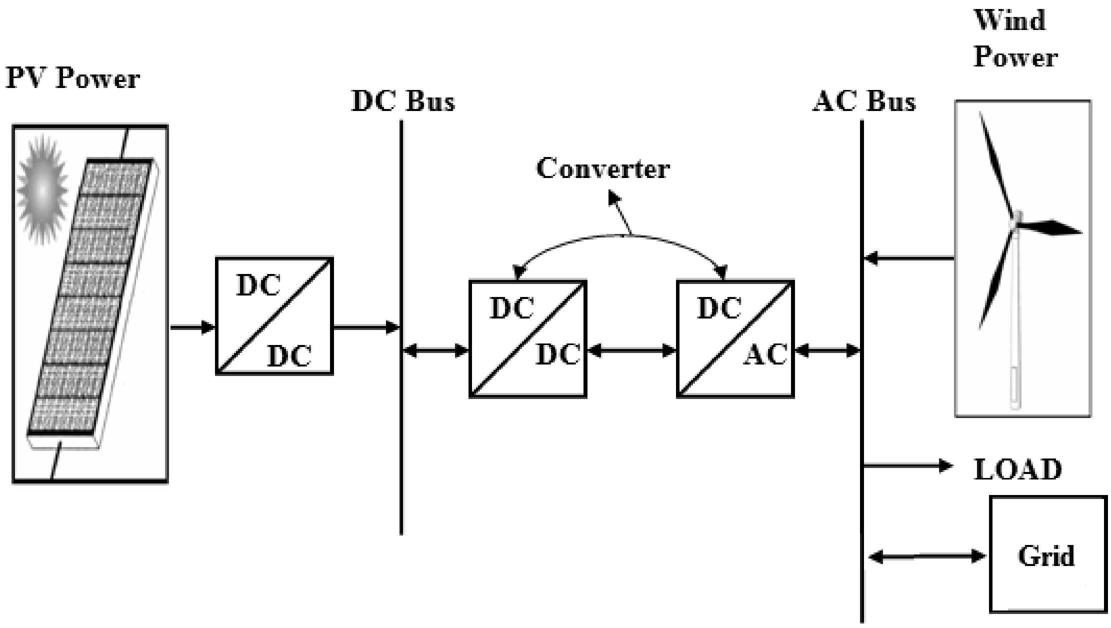



**Figure 2.22: Gird Connected Hybrid Wind/PV system**

# CHAPTER THREE

## *OPTIMAL LOCATION OF HYBRID WIND/PV SYSTEM IN JORDAN*

### 3.1 Overview

The Hashemite Kingdom of Jordan is located in the heart of the Middle East, north of Saudi Arabia, south of Syria, east of Palestine and west of Iraq [27]. Jordan occupies an area of about $89000 km^2$. In July 2007, the Jordanian population number is estimated to be $six\ millions$. Its geographical coordinates range between $(29^o - 34^o)$N to $(35^o - 39^o)$E. Jordan combines both Mediterranean and arid (dry) desert climates. In general, Jordan has warm, dry summer and mild, wet winter [28].

The site selection is a substantial step in renewable energy projects. The effectiveness of renewable energy systems for power generation depends greatly on the renewable energy resources in the location where renewable components are to be installed. Values such as wind speed, wind continuity, solar radiation and solar annual hours are functions of time. Therefore, gaining an optimal location for a hybrid wind-photovoltaic system is a vital decision.

The final decision for the proposed site can be carried out after collecting wind speed data and solar insolation data for various candidate sites in Jordan from formal organizations such as Jordanian Royal Scientific Society and National Center for Research and Development. After that, an intensive survey is done on the data in order to find the most appropriate location for a Hybrid Wind-Photovoltaic system in Jordan.

### 3.2 Solar Energy in Jordan

Jordan is blessed with the abundance of solar energy resources. Moreover, it has an optimum global solar irradiation and it has one of the highest radiation values worldwide [29], the annual daily average solar irradiance ranges between 4-7 $kWh/m^2/day$. The average sunshine duration is more than 300 days per year. The average numbers of clear days (days without any obstacles that prevent the illumination to reach the earth) and average number of hours of sunshine in Jordan are shown in Table 3.1 [13].

**Table 3.1: The average values of clear days and hours of sunshine**

| Month | Average No. of clear days | Average No. of hours of sunshine |
|---|---|---|
| **January** | 20 | 232 |
| **February** | 22 | 260 |
| **March** | 24 | 296 |
| **April** | 25 | 275 |
| **May** | 25 | 348 |
| **June** | 30 | 405 |
| **July** | 31 | 380 |
| **August** | 31 | 390 |
| **September** | 29 | 334 |
| **October** | 25 | 280 |
| **November** | 26 | 264 |
| **December** | 22 | 233 |

According to the solar atlas of Jordan, the country is divided into five regions (see Figure 3.1 and Table 3.2), the approximate global average solar irradiation is given for each area inside the five regions:

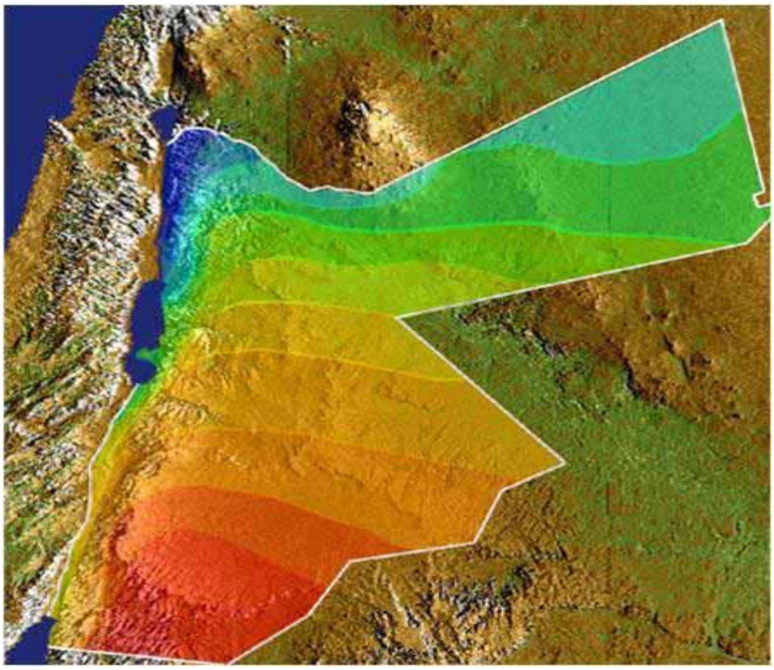


**Figure 3.1: Five regions according to the Jordanian solar Atlas**

Table 3.2: The approximate global average insolation for Jordanian areas inside five regions

| Region | Area | Global Average insolation |
|---|---|---|
| **1.The Southern Region** | Ma'an & Aqaba | Highest solar isolation in the country. The annual average daily global irradiance is between 6-7 $kWh/m^2/day$ |
| **2.The Eastern Region** | Desert & The Badia or remote area | An annual daily between 5.5-6 $kWh/m^2/day$ |
| **3.The Middle Region** | Middle Areas | An average global irradiance is between 4.5 – 5 $kWh/m^2/day$. |
| **4.The Northern Region** | Northern Areas | The annual daily global irradiance is about 5.5 $kWh/m^2/day$. |
| **5.The Western Region** | Jordan Valley area & Situations below sea level | An average annual daily global irradiance is around 4.5 $kWh/m^2/day$. |

Solar energy is one of the environmentally sustainable resources for producing electricity using photovoltaic systems. The main input data used in the planning process is solar radiation. The monthly average solar irradiation data are obtained from Photovoltaic Geographical Information System (PVGIS) which provides a map-based inventory of solar energy resource and assessment of the electricity generation from photovoltaic systems in various continents such as: Europe, Africa, and Asia [31].

Monthly and Annul average solar insolation in $kWh/m^2/day$ for various candidate sites in Jordan are obtained using PVGIS (See Table 3.3 and Figure 3.2) that is used by the energy center which is located in the Royal Scientific Society.

Table 3.3: Average solar insolation in $kWh/m^2/day$ for candidate sites in Jordan

| Site / Month | Jafer | Ma'an | Batn Elghoul | Ras Elnaqab | Swaqa |
|---|---|---|---|---|---|
| **January** | 3.45 | 3.37 | 3.52 | 3.50 | 2.81 |
| **February** | 4.39 | 4.31 | 4.48 | 4.44 | 3.74 |
| **March** | 5.53 | 5.48 | 5.63 | 5.71 | 5.04 |
| **April** | 6.43 | 6.44 | 6.56 | 6.74 | 6.10 |
| **May** | 7.06 | 7.11 | 7.11 | 7.42 | 7.03 |
| **June** | 8.30 | 8.21 | 8.23 | 8.57 | 8.09 |
| **July** | 8.02 | 7.92 | 7.93 | 8.26 | 7.85 |
| **August** | 7.32 | 7.18 | 7.23 | 7.51 | 7.12 |
| **September** | 6.32 | 6.25 | 6.26 | 6.57 | 6.01 |
| **October** | 4.92 | 4.86 | 4.98 | 5.12 | 4.52 |
| **November** | 3.71 | 3.65 | 3.80 | 3.84 | 3.28 |
| **December** | 3.29 | 3.23 | 3.37 | 3.40 | 2.71 |
| **Yearly Average** | 5.73 | 5.67 | 5.76 | 5.93 | 5.37 |

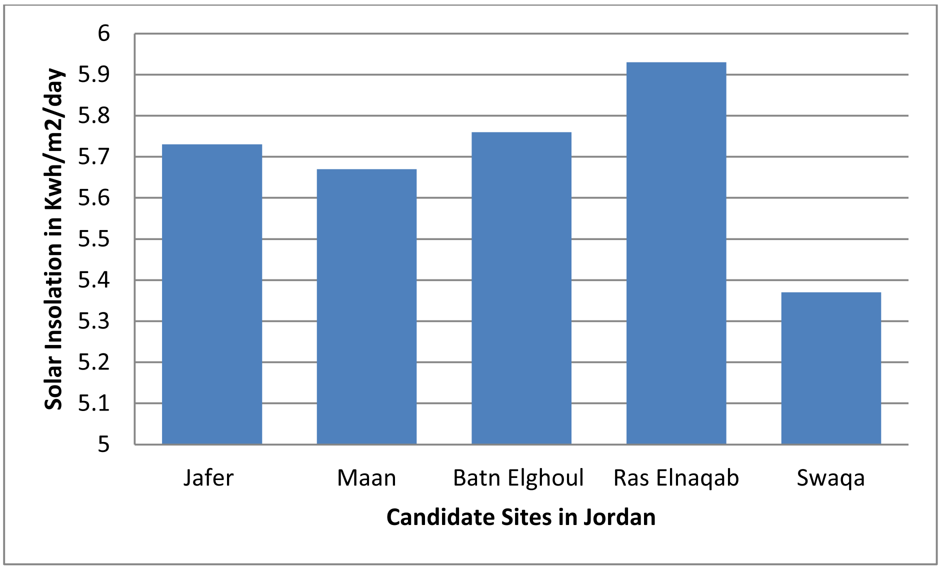



**Figure 3.2: Annual Average Solar Insolation in $kWh/m^2/day$ for Candidate Sites in Jordan**

As a result, Ras Elnaqab which is located in the southern region of Jordan has the highest average annual solar irradiation (5.93 $kWh/m^2/day$) between other candidate sites in the country. Therefore, Ras Elnaqab is recommended for solar energy renewable projects.

## 3.3 Wind Energy in Jordan

Jordan has high potential of wind energy resources where there are optimum values of average annual wind speed in many locations across the country. The long term climate data are available at the Ministry of Energy and Mineral Resources (MEMR). In addition, other formal organizations such as: Jordan Meteorological Department (JMD) and Royal Scientific Society (RSS) have experimental measurements necessary for evaluating wind energy potential as a prime mover to electrical power generation in Jordan [30].

The wind map for Jordan using the contour technique is used in order to determine the average wind speed level through various regions across the country (See Figure 3.3) [32].

The average annual wind speed for different candidate sites in Jordan is shown in Figure 3.4 for the year of 2011, these data are obtained from both institutions: RSS and NCRD. Referring to Table 1.2 in chapter one, different locations in Jordan have higher average wind speed values that result in a *Good to very good* and *Exceptional* values.

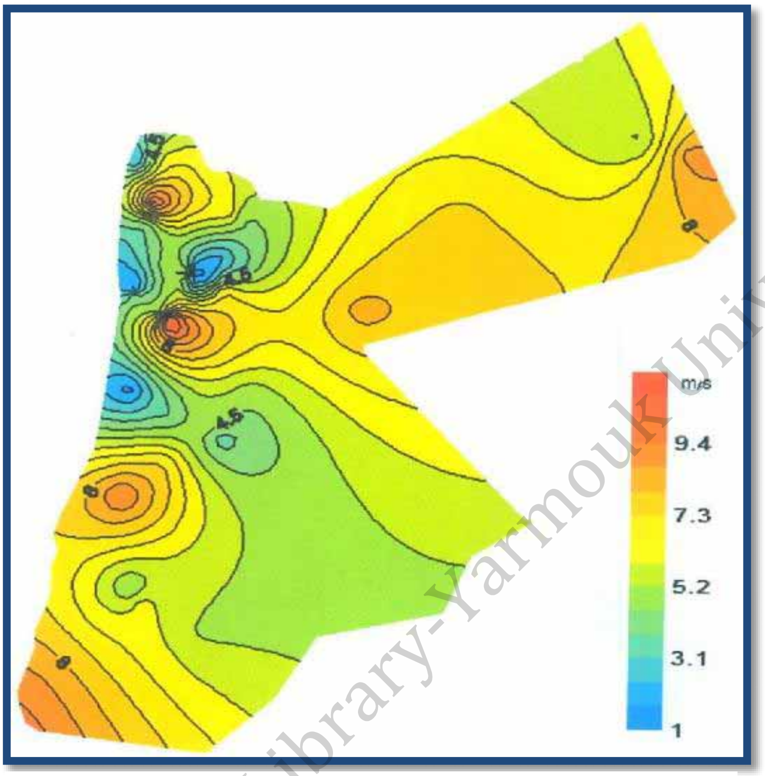



**Figure 3.3: Jordanian Wind Map using the Contour Technique**

Monthly and annul average wind speed in $m/s$ for various candidate sites in Jordan are available (See Figure 3.2 and Table 3.4) from actual measurements done by the Energy Centre which is located in the RSS.

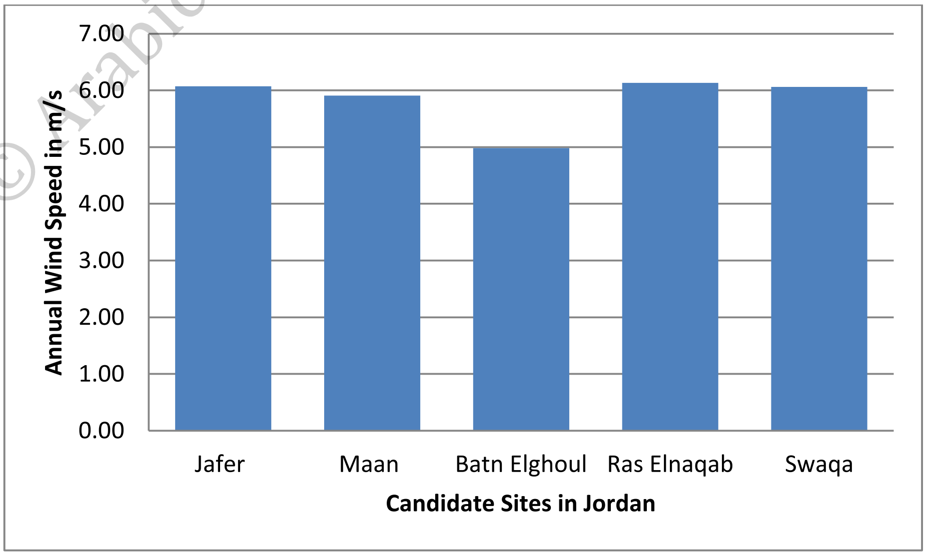



**Figure 3.4: Annual Average Wind Speed for Candidate Sites in Jordan**

Table 3.4: Average wind speed in m/s for candidate sites in Jordan

| Site / Month | Jafer | Ma'an | Batn Elghoul | Ras Elnaqab | Swaqa |
|---|---|---|---|---|---|
| **January** | 5.37 | 4.95 | 4.54 | 6.10 | 6.46 |
| **February** | 6.28 | 7.27 | 5.99 | 7.51 | 6.55 |
| **March** | 5.69 | 5.69 | 5.32 | 6.76 | 5.81 |
| **April** | 6.16 | 6.26 | 5.82 | 6.62 | 5.56 |
| **May** | 6.64 | 6.64 | 5.83 | 6.68 | 5.95 |
| **June** | 7.44 | 7.07 | 5.42 | 6.79 | 7.11 |
| **July** | 6.97 | 6.88 | 5.10 | 5.89 | 6.26 |
| **August** | 7.27 | 5.91 | 4.46 | 5.37 | 6.77 |
| **September** | 6.32 | 5.49 | 4.81 | 5.31 | 5.46 |
| **October** | 5.52 | 5.01 | 4.57 | 4.84 | 4.95 |
| **November** | 4.37 | 4.38 | 4.25 | 5.37 | 5.24 |
| **December** | 4.82 | 5.33 | 3.68 | 6.34 | 6.60 |
| **Year** | 6.07 | 5.91 | 4.98 | 6.13 | 6.06 |

As a result, Table 3.4 shows that Ras Elnaqab which is located in Ma'an District has the highest average annual wind speed (6.13 $m/s$) between other candidate sites in the country. Therefore, Ras Elnaqab is recommended for renewable projects wind energy.

## 3.4 The selected site of a Hybrid Wind/PV system in Jordan

Referring to data collected from formal organizations in Jordan such as RSS and NCRD, Ras Elnaqab has the highest average values of both annual wind speed (6.13 $m/s$) and solar insolation (5.93 $kWh/m^2/day$). Therefore, Ras Elnaqab combines optimum potential for both wind and photo-voltaic energies. As a result, Ras Elnaqab is an appropriate and excellent choice for the proposed hybrid wind-photovoltaic renewable energy system in Jordan.

Ras Elnaqab (See Figure 3.5) is located far south of Jordan on the desert road between Ma'an and Aqaba districts, its coordinates are (E 35.451139°, N 30.043250°).

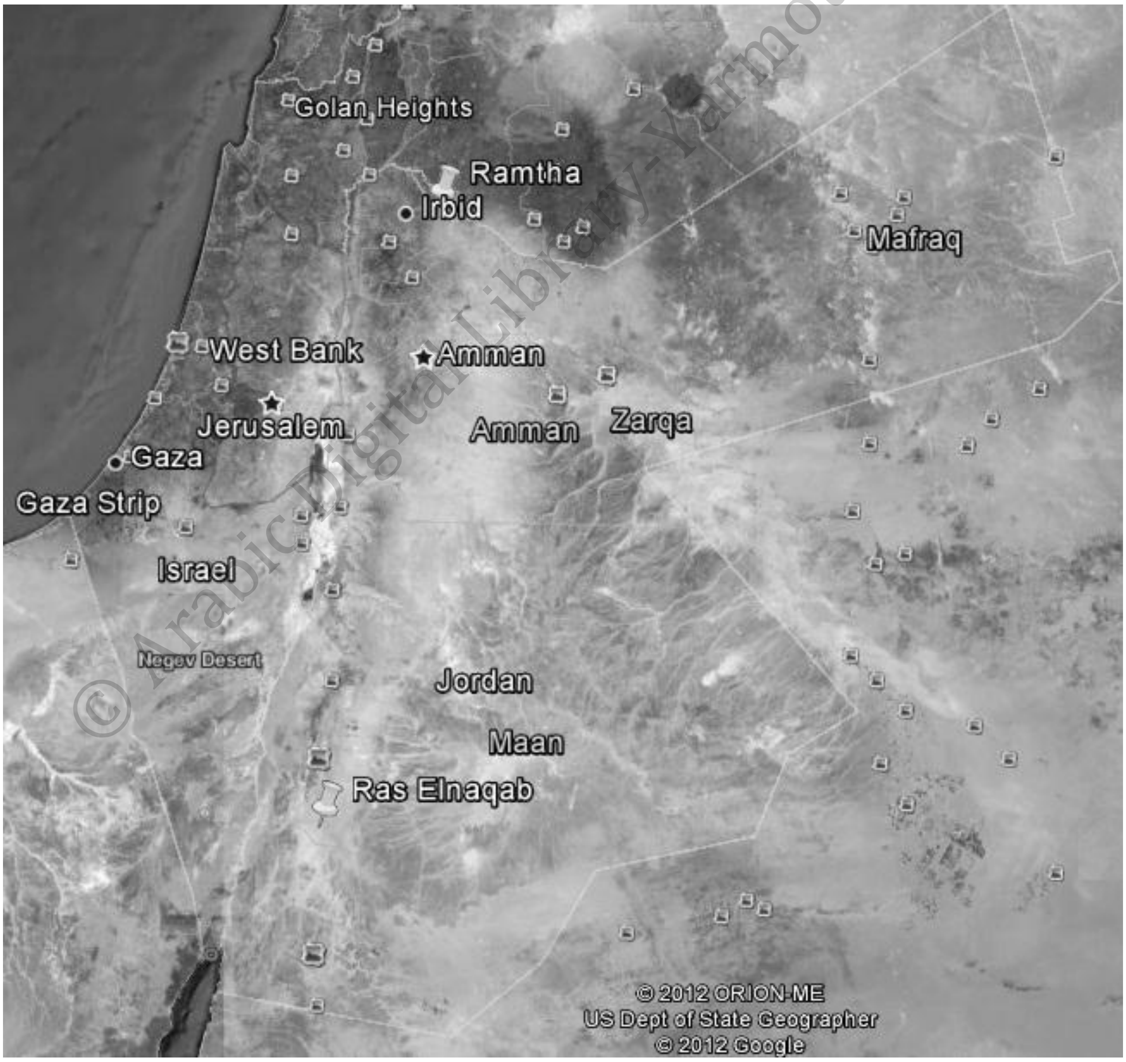



**Figure 3.5: Ras Elnaqab in Jordan**

Google Earth software provides the ability to obtain altitude of Ras Elnaqab above sea level, which is approximately (1600 m, See Figure 3.6). Moreover, Google Maps depict project actual location in Ras Elnaqab (See Figure 3.7).


**Figure 3.6: Altitude of Ras Elnaqab**


**Figure 3.7: Project Actual location in Ras Elnaqab**

## 3.5 Potential of Wind/PV energies in Ras Elnaqab

Figure 3.4 shows that Ras Elnaqab has the highest annual wind speed value (6.13 $m/s$) between other candidate sites. Monthly average wind speeds in Ras Elnaqab for the year of 2011 are shown in Figure 3.8 [34].

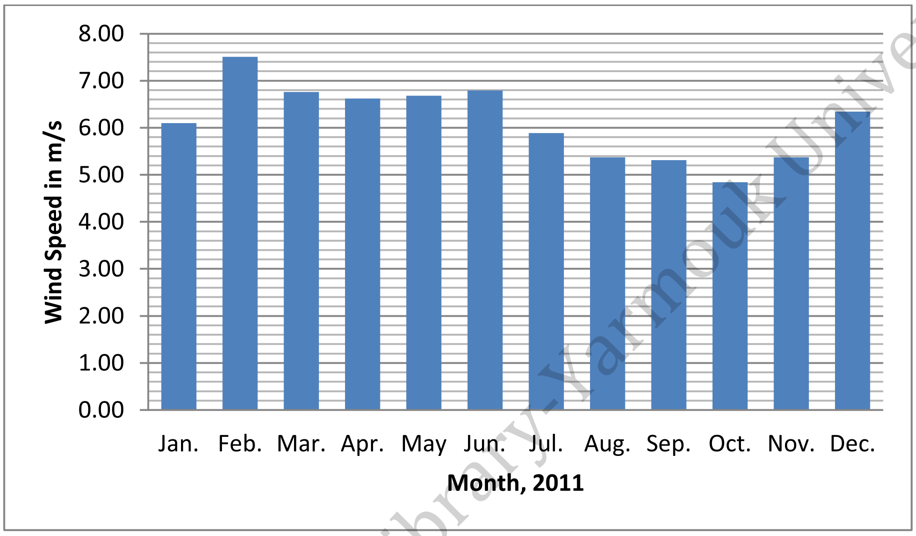



**Figure 3.8: Monthly Average wind speeds for Ras Elnaqab**

Regarding to PV energy, Figure 3.2 shows that Ras Elnaqab has the highest annual solar irradiation value (5.93 $kWh/m^2/day$) between other candidate sites. Monthly average solar insolation in Ras Elnaqab is shown in Figure 3.9 [31].

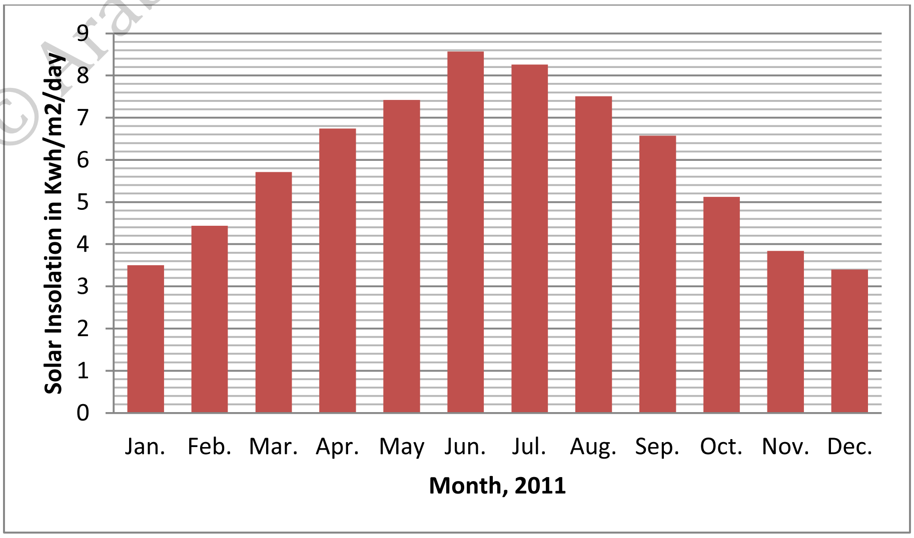



**Figure 3.9: Monthly Average Solar insolation for Ras Elnaqab**

In conclusion, these results lead to a strong recommendation to apply hybrid wind/photo-voltaic renewable energy projects in Ras Elnaqab located in Ma'an, Jordan.

## 3.6 Load Profile

Instantaneous demand, variations during the day, is represented in a load profile. Load profile can be drawn at any level of aggregation like representing a statistical in a given month [37].

Obtaining the load demand is an essential point in most renewable energy projects and it is used to size components of the Hybrid Wind/PV system. Moreover, load characteristic is critically important to the system optimization [35].

Load profile for Ma'an substation is obtained from the National Control Center (NCC) of the National Electric Power Company (NEPCO) which is responsible for power transmission in Jordan. These load data is obtained using SCADA system every 60 min (hourly data) for every day for the whole year of 2011. The number of entries is counted using Microsoft Excel 2007 to be 8760 entry as expected which equals the number of hours in a year.

After that, hourly load data are analyzed and averaged using EXCEL 2007. The hourly load average demands for all 2011 months are shown in Table 3.6.

The average hourly load data in Table 3.6 were inserted to the hybrid optimization model for electric renewable (HOMER). HOMER summarizes these data and shows main load characteristics Table 3.5.

**Table 3.5: Ma'an substation Load profile characteristics.**

| | |
|---|---|
| **Average ( MWh/day )** | 563.477 |
| **Average (MW)** | 23.478 |
| **Peak (MW)** | 38.222 |
| **Load Factor** | 0.614 |

Load Factor is defined as the ratio of the average to peak demand. It gives an indication to which peak the load is maintained during the period under study. Moreover, high load factor means the load is at peak most of the time [36]. Therefore, 61.4% of Ma’an substation demands is around the peak value.

**Table 3.6: Monthly Average Load in MW for Ma'an Substation**

| Hour \ Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **00:00-01:00** | 23.58 | 21.47 | 21.93 | 19.38 | 19.88 | 21.13 | 23.59 | 25.29 | 21.23 | 18.15 | 19.56 | 21.14 |
| **00:01-02:00** | 22.42 | 19.44 | 20.13 | 18.30 | 18.80 | 20.05 | 22.80 | 24.21 | 20.35 | 17.33 | 18.53 | 19.95 |
| **00:02-03:00** | 21.85 | 18.28 | 19.07 | 17.68 | 18.18 | 19.43 | 22.34 | 23.39 | 19.72 | 16.86 | 17.88 | 19.34 |
| **00:03-04:00** | 21.51 | 17.62 | 18.59 | 17.67 | 18.17 | 19.42 | 22.22 | 23.13 | 19.33 | 16.71 | 18.49 | 19.65 |
| **00:04-05:00** | 21.58 | 17.71 | 19.11 | 16.53 | 17.03 | 18.28 | 21.51 | 21.45 | 19.58 | 17.08 | 19.58 | 21.65 |
| **00:05-06:00** | 22.59 | 19.36 | 19.67 | 15.16 | 15.66 | 16.91 | 20.21 | 18.33 | 18.76 | 17.36 | 19.52 | 22.32 |
| **00:06-07:00** | 22.90 | 19.59 | 19.94 | 16.80 | 17.30 | 18.55 | 21.01 | 18.07 | 19.10 | 18.36 | 21.94 | 24.49 |
| **00:07-08:00** | 23.31 | 21.14 | 23.04 | 19.14 | 19.64 | 20.89 | 22.74 | 19.25 | 21.36 | 20.47 | 23.41 | 26.15 |
| **00:08-09:00** | 24.58 | 23.03 | 24.66 | 20.58 | 21.08 | 22.33 | 23.89 | 20.81 | 22.75 | 21.55 | 24.60 | 27.54 |
| **00:09-10:00** | 25.78 | 24.40 | 25.61 | 21.21 | 21.71 | 22.96 | 24.38 | 22.24 | 23.53 | 21.84 | 24.98 | 28.37 |
| **00:10-11:00** | 26.42 | 25.23 | 25.87 | 21.81 | 22.31 | 23.56 | 24.94 | 23.07 | 24.10 | 22.14 | 25.43 | 28.65 |
| **00:11-12:00** | 26.43 | 25.75 | 25.78 | 21.89 | 22.39 | 23.64 | 25.22 | 23.55 | 24.28 | 21.95 | 25.16 | 28.61 |
| **00:12-13:00** | 26.81 | 25.99 | 25.56 | 21.67 | 22.17 | 23.42 | 25.20 | 24.02 | 23.97 | 21.71 | 24.86 | 28.24 |
| **00:13-14:00** | 26.55 | 25.85 | 25.32 | 21.40 | 21.90 | 23.15 | 25.07 | 23.82 | 23.74 | 21.73 | 25.15 | 28.75 |
| **00:14-15:00** | 26.34 | 25.67 | 25.49 | 20.86 | 21.36 | 22.61 | 24.82 | 23.58 | 23.34 | 21.58 | 25.55 | 28.80 |
| **00:15-16:00** | 26.26 | 25.63 | 25.37 | 20.77 | 21.27 | 22.52 | 24.72 | 23.64 | 22.97 | 21.20 | 27.26 | 30.70 |
| **00:16-17:00** | 26.27 | 25.59 | 24.93 | 20.72 | 21.22 | 22.47 | 24.58 | 23.85 | 22.85 | 21.51 | 31.76 | 35.05 |
| **00:17-18:00** | 28.76 | 28.66 | 26.38 | 20.21 | 20.71 | 21.96 | 24.30 | 23.45 | 23.95 | 25.04 | 31.68 | 34.75 |
| **00:18-19:00** | 29.54 | 31.77 | 31.10 | 21.09 | 21.59 | 22.84 | 24.56 | 24.99 | 28.05 | 26.41 | 30.59 | 33.70 |
| **00:19-20:00** | 28.90 | 30.83 | 31.15 | 25.87 | 26.37 | 27.62 | 27.68 | 28.13 | 28.36 | 25.56 | 29.82 | 32.80 |
| **00:20-21:00** | 28.40 | 29.85 | 30.15 | 25.99 | 26.49 | 27.74 | 27.86 | 29.01 | 27.34 | 24.63 | 28.59 | 31.39 |
| **00:21-22:00** | 27.73 | 28.82 | 28.98 | 24.92 | 25.42 | 26.67 | 27.20 | 28.38 | 26.28 | 23.09 | 26.52 | 28.88 |
| **00:22-23:00** | 26.61 | 27.01 | 26.98 | 23.12 | 23.62 | 24.87 | 26.21 | 27.56 | 24.57 | 21.11 | 23.88 | 25.81 |
| **00:23-00:00** | 25.13 | 24.28 | 24.41 | 20.99 | 21.49 | 22.74 | 24.84 | 26.65 | 22.74 | 19.39 | 21.29 | 23.05 |

## 3.7 Load curves

### 3.7.1 Monthly averages load curve.

The monthly average load curve represents the average load and load variation during months of year. This curve indicates the behavior of the load in each month; five main values are calculated by HOMER for each month (See Figure 3.10).

- **Max demand:** Maximum demand represents the maximum value of the load consumption in kW through the whole month.
- **Min demand:** Minimum demand represents the minimum value of the load consumption in kW through the whole month.
- **Daily high:** Maximum average daily hourly demand that occurs during the whole month period.
- **Daily low:** Minimum average daily hourly demand that occurs during the whole month period.
- **Mean:** Average daily load consumption for all the month period.

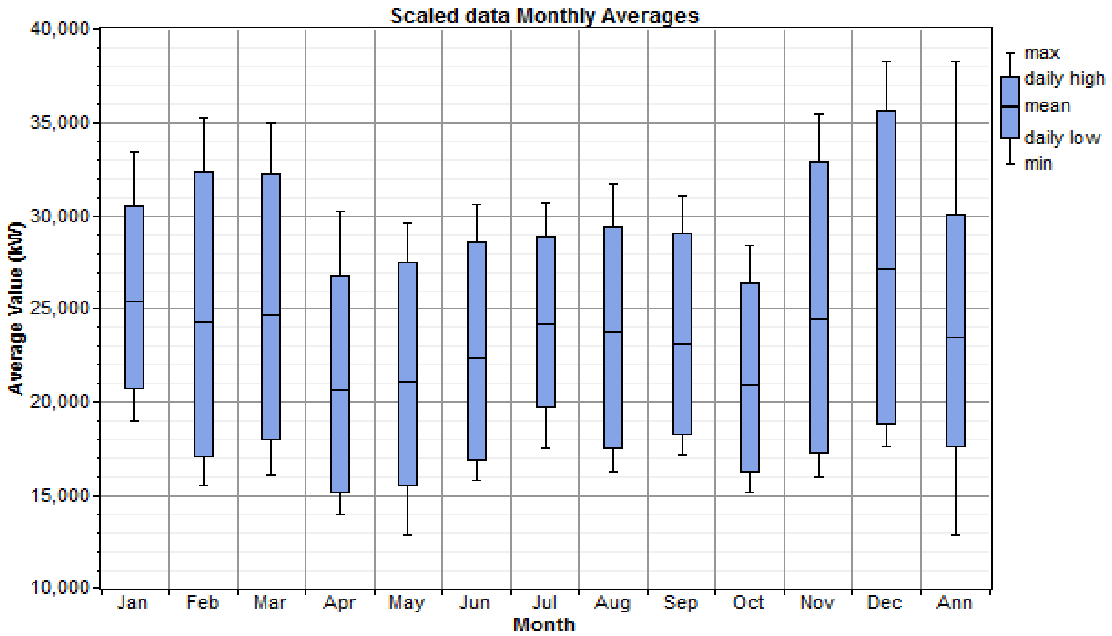



**Figure 3.10: Monthly load averages for Ma'an substation**

### 3.7.2 Daily Load Profile Data

It represents each month with a single day that contains the hourly load average from data in Table 3.6. The points of interests are: the peak demand, the hour of peak demand. The daily load average curve gives details about the load demand during 24 hours a day and gives us an indication in order to compare between different days of the year. Figure 3.11 shows monthly load profile curve for all months of 2011 year for Ma'an substation.

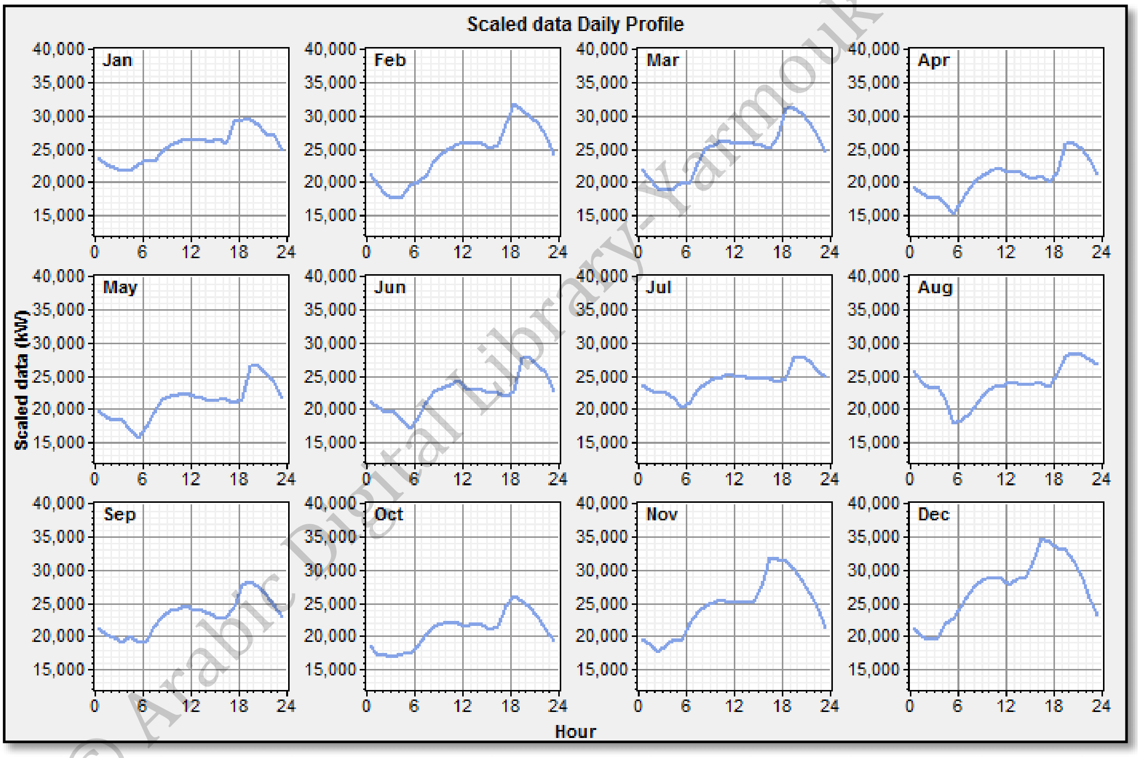



**Figure 3.11: Daily Load Profile for 2011 year in Ma'an.**

### 3.7.3 Load duration curve

Another way to represent the load profile is a load duration curve (See Figure 3.12). The load duration curve depicts instantaneous demand in 8760 hours. It sorts the demands in descending order according to the demand in each hour. Therefore, the highest demand hour of the year appears to be the first hour, followed by the second highest demand hour which may occur in a different day, and so on. Usually, night hours appear at the low-demand on the right-hand side of the load duration curve [37]. Figure 3.12 shows the load duration curve for Ma'an substation that is made using HOMER.

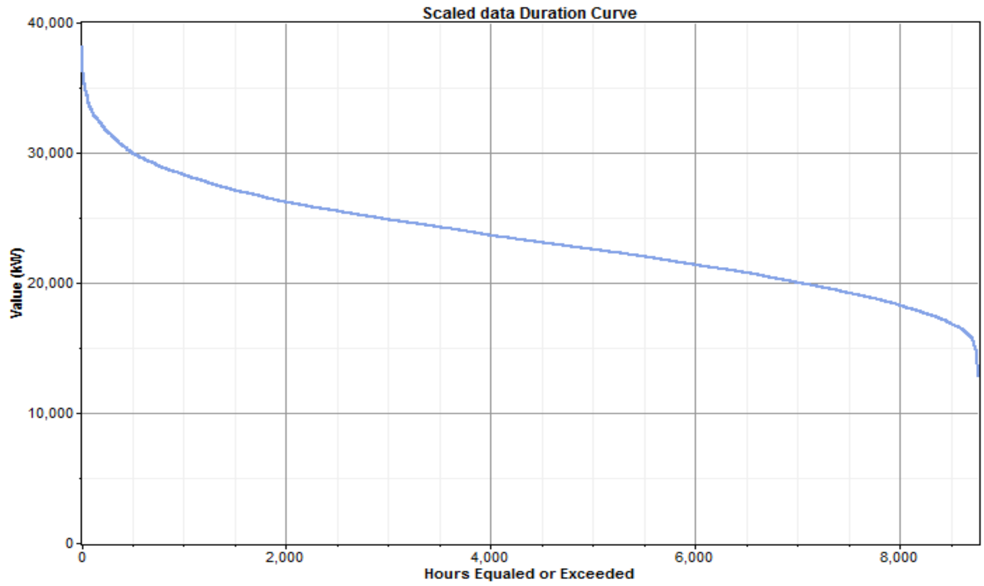



**Figure 3.12: Load Duration Curve for Ma'an Substation**

From the standpoint of utilities, a relatively flat load duration curve with a high load factor is clearly desirable for utilities. This is because the system has to be designed to handle maximum demand. In order to encourage the improvement of load factor, some utilities penalize customers on the electric bill for having low values of load factor [56].

### 3.7.4 Load probability distribution curve

The load probability distribution curve (See Figure 3.13) shows the hourly duration for each demand level through the year. It can be shown as a percentage or frequency (in %). Figure 3.13 shows the load probability distribution curve for Ma'an.

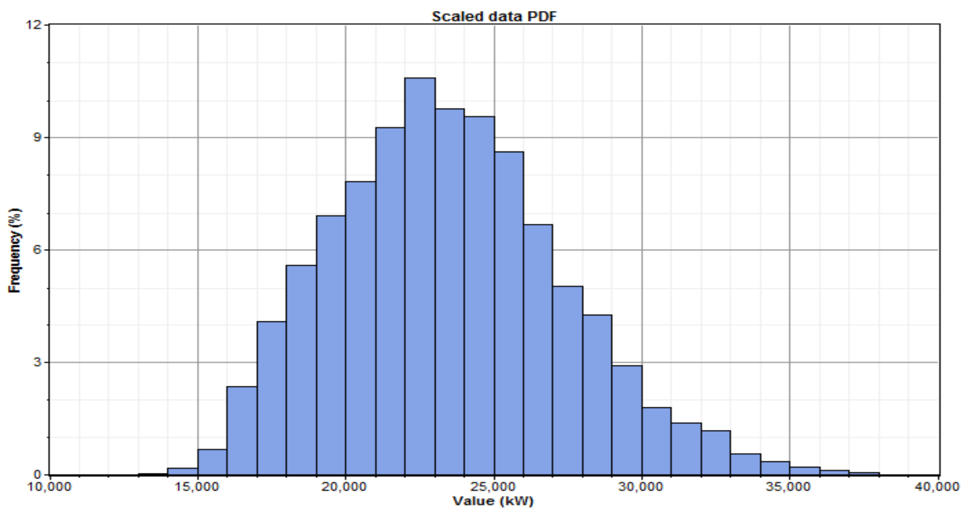



**Figure 3.13: Load Probability Distribution curve for Ma'an**

# CHAPTER FOUR

## *SIZING OF SYSTEM ELEMENTS*

### 4.1 Overview

The hybrid wind-photovoltaic system should be sized in order to meet the power demand fully or partially depending on the renewable fraction. Based on the available data of solar insolation, wind speed or the corresponding wind turbine output and the power demand; the generation capacity is determined to best match the load demand [38].

The major factors affecting the system sizing are:

1- **Load:** The power demand of Ma'an substation is integrated over the year period in order to gain the yearly energy demand.

2- **Location of the system:** Ras Elnaqab, because of the high potential of both solar insolation and wind speed, this should affect the size of the hybrid renewable system.

3- **Rated power:** The number of wind turbines and PV panels is inversely related to their sizes (rated power of renewable components) to supply a specific demand.

4- **Sharing percent:** The load demand is met by PV panels and wind turbines with an appropriate percent for each one. This percent depends on many factors, and all of that determines the system feasibility.

### 4.2 Sharing Percent

In order to gain a suitable sharing percent of both PV panels and wind turbines, three factors (with assumed limits) are taken into consideration:

1- (COE) or Cost of Energy. In Jordan COE is equal to 0.08$/KWh or 0.057JD/KWh [40,52].
2- (RF) or Renewable Fraction. It is the ratio of energy supplied by the renewable hybrid wind/PV resources to the total energy supplied to the load. Renewable Fraction is always less than one. Suitably, selection for minimum RF provides optimal cost for the whole system [39]. It is suitable to assume a 65% minimum renewable fraction.
3- (GP) or Grid Purchase. It has the complement percent of RF. So that, it is suitable to assume a 35% maximum grid purchase.

The following MATLAB code is used to gain the suitable sharing percent. Note that while running the program; it checks the previous three factors. After several iterations, the sharing percent is 22.38% for PV power and 77.62% for wind power.

```
while (1)

disp('//////////////////////////////////////////////////////////////////////
///////////////');
   disp('Initial Hybrid Wind/PV ratios are: ');
   disp(' ');
   disp(' ');
   pv_ratio=rand;
   wind_ratio=1-pv_ratio;

   disp('PV ratio is =');
   disp(' ');
   disp(pv_ratio)
   disp('Wind ratio is =');
   disp(' ');
   disp(wind_ratio)
   disp(' ');
   disp(' ');
   disp('You have to run the HOMER simulation. After that, enter the
following 3 values: ');
   disp(' ');
   disp(' ');
    coe=input('Enter the cost of energy in ($/KWh)=\n');
    rf=input('Enter the renewable fraction in (%)=\n');
    gp=input('Enter the grid purchase in (%)=\n');

    if(coe<0.08)&(rf>0.65)&(gp<0.35)
        break;
    else
        continue;
    end
end
 disp(' ');
 disp(' ');
 disp('The suitable Hybrid Wind/PV ratios are: ');
 disp(' ');
 disp(' ');
 disp('PV ratio is =');
 disp(' ');
 disp(pv_ratio)
 disp('Wind ratio is =');
 disp(' ');
 disp(wind_ratio)
```

### 4.3 Energy Distribution (EDC) & Probability Distribution Frequency (PDF) Curves

The selection of a suitable wind turbine is related to the rated wind speed that can be found by studying two curves. Firstly, probability distribution frequency for Ras Elnaqab (PDF, See Figure 4.1) which is a plot of the duration or frequency (%) versus the wind speeds in (m/s).

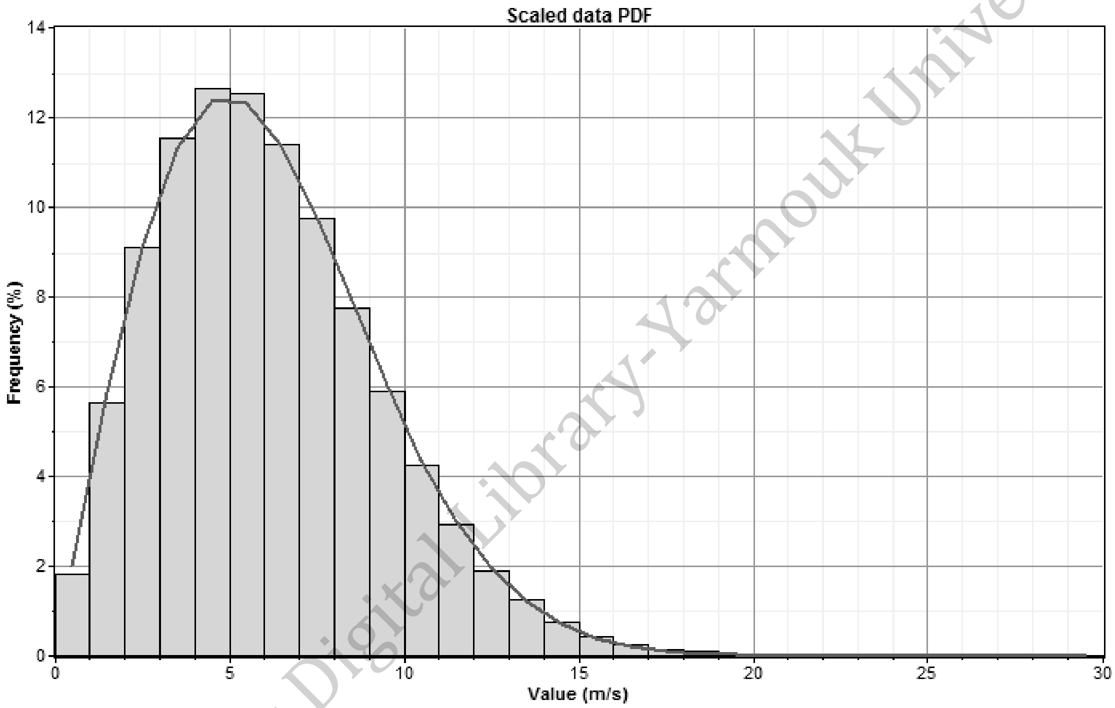



**Figure 4.1: Probability Distribution Frequency (PDF) Curve**

Secondly, energy distribution (EDC) curve which shows the energy content of various wind speeds. EDC is built using PDF curve. Note that, the energy produced depends on cubic of wind speed and wind speed duration. The rated speed for the wind turbine is the speed corresponding to the peak point of the energy distribution curve. Figure 4.2 shows the energy distribution curve (EDC) for Ras Elnaqab that is obtained using PDF curve. The following MATLAB code is used to plot the EDC and PDF curves and to obtain the rated wind speed value from Ras Elnaqab wind speed data:

```
clc
hr=pdf(:,2)/100 *8760;
speed=pdf(:,1);
v=speed.^3;
energy=v.*hr;
en=energy/1000;
plot(speed,hr,speed,en);
[y,x]=max(en);
sprintf('The optimum rated wind speed',speed(x))
```

Figure 4.2 shows that the rated wind speed is equal to 9.5 m/s. After that, we have to search for a wind turbine with around this rated wind speed.

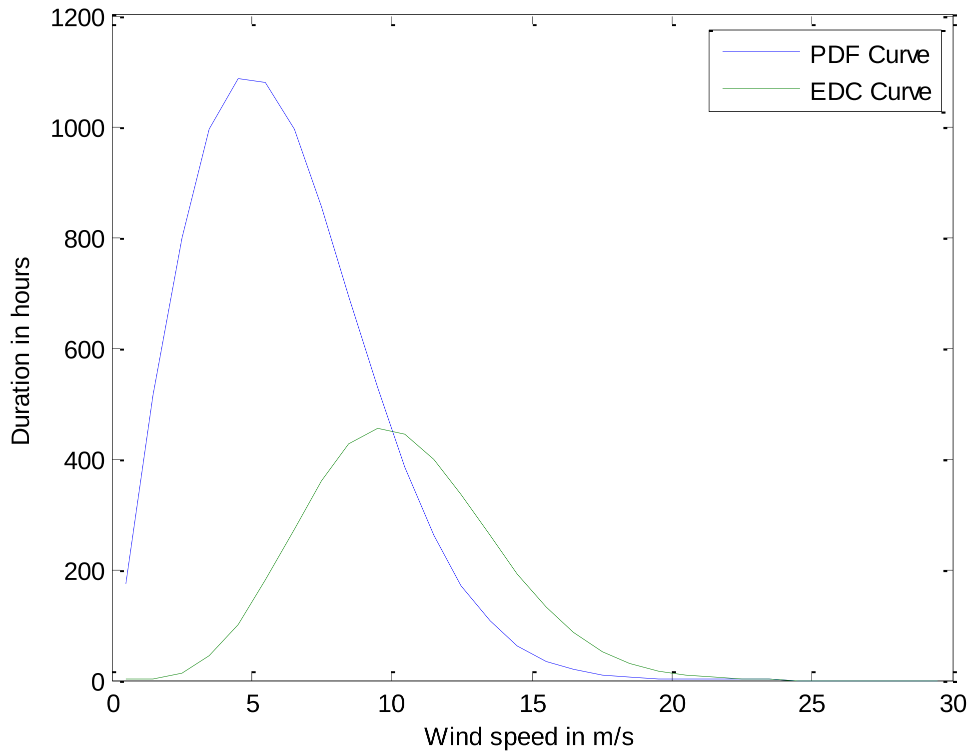



**Figure 4.2: Energy Distribution (EDC) & Probability Distribution Frequency (PDF) Curves**



## 4.4 GOLDWIND87-1.5MW Wind Turbine

An American GOLDWIND87-1.5MW (See Figure 4.3) is a Wind Turbine manufactured by GOLDWIND which is the 4th largest wind turbine manufacturers in the world [41]. The specifications of the selected wind turbine are shown in Table 4.1.

**Table 4.1: Specifications of GW87-1.5MW**

| Parameter | Value |
|---|---|
| **Model** | GOLDWIND87 |
| **Rated output** | 1500 KW |
| **Rated wind speed** | 9.9 m/s |
| **Rotor diameter** | 87m |
| **Cut-in wind speed** | 3 m/s |
| **Cut-out wind speed** | 25 m/s |
| **Hub height** | 85 m |


**Figure 4.3: GOLDWIND87-1.5MW Wind Turbine**

## 4.5 SUNTECH STP280Watt SOLAR PANEL

Suntech's American technology improves the anti-reflecting coating in order to improve the conversion efficiency. In addition, the design of the drainage holes prevents the rain or snow to accumulate and freeze in the frame, therefore bending the frame [43]. Suntech's PV panel is made of polycrystalline which consists of multiple small silicon crystals. It is economical, efficient and has a rigid construction that prevents the frame to deform or break due to any forces. The specifications of the selected PV panels are shown in Table 4.2. In addition, Figure 4.4 shows the selected PV module.

**Table 4.2: Specifications of SUNTECH-280 solar panel**

| Parameter | Value |
|---|---|
| $P_{nominal}$ | 280 Watt |
| $V_{oc}$ | 44.8 V |
| $I_{sc}$ | 8.33 A |
| $V_{mp}$ | 35.2 V |
| $I_{mp}$ | 7.95 A |
| Efficiency | 14.4 % |
| Area | 1.94 $m^2$ |

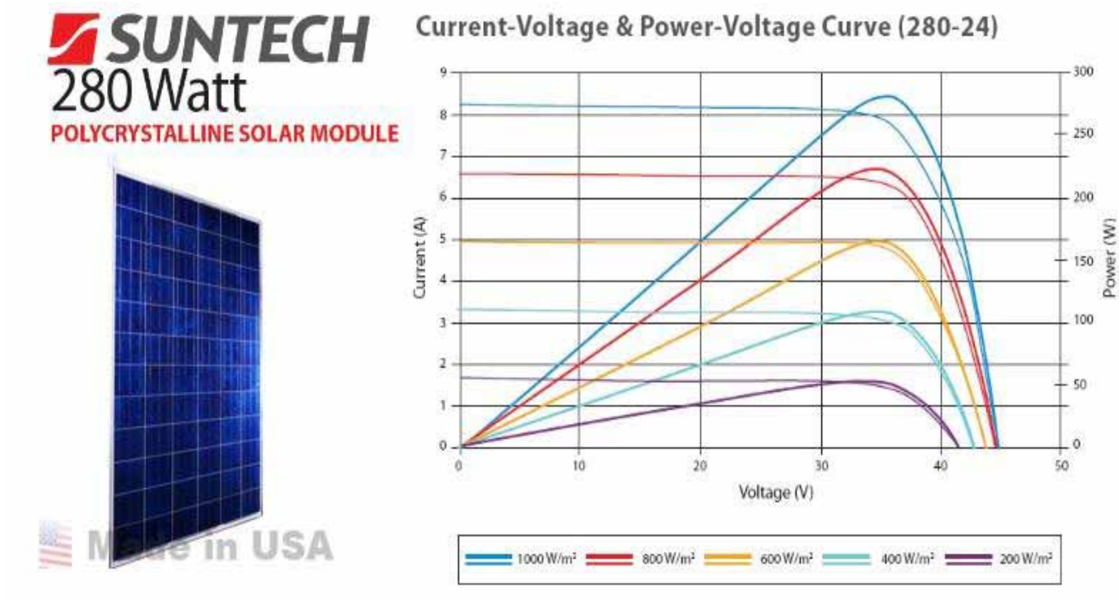



**Figure 4.4: SUNTECH STP280WATT SOLAR MODULE**

## 4.6 Sizing Criteria

1. **Electrical Load**

The load data in *kilowatt* are exported from HOMER as a text file then it will be manipulated using Microsoft Excel 2007. After that, the load signal is built using MATLAB. The load power in *kilowatt* is integrated over the year period (8760 hours) in order to obtain the yearly energy demand in *kilowatt-hour*.

$$Load\ Energy\ (kWhr) = \int_0^{8760} Load\ Power\ (kW) \tag{4.1}$$

2. **PV Modules**

The solar insolation data in *kilowatt per square meters* are exported from HOMER as a text file then it will be manipulated using Microsoft Excel 2007. After that, the solar irradiation signal is built using MATLAB. The solar radiation in *kilowatt per square meters* is multiplied by both area and efficiency of a single PV panel, then it is integrated over the year period (8760 hours) in order to obtain the yearly insolation energy of an individual PV module in *kilowatt-hour*. Total Number of PV panels are obtained by dividing the part of the load which is covered by PV arrays in *kilowatt-hour* to the single PV panel energy output in *kilowatt-hour* (See Formula 4.2).

$$Number\ of\ PV\ Modules = \frac{Load\ Energy\ (kWhr)*PV_{Ratio}}{Single\ PV\ Panel\ energy\ Output\ (kWhr)} \quad (4.2)$$

In general most photo-voltaic arrays generate 53.82 to 107.64 watts per square meters of area array. This depends on the efficiency of various PV types. In addition, PV array area is calculated such that *a typical 1 KW photovoltaic system will need around 15 square meters* [48].

### 3. Wind turbines

The output power data of a single wind turbine in *kilowatt* are exported from HOMER as a text file then it will be manipulated using Microsoft Excel 2007. After that, the wind turbine signal is built using MATLAB. The output power in *kilowatt*, then it is integrated over the year period (8760 hours) in order to obtain the yearly wind energy of an individual wind turbine in *kilowatt-hour*. Total Number of wind turbines are obtained by dividing the part of the load which is covered by wind farm in *kilowatt-hour* to the energy output of a single wind turbine in *kilowatt-hour* (See Formula 4.3).

$$Number\ of\ Wind\ turbines = \frac{Load\ Energy\ (kWhr)*Wind_{Ratio}}{Single\ Wind\ Turbine\ energy\ Output\ (kWhr)} \quad (4.3)$$

In order to calculate the wind farm area, the turbulence due to the rotation of the blades may affect the adjacent turbines; this effect can be reduced by providing a suitable minimum spacing of *10RD* between the rows and *3RD* between the turbines in each row, where *RD* is the rotor diameter. As a result, the wind farm area can be calculated from Figure 4.5 [18].

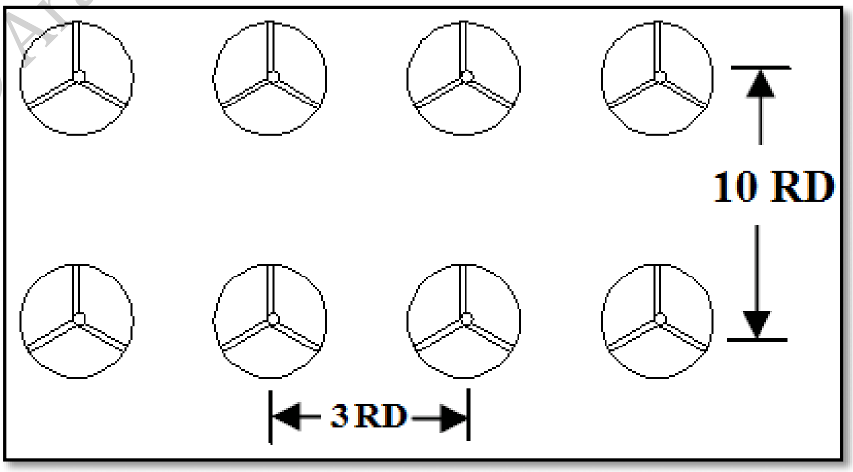



**Figure 4.5: Typical spacing for wind farm**

## 4.7 System Components Costs

In all engineering works, the question of first importance is cost. Which decides whether a project is economical or not. Electrical renewable project generates electrical energy at minimum cost to be sold with a profit. So we reduce cost as minimum as possible. The cost of hybrid wind-photovoltaic components mainly includes:

- Capital costs of the component.
- Operation and Maintenance costs of the component during its lifetime.
- Replacement costs of the component during project lifetime.

Capital costs are the upfront costs to construct each component of the hybrid system. In addition, operation and maintenance costs are the costs associated with major maintenance work that needs to be carried out during the lifetime of the system component beyond typical operating expenses. Operating costs are mainly associated with cost of fuel, subsequently renewable energy plants tends to be very low operating cost compared with fossil fuel power stations. Moreover, Replacement costs are those needed to replace the system component after the completion of its lifetime. Note that, no replacement costs are needed if the component life time is more than or equal to the project lifetime.

Hybrid Optimization Model for Electric Renewable (HOMER) is used to investigate the feasibility study of the proposed hybrid wind-photovoltaic system in Ras Elnaqab in Jordan. Table 4.3 shows the costs of each component for the whole hybrid system that are entered to HOMER.

**Table 4.3: Hybrid Wind/PV system Component Costs**

| *Component* | *Value* |
|---|---|
| **PV** | |
| **Capital cost $/kW** | 1,770[43] |
| **Replacement cost $/W** | 0 |
| **Operation and maintenance $/year** | 27[44] |
| **Wind Turbine** | |
| **Capital cost / turbine** | 1,725,000 [45] |
| **Replacement cost** | 0 |
| **Operation & maintenance $/year** | 11,700 |
| **Converter** | |
| **Capital cost $/kW** | 715 [46] |
| **Replacement $/kW** | 0 |
| **Operation & maintenance $/unit/year** | 0 [47] |
| **Grid** | |
| **Power Price $/kWh** | 0.08 [52] |
| **Sellback $/kWh** | 0.05 [52] |

# CHAPTER FIVE

## *CASE STUDY SIMULATION & RESULTS*

## 5.1 Software

### 5.1.1 Introduction

MATLAB (SIMULINK) and HOMER are used in this thesis because of their unique characteristics and abilities; each one has its own purpose. MATLAB (SIMULINK) is used to build a model in order to size the hybrid wind-photovoltaic components, i.e. to match Ma'an station load by a number of wind turbines and PV panels.

HOMER provides ready models for hybrid system such as: wind turbines, PV arrays, converter, grid and load. HOMER provides us by results to be used in the feasibility analysis.

### 5.1.2 MATLAB

MATLAB is a high-performance language that is used for technical computing. It is an easy to use and it expresses problems and solutions in familiar mathematical notation. Main uses are:

- Math and computation.
- Algorithm development.
- SIMULINK and Modeling.
- Scientific and engineering graphics.

Its basic data element is an array, the name MATLAB stands for Matrix Laboratory. MATLAB features a family of add-on application-specific solutions called Toolboxes. It is a software package that is used for numerical computation and visualization. The combination of analysis capabilities, flexibility, reliability, and power graphics makes MATLAB the premier software package for electrical engineers.

MATLAB provides an environment with hundreds of reliable and accurate built in mathematical function. These functions provide solution to various mathematical problems, including matrix algebra, complex arithmetic, linear system, differential equation, signal processing optimization, non-linear system and many other types of scientific computation. It is very easy to learn and use, and allows user-developed function.

MATLAB is case-sensitivity for both lower and upper case letters that represent two different variables.

MATLAB has been enhanced by very powerful SIMULINK program. SIMULINK is a graphical mouse-driven program for the purpose of simulation and modeling for dynamic systems. SIMULINK enables student to simulate linear as well as non-linear systems easily and efficiently.

For modeling, SIMULINK provides a graphical user interface, for building models with block diagrams. It includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors.

Simulating a dynamic system is a two-step process with SIMULINK. Firstly, a user creates a block diagram, using the SIMULINK model editor that graphically depicts time-dependent mathematical relationships among the system's inputs, states, and outputs. The user then commands SIMULINK to simulate the system represented by the model from a specified start time to a specified stop time [50].



### 5.1.3 HOMER

HOMER was developed in the 1990s by the National Renewable Energy Laboratory (NREL). At the time, NREL had a program focused on helping developing countries to incorporate renewable power into their rural electrification program, called the Village Power Program. HOMER's capabilities have evolved through the years to meet NREL's and the public's need to optimize on-grid and off-grid configurations [49].

Moreover, HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation (DG) applications. HOMER's optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options and to account for technology costs, energy resource availability, and other variables.

As a result, signals of solar irradiation in $KW/m^2$, power demand in $KW$ and wind turbine output power in $KW$ are exported from HOMER as texts and manipulated using Microsoft Excel 2007. After that, these signals are built using MATLAB.

## 5.2 Modeling of Renewable Components

### 5.2.1 Wind Turbine

MATLAB program is used to represent GOLDWIND87-1.5MW wind turbine characteristics referring to the system of equations of (5.1).

$$P_{WT} = \begin{cases} \mathbf{0} & , \quad v < v_{cut_{in}} \\ \frac{1}{2}\rho A v^3 Cp\, \eta & , \quad v_{cut_{in}} \le v \le v_{rated} \\ \frac{1}{2}\rho A {v_{rated}}^3 Cp\, \eta & , \quad v_{rated} \le v \le v_{cut_{out}} \\ \mathbf{0} & , \quad v > v_{cut_{out}} \end{cases} \tag{5.1}$$

The following MATLAB code of Figure 5.1 shows the output characteristics of the wind turbine (Output power in $MW$ versus Wind speed in m/s, See Figure 5.2).

```
% assume that η of the wind turbine is one.
% Rated Power
Pr=input('Enter Rated Power of GoldWind wind turbine in (MW) =\n');

% Rotor diameter
RD=input('Enter rotor diameter of GoldWind wind turbine in (m) =\n');

% Cut in wind speed
Vci=input('Enter Cutin wind speed of GoldWind wind turbine in (m/s)
=\n');

% Rated wind speed
Vr=input('Enter Rated wind speed of GoldWind wind turbine in (m/s)
=\n');

% Cutout wind speed
Vco=input('Enter Cutout wind speed of GoldWind wind turbine in (m/s)
=\n');

% Air density
RO=input('Enter Air density at sea level in (Kg/m^3) =\n');

%Swept area
SA=pi*(RD/2)^2;
disp('Swept Area in square meters is =');
disp(' ');
disp(SA)
% power coefficient(for 1.5 MW wind turbine)=Pr/Power in wind
CP=Pr*10^6/(0.5*RO*SA*Vr^3);
disp('Power coefficient  =');
disp(' ');
disp(CP)
```

```
for i= 1:31
    if(V(i)>=0 & V(i)<Vci)
        P(i)=0;
    end
    if(V(i)>Vco)
        P(i)=0;
    end
    if(V(i)>=Vci & V(i)<=Vr)
        P(i)=CP*0.5*RO*SA*V(i)^3*10^-6;
    end
     if(V(i)>=Vr & V(i)<=Vco)
        P(i)=CP*0.5*RO*SA*Vr^3*10^-6;
    end
end
 plot(V,P)
```

**Figure 5.1: GW87-1.5MW Wind Turbine characteristics code**

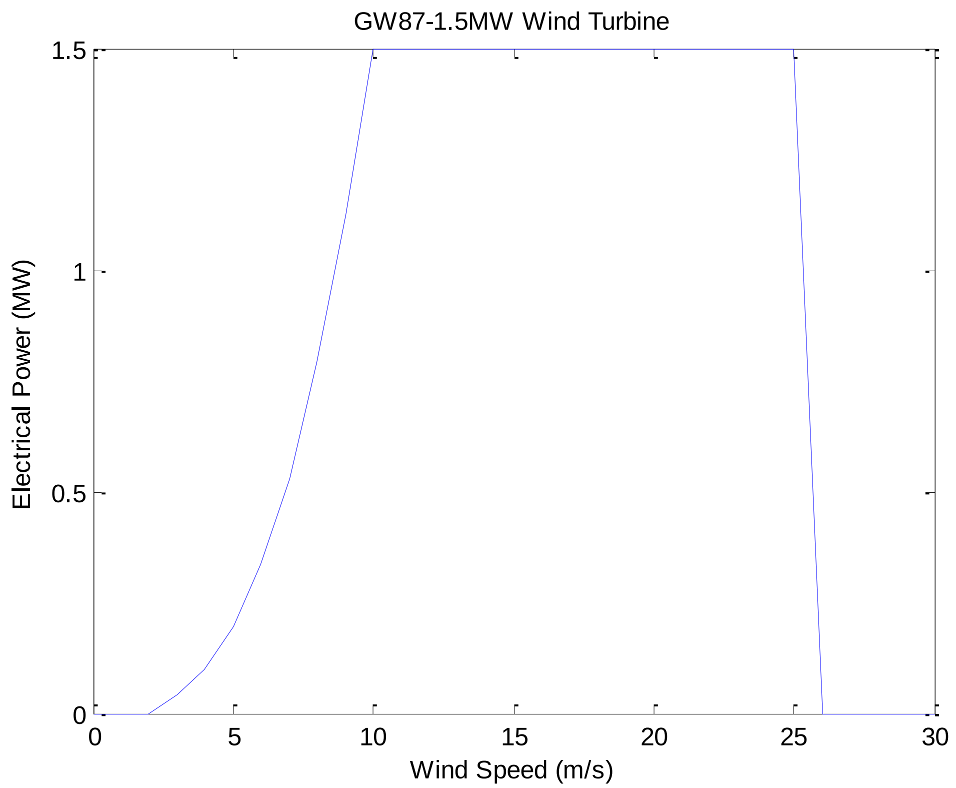



**Figure 5.2: GOLDWIND87-1.5MW Output Characteristics**

Regarding the power coefficient $C_P$, it is the ratio between the nominal power of the wind turbine to the power content of the wind at rated wind speed.

### 5.2.2 Photo-voltaic Panel

MATLAB/SIMULINK is used to build the photovoltaic output characteristics. SIMULINK model of Figure 5.4 results in the output characteristics of any PV cell (Output current and power versus voltage, See Figure 5.5 and Figure 5.6).

Model equations for the PV module are shown below. Note that, equations 5.3 and 5.4 represent the input and output respectively. In addition, circuit model is shown in Figure 5.3.

$$i_D = I_o\left(e^{\frac{V_D}{V_T}} - 1\right) \quad (5.2)$$

$$V_D = V_{PV} \quad (5.3)$$

$$i_{PV} = I_{SC} - i_D \quad (5.4)$$

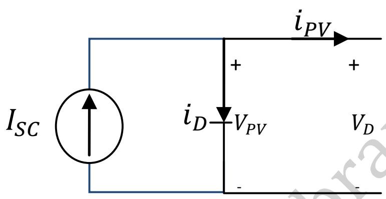



**Figure 5.3: Circuit Model for PV cell**

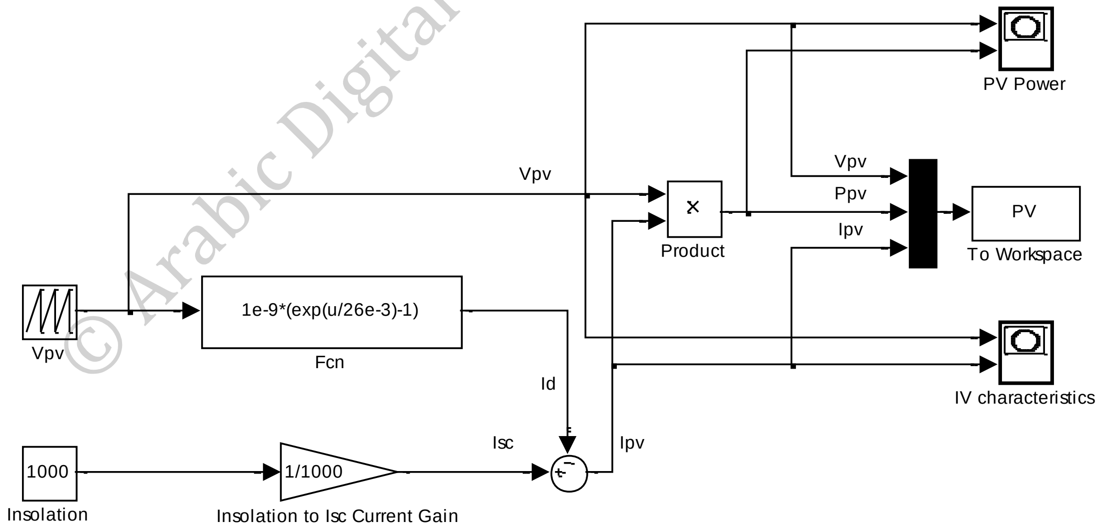



**Figure 5.4: SIMULINK for Photovoltaic Cell**

The expected characteristics IV and PV curves for any photovoltaic panel or cell are respectively shown below.

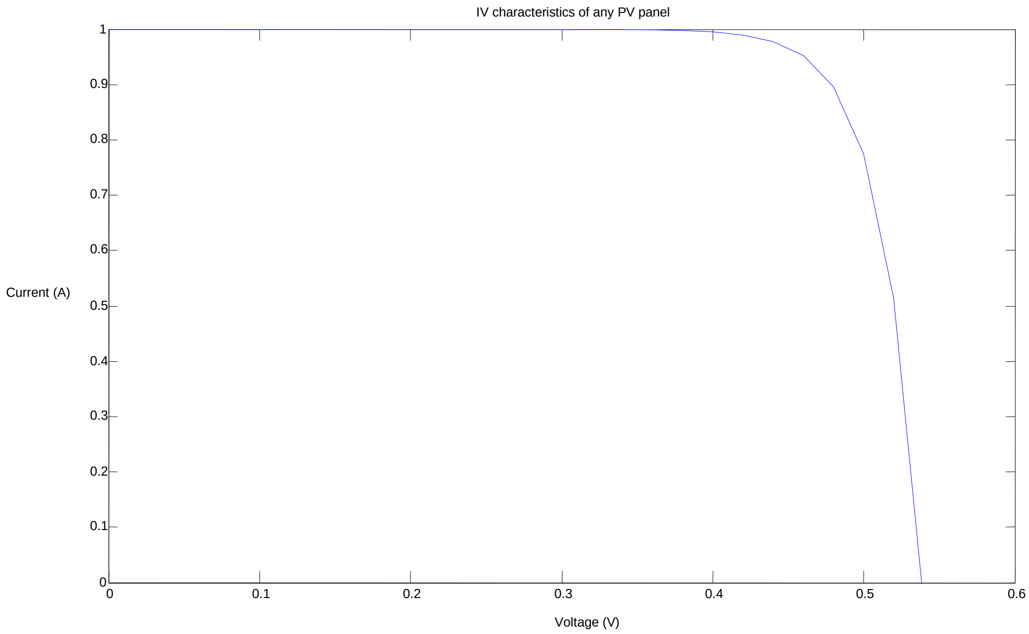



**Figure 5.5: I-V curve for any PV cell or panel.**

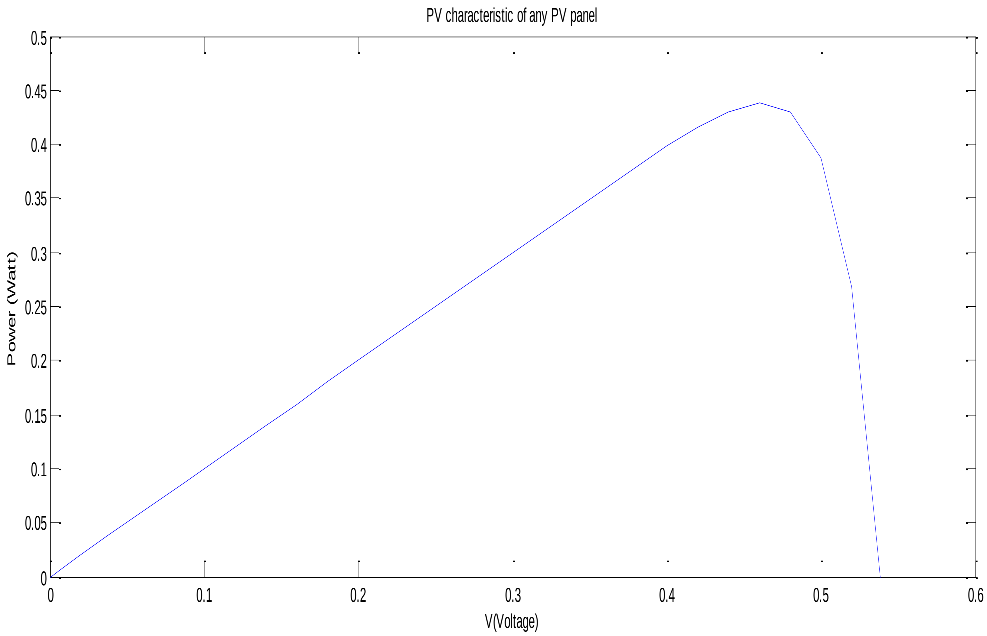



**Figure 5.6: P-V curve for any PV cell or panel.**

## 5.3 Sizing Model

The main goal of sizing the hybrid wind/PV system is to minimize the total costs, this includes capital costs and Operation & Maintenance costs [51]. MATLAB/SIMULINK in Figure 5.7 is built by the application of equations (4.1, 4.2 and 4.3).

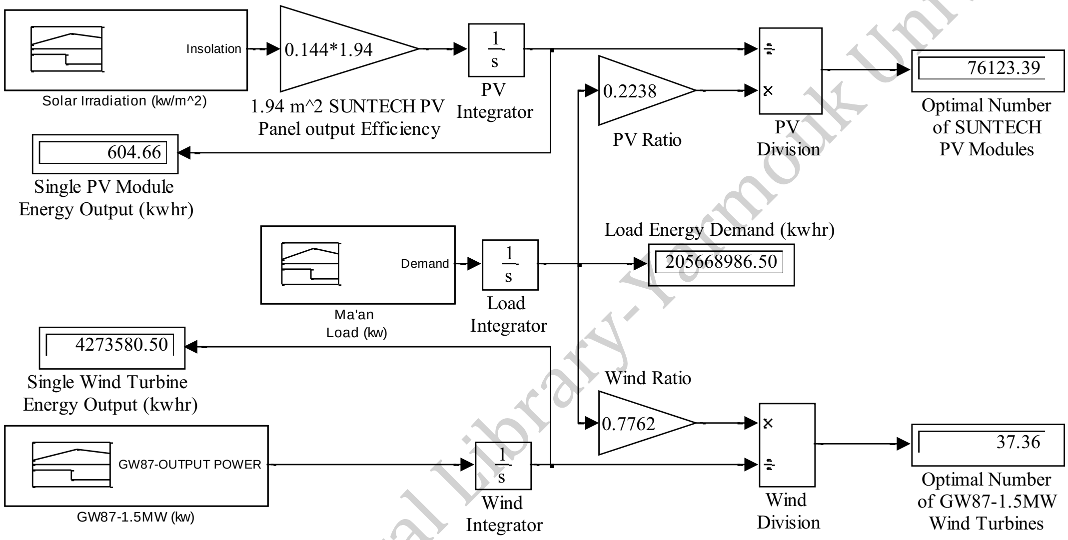



**Figure 5.7: System Component Sizing**

The purpose of the sizing model is to determine the optimal number of each generating elements depending on the sharing percent that is determined by a MATLAB code in chapter four, the optimum sharing percents is found to be 22.38% for PV power and 77.62% for wind power.

The load demand of Ma'an substation during the year of 2011 (See Figure 5.8) in *KW* block data was obtained from the synthesized data from HOMER for 8760 hours, this data is integrated over the whole year period to obtain the yearly energy and then divided into two ratios, the wind ratio is 0.7762 of the total energy while the remaining of 0.2238 will be supplied from PV.

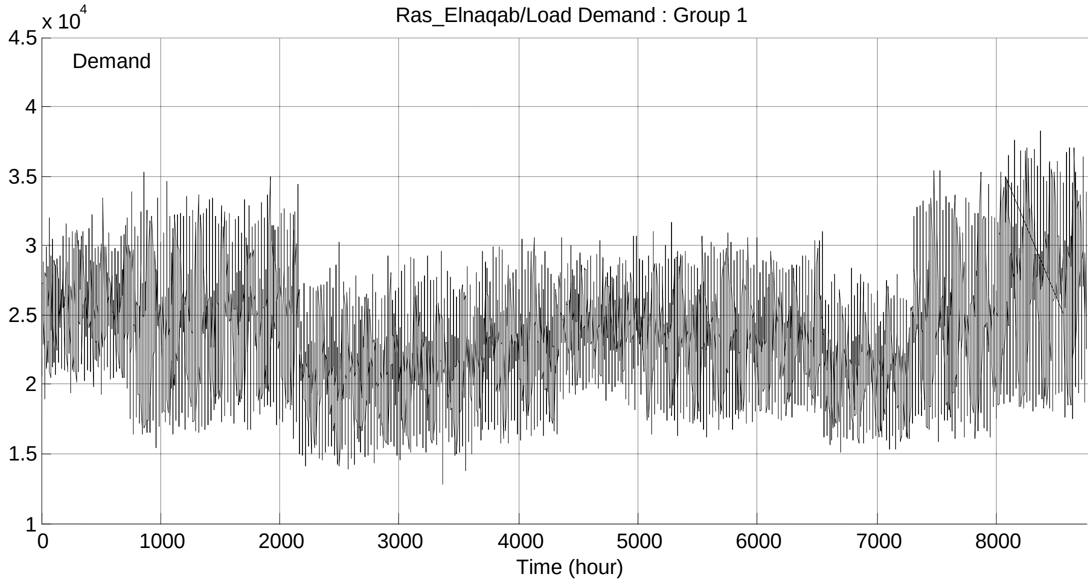



**Figure 5.8: Load Demand (in KW) of Ma'an Substation in 2011**

The second block is the solar irradiation in $KW/m^2$ in Ras Elnaqab (See Figure 5.9). The data for the 8760 hours were obtained from [31], this data is multiplied by the efficiency and area of the SUNTECH photovoltaic panel to obtain the output of a single PV panel and then integrated over the 8760 hours to get the single PV panel yearly energy. To calculate the number of PV panels needed to supply the load, the yearly PV energy demand share is divided by the single PV panel yearly energy output.

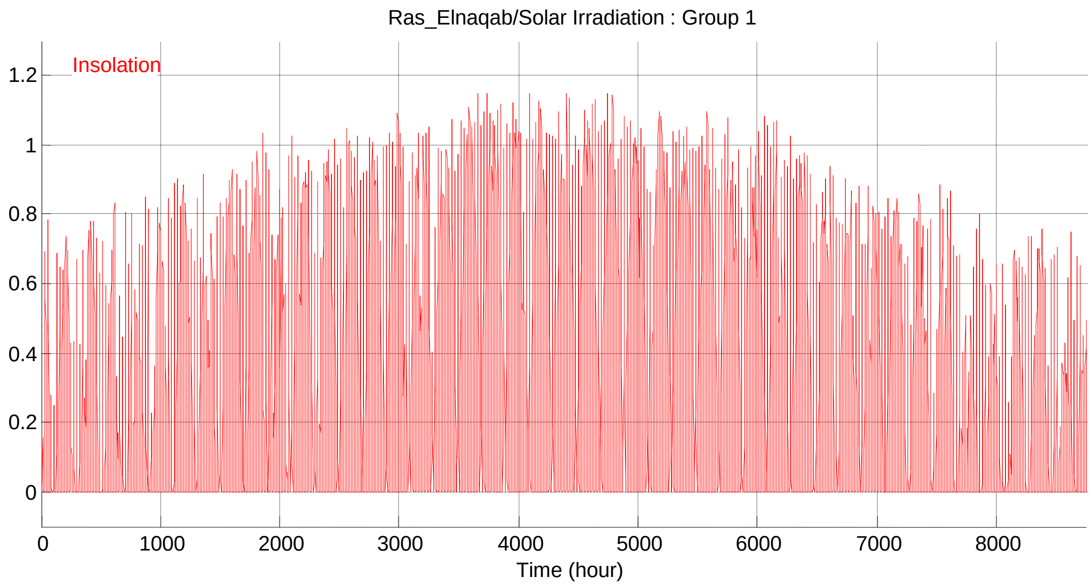



**Figure 5.9: Solar irradiation (in KW/$m^2$) of Ras Elnaqab in 2011**

The third block represents the output of GOLDWIND87-1.5MW wind turbine (See Figure 5.10) under the wind speeds condition of Ras Elnaqab throughout the year. This curve is integrated to obtain the yearly energy yield. To calculate the needed number of wind turbines, the wind share of the load demand is divided by the energy yield of a single wind turbine. Note that, the wind turbine efficiency is found to be 86.67%. This is because Figure 5.10 shows that the output is approximately 1.3 MW.

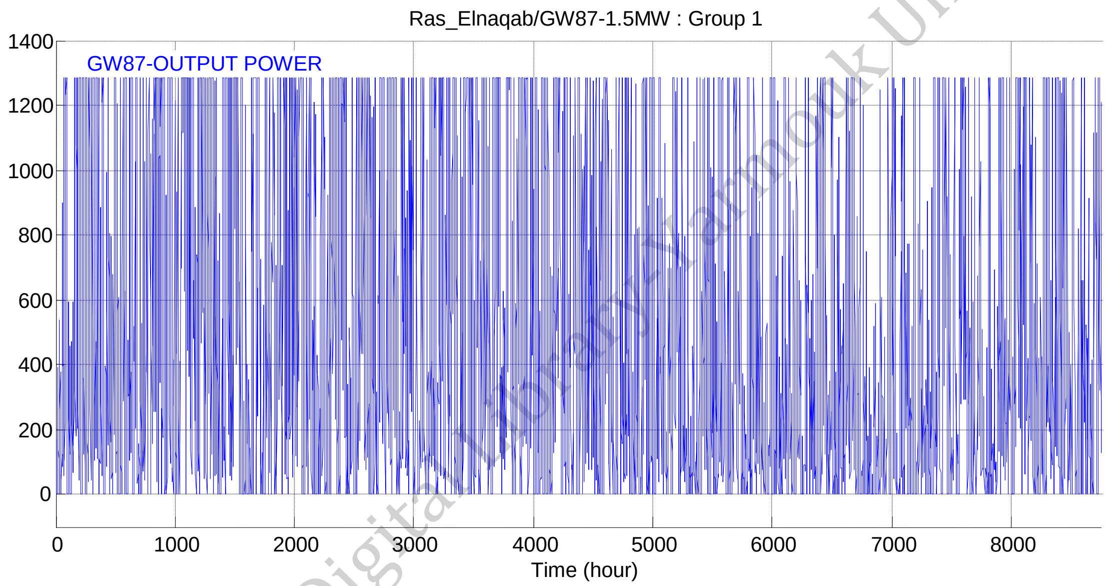



**Figure 5.10: The Output of GW87-1.5MW wind turbine (in KW) in 2011**

As a result, the optimum numbers of PV panels and wind turbines are shown in Table 5.1.

**Table 5.1: Sizing Results**

| Parameter | Unit | Value |
|---|---|---|
| **Load Energy Demand** | KWhr | 205,668,986.50 |
| **Single PV Panel Energy** | KWhr | 604.66 |
| **Number of PV panels** | / | 76,124 |
| **Single Wind Turbine Energy** | KWhr | 4,273,580.50 |
| **Number of Wind Turbines** | / | 38 |
| **PV array area** | $m^2$ | 319,720.8 |
| **Wind farm area** | $m^2$ | 4,087,260 |
| **Project Required Area** | $Km^2$ | 4.4069808 |

## 5.4 Configuration of the Hybrid System in HOMER

The wind-photovoltaic hybrid renewable system is a grid-connected generation system; it consists of both wind and PV generation to supply the load. As mentioned in chapter one, the optimum configuration is the "Mixed Coupled Hybrid System" which is provided by HOMER. Moreover, the wind turbines (GW87-1.5MW) and the load (Ma'an Load) are directly connected to the AC bus while the PV modules are connected to the DC bus. AC and DC buses are linked together by a converter. A schematic diagram for the hybrid system is shown in Figure 5.11.

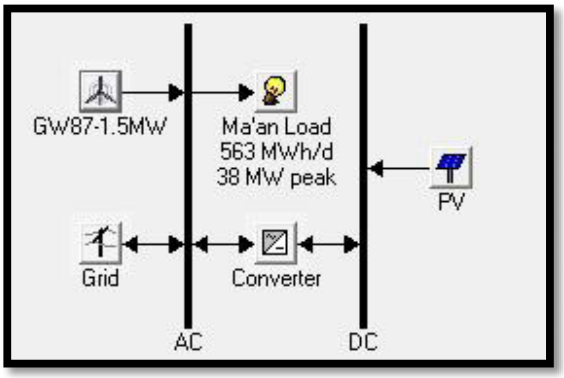



**Figure 5.11: Schematic Diagram of Hybrid Wind/PV system in HOMER**

### 5.4.1 GW87-1.5MW

HOMER parameters for the GW87-1.5MW wind turbine are shown in Table 5.2 and Figure 5.12. These parameters determine model and characteristics of the wind turbine.

**Table 5.2: HOMER parameters for GW87-1.5MW wind turbine**

| Parameter | Value | Description |
|---|---|---|
| **Turbine type** | **GW87-1.5MW** | **Since GW87-1.5MW wind turbine is not built in HOMER, it is created by the author.** |
| **Costs** | | |
| **Quantity** | **1** | |
| **Capital ($)** | **1725000 [45]** | |
| **Replacement ($)** | **0** | |
| **O&M ($/year)** | **11700[45]** | |
| **Sizing Results** | | |
| **Quantity** | **38** | The number of wind turbines to be used in the system, according to the sizing model. |
| **Other** | | |
| **Lifetime & Hub height** | **25 & 85** | (The number of years the turbine is expected to last before it requires replacement) & (the height above ground in meters). |

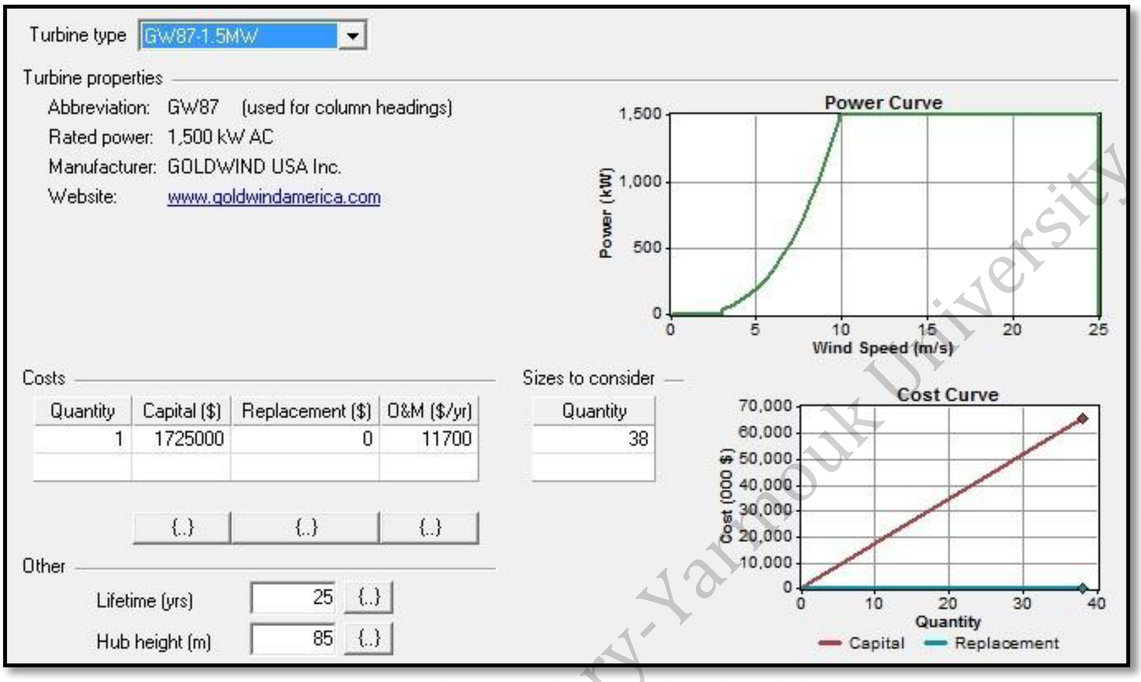



**Figure 5.12: HOMER dialogue for GW87-1.5MW wind turbine**

### 5.4.2 SUNTECH - STP280Watt

HOMER parameters for the SUNTECH-STP280Watt photovoltaic panel are shown in Table 5.3 and Figure 5.13. These parameters determine model and characteristics of the PV panel.

**Table 5.3: HOMER parameters for SUNTECH PV panel**

| Parameter | Value | Description |
|---|---|---|
| **Costs** | | |
| **Size (kW)** | **1** | |
| **Capital ($/kW)** | **1770[43]** | |
| **Replacement ($/kW)** | **0** | |
| **O&M ($/year)** | **27[44]** | |
| **Sizing Results** | | |
| **Size (kW)** | **21314.549** | The total size of the PV array to be used in the system, according to the sizing model. |
| **Other** | | |
| **Output current** | **DC** | All PV arrays produce DC current, but some PV arrays have built-in inverters to convert to AC. |
| **Lifetime** | **25** | The number of years the PV panel is expected to last before it requires replacement. |
| **De-rating factor** | **95%** | Use of a 95% de-rating factor represents module outputs that are 5% less than the manufacturer's nameplate rating. |
| **Slope** | **$30.4333^o$** | The angle at which the panels are mounted relative to the horizontal. |

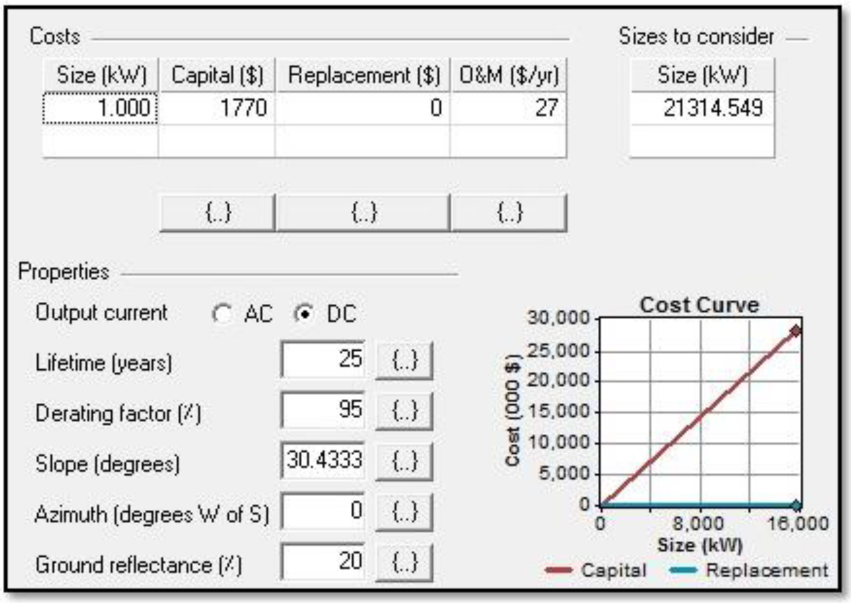



**Figure 5.13: HOMER dialogue for SUNTECH-280Watt PV panel**

### 5.4.3 CONVERTER

HOMER parameters for the Converter are shown in Table 5.4 and Figure 5.14. These parameters represent characteristics of the converter.

**Table 5.4: HOMER parameters for the converter**

| Parameter | Value | Description |
|---|---|---|
| **Costs** | | |
| **Size (kW)** | **1** | |
| **Capital ($/kW)** | **715 [46]** | |
| **Replacement ($/kW)** | **0** | |
| **O&M ($/year)** | **0 [47]** | |
| **Sizing Results** | | |
| **Size (kW)** | **21314.549** | The total size of the converter to be used in the system, according to the sizing model. |
| **Inverter inputs** | | |
| **Lifetime** | **25** | the number of years the converter is expected to last before it requires replacement |
| **Efficiency** | **95%** | The efficiency with which the inverter converts DC electricity to AC electricity, in %. |
| **Inverter can operate simultaneously with an AC generator** | **On** | The inverter can operate simultaneously with one or more AC generators. |
| **Rectifier inputs** | | |
| **Capacity relative to inverter** | **0** | The rated capacity of the rectifier relative to that of the inverter is 0 % since inversion is the required function. |
| **Efficiency** | **1** | The efficiency with which the rectifier converts AC electricity to DC electricity, in %. |

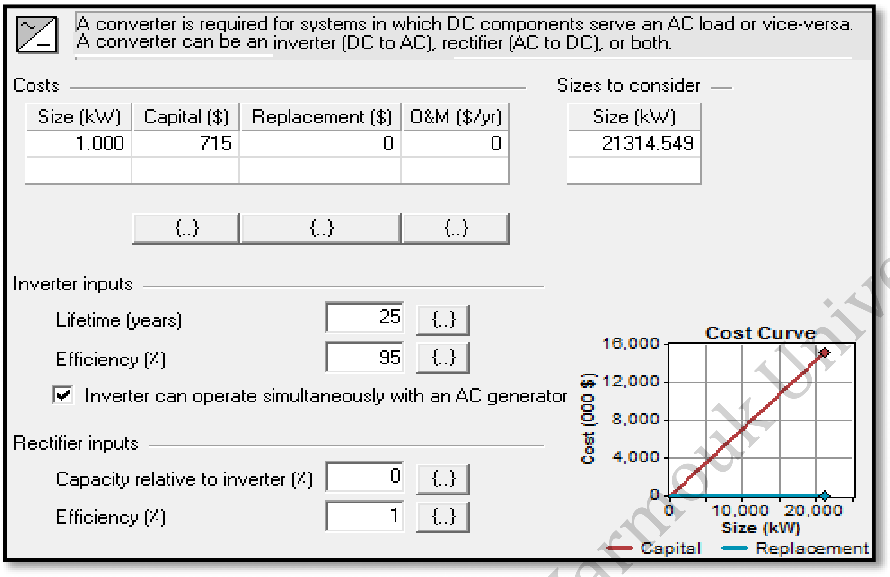



**Figure 5.14: HOMER dialogue for the Converter**

### 5.4.4 The grid

HOMER parameters for the grid are shown in Table 5.5 and Figure 5.15. These parameters determine model and characteristics of the PV panel.

**Table 5.5: HOMER parameters for the grid**

| Parameter | Value | Description |
|---|---|---|
| Rates | | |
| **Power price ($)** | **0.08 [52]** | The average cost of electrical energy from the Jordanian grid in $/kWhr. |
| **Sellback Rate($)** | **0.05 [52]** | The cost of selling electrical energy from the hybrid wind-photovoltaic system to the grid in $/kWhr. |
| **Net metering** | **On** | It is an electricity policy for consumers who have renewable grid connected systems and it has the objective of what remains after deduction. |

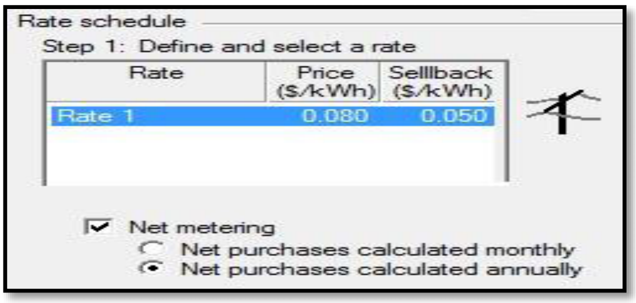



**Figure 5.15: HOMER dialogue for the Grid**

## 5.5 Feasibility Results

The pre-feasibility study and economical investigation shall be done before the application of any renewable energy hybrid system projects that will present recommendations and assist owners and investors to make decisions on the best way to accomplish a profitable hybrid renewable project.

### 5.5.1 Cash Flow Summary

Table 5.6 shows the capital, replacement, Operation and Maintenance (O&M) for each component in the hybrid system shown in Figure 5.11. In addition, the total cost for the whole system is shown in the same table.

**Table 5.6: Cash Flow Summary**

| Component | Capital ($) | Replacement ($) | O&M ($) | Total ($) |
|---|---|---|---|---|
| **PV** | 37,726,752 | 0 | 7,356,732 | 45,083,480 |
| **GW87-1.5MW** | 65,550,000 | 0 | 5,683,484 | 71,233,488 |
| **Grid** | 0 | 0 | -1,440,929 | -1,440,929 |
| **Converter** | 15,239,902 | 0 | 0 | 15,239,902 |
| **System** | 118,516,656 | 0 | 11,599,288 | 130,115,952 |

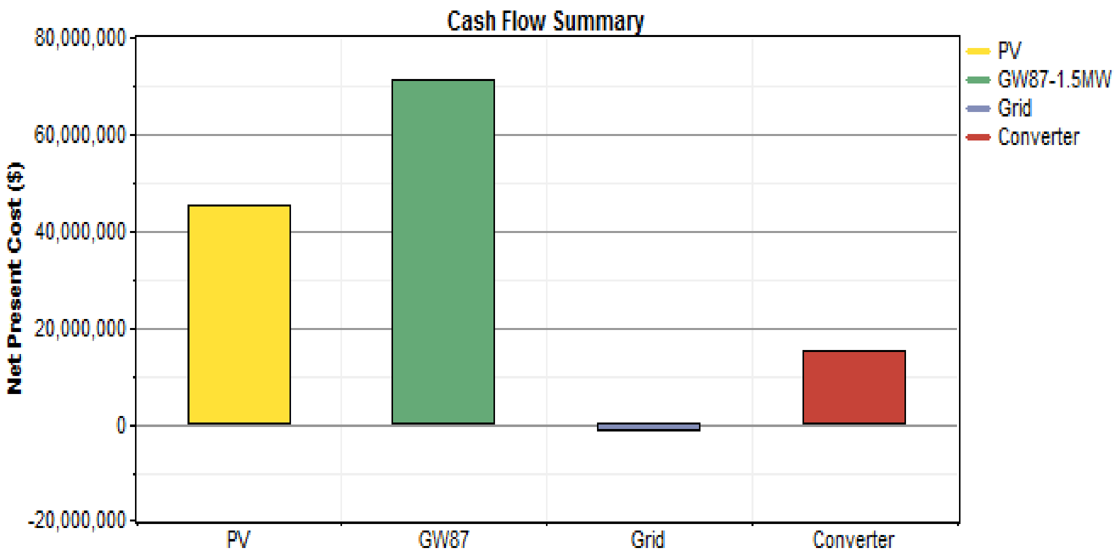



**Figure 5.16: Cash Flow Summary**

The total cost of the system which is equal 130,115,952$ is an acceptable cost for such hybrid system. This fact will be made clearer when the cost of energy (COE) is considered. The COE and yearly operation costs are shown in Table 5.7 that is actually the crucial point in the proposed hybrid system.

**Table 5.7: Cost Summary**

| Cost Summary | |
|---|---|
| **Total net present cost** | 130,115,936$ |
| **Cost Of Energy (COE)** | 0.049$/kWhr |
| **Operating cost** | 907,374$/yr |

### 5.5.2 Production & Consumption of Electricity

The details about the annual production and consumption of electrical energy by the system and the total amount of energy that flows to serve the system's electrical loads are shown in Tables 5.8, 5.9. In addition, annually excess electricity and unmet load are shown in Table 5.10.

**Table 5.8: Annually Production of Electricity**

| Production | kWh/yr | % |
|---|---|---|
| **PV array** | 48,002,952 | 17% |
| **Wind turbines** | 162,398,672 | 57% |
| **Grid purchases** | 73,424,944 | 26% |
| **Total** | 283,826,560 | 100% |

**Table 5.9: Annually Consumption of Electricity & RF**

| Consumption | Value | % | Description |
|---|---|---|---|
| **AC primary load (kWhr/yr)** | 205,669,168 | 73% | The amount of energy that flows towards the AC primary load. |
| **Grid sales (kWhr/yr)** | 75,679,328 | 27% | The total amount of electricity sold to the grid during the year. |
| **Total (kWhr/yr)** | 281,348,480 | 100% | The total amount of electrical load served during the year. |
| **Renewable Fraction (%)** | 74.1 | | The fraction of the total electrical production that is produced by renewable resources. |

**Table 5.10: Annually Excess Electricity & Unmet Load**

| Quantity | kWhr/yr | Description |
|---|---|---|
| **Excess electricity** | 81,066 | Excess electricity is surplus electrical energy that must be dumped to serve a thermal load by means of resistive heating. Because it cannot be used to serve a load. Excess electricity occurs when there is a surplus of power being produced by a renewable source when its minimum output exceeds the load (See Table 5.11) and the grid cannot absorb all the surplus or due to insufficient conversion capability. |
| **Unmet electrical load** | 0.229 | Unmet load is electrical load that the power system is unable to serve. It occurs when the electrical demand exceeds the supply. |

**Table 5.11: HOMER Results for March 15, 2011 at 12:00 P.M.**

| Date | Global Solar | Wind Speed | AC Primary Load | PV Power | GW87-1.5MW | |
|---|---|---|---|---|---|---|
| Mar-15 | kW/m2 | m/s | kW | kW | kW | |
| | 0.953 | 5.382 | 27466.28 | 23159.72 | 9762.355 | |
| | **Grid Purchases** | **Grid Sales** | **Excess Electricity** | **Unmet Load** | **Inverter Input Power** | **Inverter Output Power** |
| | kW | kW | kW | kW | kW | kW |
| | 0 | 3610.625 | 723.353 | 0 | 22436.367 | 21314.55 |

HOMER calculates and gains the results as shown in Table 5.11 for 8760 hours; this means that there are 8760 tables like Table 5.11. Moreover, excess electricity is calculated by subtracting the AC Primary Load (27466.28 kW), Grid Sales (3610.625 kW) and Inverter Losses (22436.367-21314.55=1121.817 kW) from PV Power (23159.72 kW), GW87-1.5MW (9762.355 kW) and Grid Purchases (0 kW), the final result will be the Excess Electricity (723.353 kW) that is a surplus power that can be used to serve a resistive load. Note that, insufficient inversion capability affects the value of excess electricity.

Figure 5.17 shows monthly average electric production of the PV, Wind and Grid sources of energy.

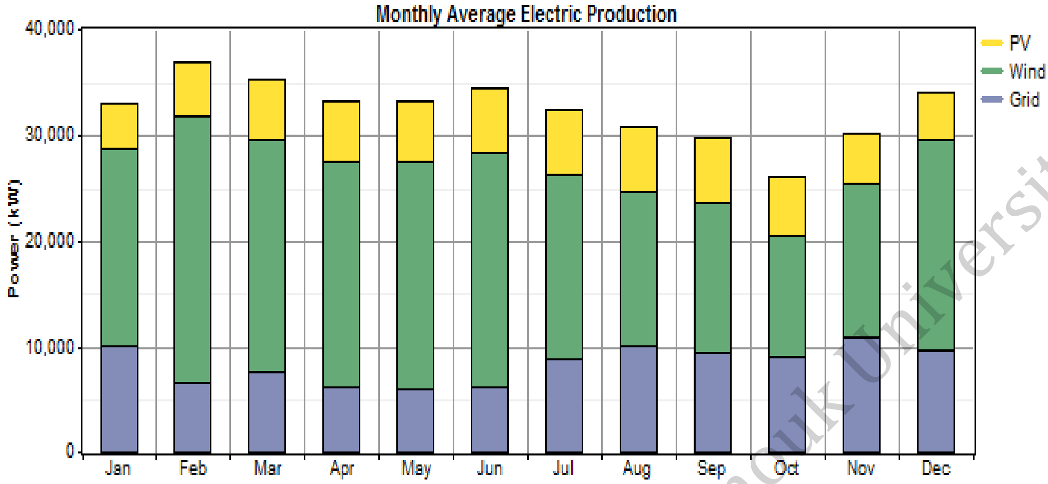



**Figure 5.17: Monthly Average Electrical Production**

Figure 5.17 shows that the most part of generated energy is supplied by the wind farm as expected. February is the month which shows the highest wind energy produced and the lowest PV energy which is related to the high wind speeds and low peak sun hours. This result was expected since February has the maximum average wind speed in Ras Elnaqab (See Figure 3.8).

### 5.5.3 Wind Farm Output

Figure 5.18 shows the continuity of wind energy generation during all hours of the day with different capacities range from zero to the rated capacity of the GW87 wind turbine that is interrelated to the wind speed values.

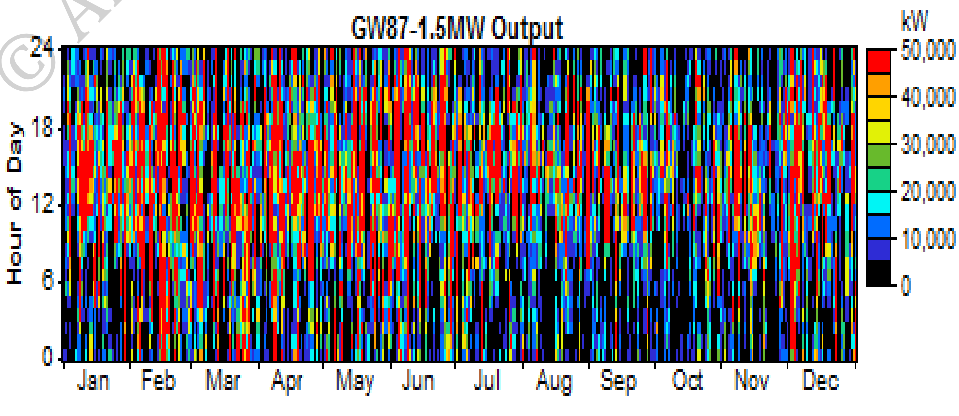



**Figure 5.18: GW87 Wind Farm Output**

Table 5.12 shows the output values of the wind farm system. Note that, the wind farm output is much higher than the PV output. This is because the sharing ratio is selected in order to minimize the cost of operation while maximizing the reliability and renewable energy fraction of the power supply of the system.

**Table 5.12: Wind Farm Output.**

| Variable | Value | Units | Explanation |
|---|---|---|---|
| **Total rated capacity** | 57,000 | kW | The rated power gained from GW87 wind farm. |
| **Mean output** | 18,539 | kW | The average power gained from GW87 wind farm. |
| **Capacity factor** | 32.5 | % | Ratio of the average power gained from GW87 wind farm to the rated power gained from GW87 wind farm. |
| **Total production** | 162,398,672 | kWhr/yr | The total yearly production of electricity by GW87 wind farm in the hybrid system. |
| **Minimum output** | 0 | kW | Minimum output power from GW87 wind farm. |
| **Maximum output** | 48,740 | kW | Maximum output power from GW87 wind farm. |
| **Wind penetration** | 79 | % | The average power output of GW87 wind farm (18,539kW) divided by the average primary load (23,478kW). |
| **Hours of operation** | 7,494 | hr/yr | Hourly duration of GW87 wind farm operation throughout the year. |
| **Levelized cost** | 0.0343 | $/kWhr | COE energy produced by the GW87 wind farm. |

Table 5.12 shows that the total rated output is equal to the rated output of a single wind turbine multiplied by the number of wind turbines ($\text{Total rated capacity} = 1.5 * 38 = 57\text{Mw}$). The hours of operations that the turbines are no in service represent the maintenance time and the time of very low or extremely high wind speeds. The levelized COE of the wind farm system is lower than other sources which emphasizes the importance of wind energy generation.

### 5.5.4 Photovoltaic Array Output

The nature of the solar energy implies a lower mean output and lower capacity factor but PV system is included because it increases the reliability of the hybrid system. Table 5.13 shows the output values of the photovoltaic array system.

**Table 5.13: PV array Output**

| Variable | Value | Units | Description |
|---|---|---|---|
| **Rated capacity** | 21,315 | kW | The rated power gained from SUNTECH PV array. |
| **Mean output** | 5,480 | kW | The average power gained from SUNTECH PV array. |
| **Mean output** | 131,515 | kWh/d | The mean energy gained from PV array per day throughout the year. |
| **Capacity factor** | 25.7 | % | The average power output of the PV array (in kW) divided by its rated power. |
| **Total production** | 48,002,952 | kWhr/yr | The total yearly production of electricity by SUNTECH PV array in the hybrid system. |
| **Minimum output** | 0 | kW | Minimum output power from SUNTECH PV array. |
| **Maximum output** | 25,471 | kW | Maximum output power from SUNTECH PV array. |
| **PV penetration** | 23.3 | % | The average power output of SUNTECH PV array (5,480kW) divided by the average primary load (23,478kW). |
| **Hours of operation** | 4,390 | hr/yr | Hourly duration of SUNTECH PV array operation throughout the year. |
| **Levelized cost** | 0.0735 | $/kWhr | COE energy produced by the SUNTECH PV array. |

The COE of the PV plant (0.0735 $/KWhr) is higher than the COE of the wind farm (0.0343 $/KWhr); this reflects the fact that PV energy is more expensive than wind energy. In the proposed hybrid system the cost per kw of the SUNTECH PV energy is (1770 $/kw) while GW87 wind energy is (1150 $/kw).

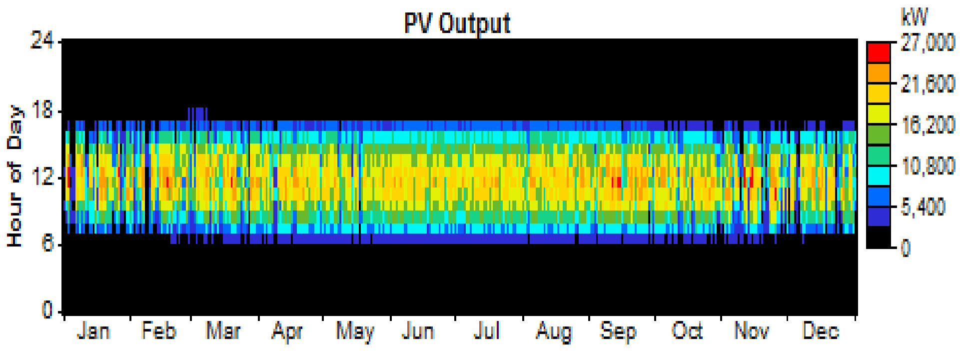



**Figure 5.19: SUNTECH PV Array Output**

Figure 5.19 shows that the photovoltaic energy generation is available during daytime with different capacities range from zero to the rated capacity of the SUNTECH PV Array that is interrelated to the solar insolation values.

### 5.5.5 Purchasing & Selling with Grid

**Table 5.14: Purchasing & Selling with Grid**

| Month | Energy Purchased (kWhr) | Energy Sold (kWhr) | Net Purchases (kWhr) |
|---|---|---|---|
| **Jan** | 7,492,586 | 5,536,932 | 1,955,654 |
| **Feb** | 4,375,339 | 8,294,791 | -3,919,452 |
| **Mar** | 5,645,115 | 7,684,909 | -2,039,795 |
| **Apr** | 4,413,875 | 8,869,245 | -4,455,371 |
| **May** | 4,420,880 | 8,822,541 | -4,401,661 |
| **Jun** | 4,433,031 | 8,481,110 | -4,048,079 |
| **Jul** | 6,549,650 | 5,867,883 | 681,768 |
| **Aug** | 7,510,843 | 4,963,336 | 2,547,507 |
| **Sep** | 6,809,998 | 4,579,889 | 2,230,109 |
| **Oct** | 6,718,507 | 3,663,494 | 3,055,013 |
| **Nov** | 7,851,559 | 3,929,969 | 3,921,590 |
| **Dec** | 7,203,568 | 4,985,231 | 2,218,337 |
| **Annual** | 73,424,944 | 75,679,328 | -2,254,382 |

Table 5.14 shows details of the expected purchases from and sales to the grid for all months of the year 2011. The first column shows the expected energy to be purchased (in kWhr) from the national grid for each month. The second column shows the expected energy to be sold to the national grid (in kWhr) for each month. The third column shows the net purchases from and to the national grid. The positive result indicates that kWhr to be purchased is higher than the kWhr to be sold. The negative result indicates that kWhr to be sold is higher than the kWhr to be purchased. The last row shows the total of the year. Moreover, the last row indicates that the hybrid system sells more than it purchases by 2,254,382 kWhr.

It is important to indicate that the first row is the sum of the kWhr to be purchased from the grid. i.e. at any time during the indicated month, the output of the hybrid system does not satisfy the load. i.e. energy is to be imported from the grid . The second row is the sum of the kWhr to be sold to grid. i.e. at any time, during the indicated month the output of the hybrid system exceeds the load demand. i.e. energy is to be exported to the grid.

# CHAPTER SIX

## *CONCLUSIONS, RECOMMENDATION & FUTURE WORKS*

### 6.1 Conclusions

Jordan is a potential candidate for application of wind/PV hybrid systems. This is because it owns location with high wind speed and high solar radiation. Jordan also suffers from the high cost of imported fuel necessary to generate electrical energy.

Ras Elnaqab located in Ma'an district, is selected as an optimal location to apply wind/PV hybrid system. Ras Elnaqab shows high potential of both wind speed and solar irradiation (data are collected from formal organizations such as RSS). Moreover, an economical feasibility study is applied on a large-scale wind/PV hybrid system to reduce dependency on imported fuel.

With respect to selecting the renewable component, the GW87-1.5MW wind turbine is selected after calculating the rated wind speed of Ras Elnaqab which is equal to 9.5 m/s. Moreover, the SUNTECH polycrystalline PV panel is selected according to its high efficiency and its competitive price which is equal to 1770 $/kW.

Regarding the software, the hybrid wind/PV renewable energy system is sized using MATLAB, the optimal number of PV panels and wind turbines are found in order to match the load demand of Ma'an station (See Table 5.1). In addition, the hybrid wind/PV system is designed using HOMER that makes an economic analysis for 25 years project lifetime. Moreover, the optimal sharing percent (that is found to be 22.38% for PV power and 77.62% for wind power) is found by an iterative MATLAB code taking into account three constraints: COE, RF and EP.

As a result, the AC primarily load of Ma'an substation is (205,669,168) kWhr/yr. The wind farm (38 GW87-1.5MW Wind turbines) produce (162,398,672) kWhr/yr which constitutes (57%) of the total production, while the PV array (76124 SUNTECH PV panels) produces (48,002,952) kWhr/yr which constitutes (17%) of the total production. The renewable fraction is (74.1%), the remaining of (25.9 %) is the grid purchases. Moreover, the excess renewable energy generated which was higher than the demand was sold back to the grid which constitutes (27%) of the total energy production.

Concerning to cost summary, the net present cost of the whole hybrid system is (130,115,936$) or (91,081,155.2JD) and with a cost of energy of 0.049$/kWhr or 0.0343JD/kWhr which is a very feasible and competitive price compared to other technoeconomical research and to the Jordanian utilities energy price which is about 0.08$/kWhr or 0.056JD/kWhr.

Moreover, Ma'an population reaches 50,350 by 2012 [53]. In addition, in 2010 (referring to the statistics collected by Ministry of Energy and Mineral Resources), each citizen consumes about 2011 kWhr per year [54]; this means that the cost of the consumed energy by Ma'an district will be 3.473 million JD per year if it is supplied by the proposed hybrid wind/PV renewable energy system suggested in our thesis. On the other hand, providing Ma'an district with conventional power plants leads to 5.670 million JD per year consumed energy. As a result, 2.197 million JD will be saved per year if we assume a fixed utility energy price at 0.056JD/kWhr, this will reduce financial deficit due to fuel prices increase and government support for electricity prices. This gives Jordanian utilities a strong economic incentive to begin installing hybrid wind/PV renewable energy systems, i.e. increases the percentage share of hybrid wind/PV plants in Jordan.

## 6.2 Recommendation

The present work proves the feasibility for the application of a hybrid wind/PV system in Ras Elnaqab in Ma'an district. What is left is to implement this study by the support of the Jordanian Government represented by the Ministry of Energy and Mineral Resources.

## 6.3 Future Works

In the future, similar studies can be established to investigate other possible potential locations in Jordan.

The authors believe that emission levels reduction should be included to enhance feasibility of the hybrid system.

Finally, other hybrid systems are available other than wind/PV systems. It is interesting to investigate other possibilities and compare results.

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# الملخص

**المصري، حسين محمد. الجدوى الإقتصادية لربط الأنظمة المهجنة لمولدات الرياح والخلايا الكهروضوئية بالشبكة الوطنية الأردنية. رسالة ماجستير قسم هندسة القوى الكهربائية، كلية الحجاوي للهندسة التكنولوجية، جامعة اليرموك. ٢٠١٢ (المشرف: د.فتحي عمورة)**

كلاً من برامج MATLAB و HOMER تم استخدامها لدراسة الجدوى الإقتصادية لربط النظام الهجين بالشبكة الوطنية الأردنية.

إن المعلومات الفنية التي تم جمعها من الهيئات الرسمية (الجمعية العلمية الملكية، المركز الوطني للبحث والتطوير ووزارة الطاقة والثروة المعدنية) تشير إلى أن رأس النقب (جنوب الأردن) هو المكان الأمثل للمشروع. يعود ذلك لأنه أحد المواقع التي تتمتع بتواجد سرعة رياح عالية و إشعاع شمسي عالٍ.

يجدر الذكر هنا أن من النادر الحصول على موقع يتمتع بسرعة رياح عالية و إشعاع شمسي عالٍ، بل عادة تتمتع معظم المراقع إما بسرعة رياح عالية وإشعاع شمسي منخفض والعكس بالعكس.

من بيانات الأحمال اليومية لسنة كاملة تم استنباط معدل منحنى الحمل اليومي لكل شهر بالسنة. تم إدخال البيانات السابقة إلى برنامج HOMER وبالأخذ والعطاء مع برنامج MATLAB ، تم الخروج بنتيجتين هامتين الأولى نسبة التقاسم بين الطاقة المولدة من الرياح (77.62%) وبين الطاقة المولدة من الشمس (22.38%).

أما النتيجة الثانية فهي تفاصيل كل نسبة وهي كالتالي: طاقة الرياح تحتاج إلى ٣٨ مولد رياح بقدرة ١.٥ ميجاوات لكل منها وأما المولدة من الطاقة الشمسية فهي 76,124 لوحة شمسية قدرة كل منها 280 وات.

أظهرت الدراسة كذلك أن النظام الهجين يبيع ويشتري (ك.و.س) من الشبكة الوطنية، وذلك لسد حاجة الحمل اليومي للمنطقة المَعنية في أي لحظة.

وأظهرت الدراسة أن المحصلة (لسنة ٢٠١١م كاملة) هي أن النظام الهجين يبيع ما مقداره 2,254,382 ك.و.س للشبكة الوطنية.

وفي النتيجة، فإن هذا المشروع ذو إقتصادية واضحة.

**الكلمات المفتاحية**— HOMER، النظام المهجن من مولدات الرياح والخلايا الكهروضوئية، الجدوى الإقتصادية.