MODELING AND ANALYSIS OF HYBRID PV/WIND OFF-GRID POWER GENERATION SYSTEM IN THE KINGDOM OF SAUDI ARABIA

BY

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الإهـــــــــداء

أهدي هذا العمل

إلى والـــــــدي العزيـــــزين ..... ثمرة من ثمار تربيتهم وغرسهم
إلى أخوتـــــــــــــــــــى ..... لدعمـهم المستمـــر ونصحـــهم
إلى زوجتـى العزيــزه وأولادي ..... وفاءً لهم ولصبرهم وتضحيتـــهم

DEDICATED

To My Parents … To My Family

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I am most grateful to Almighty ALLAH, the Beneficent, the Merciful, for enabling me to complete this work. Peace and blessings of ALLAH be upon his Last messenger Mohammed (Sallallah-Alaihe-Wasallam) and his family, who guided us to the right path. First and the foremost acknowledgments are due to the King Fahd University of Petroleum and Minerals and to the Department of Mechanical Engineering for supporting my research work. I wish to express my deep appreciation and heartfelt gratitude to Dr. Esmail M. A. Mokheimer, my thesis advisor for his unfailing encouragement, advices and suggestions through this work. I also wish to thank my committee members, Dr. Mohamed A. Habib and Dr. Mohammad A. Abido for their constructive guidance and support. Also I want to thank Dr. Iyad Al-Zaharna for his suggestions during my work.

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The continuous use of fossil fuels causes a significant pollution impact on the atmosphere. As a result of such pollution effects, unwanted greenhouse and climate change effects are seen in every part of the world. In order to keep the environment friendly, research is ongoing to exploit clean energy resources, such as wind and solar energy. The dynamic behavior of climatic conditions including solar irradiance, wind speed, temperature, etc, results in instability shortcomings for electric power production from photovoltaic (PV) modules and wind turbines. In order to achieve the high energy availability required in some application such as lighting, electrification of remote areas and telecommunications, it is necessary to oversize the rating of the generating system (e.g., surface of the photovoltaic array, rating of wind turbine) which is an expensive solution. On the other hand, it is possible to use hybrid system where two or more renewable energy sources are exploited. This approach requires the sizing optimization of hybrid systems.

The present thesis aimed at the development of a computational model for the sizing optimization of a hybrid PV/wind power generation system. The model involves a PV model, wind power model and a model for the required battery. The developed model has been used to optimize the hybrid PV/wind system for an off grid house in the eastern province of the Kingdom of Saudi Arabia. The simulation results showed that for a house with a typical nominal load (473 W average) and for almost zero loss of power supply

probability (LPSP), using a system comprises one wind turbine, the optimum number of PV modules and batteries are 47 and 35 respectively and the levelized cost of energy is (1.05 $/kWh). With two wind turbine the optimum configuration includes 41 PV modules and 30 batteries with (0.93 $/kWh). Further increasing the number of wind turbine to three, will reduce the levelized cost of energy to (0.82 $/kWh) with 30 PV modules and 27 batteries.

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Keywords: Renewable energy, Solar energy, Wind energy, Hybrid system

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THESIS ABSTRACT (ARABIC)

ملخص الرسالـــــة

الاسم : عبدالله محمد حسين الشرفي

العنوان : نمذجة وتحليل نظام هجين من الطاقة الشمسية وطاقة الرياح لتوليد الطاقة في المملكة العربية السعودية

التخصص : الهندسة الميكانيكية

التاريخ : مايو 2011

يسبب الاستخدام المستمر للوقود الأحفوري زيادة ملحوظة في الملوثات المنبعثة إلى الغلاف الجوي الأمر الذي يؤدي إلى زيادة ظاهرة الإحتباس الحراري. حالياً هنالك العديد من الأبحاث لإيجاد البديل الأمثل من مصادر الطاقة النظيفة مثل طاقة الرياح أو الطاقة الشمسية. إن السلوك الديناميكي للظروف الجوية كالإشعاع الشمسي ، سرعة الرياح ، درجة الحرارة ، الخ..... ، يسبب عدم الإستقرار في الطاقة الناتجة من الخلايا الشمسية أو مولدات الرياح. إن تحقيق الإعتمادية العالية للطاقة المطلوبة في بعض التطبيقات كالإضاءة أو تزويد المناطق النائية بالطاقة أو الاتصالات ، يتطلب زيادة حجم نظام توليد الطاقة (مساحة سطح أكبر للخلايا الشمسية أو قدرة أكبر لتوربينات الرياح) والذي يعتبر أمرا مكلفا إقتصادياً. من ناحية أخرى ، من الممكن إستخدام نظام هجين حيث يوجد مصدرين أو أكثر للطاقة المتجددة الأمر الذي يتطلب تقييم أداء مثالي للنظام الهجين.

تم في هذه الرسالة إيجاد نموذج للنظام الهجين المكون من الطاقة الشمسية وطاقة الرياح. يحتوي النموذج الحسابي على نموذج للخلايا الشمسية ونموذج لتوربينات الرياح ونموذج للبطاريات المطلوبة. تم تطبيق النموذج لإيجاد التركيب الأمثل لمكونات النظام الهجين لتغذية منزل غير مرتبط بالشبكة بالطاقة الكهربائية في المنطقة الشرقية بالمملكة العربية السعودية. أظهرت نتائج المحاكاة أنه لتغذية منزل ذو حمل إسمي محدد (المتوسط 437 وات), فإن العدد الأمثل للخلايا الشمسية وللبطاريات المطلوبة في نظام هجين يحتوي على توربين رياح واحد, هي 47 و 35 على التوالي فيما كانت تكلفة الطاقة (1.05 دولار/كيلو وات ساعة). ومع عدد إثنين توربينات رياح فإن التركيب الأمثل لمكونات النظام الهجين يحتوي على 41 خلية شمسية و 35 بطارية مع (0.93 دولار/كيلو وات ساعة). إن زيادة عدد توربينات الرياح لتصبح ثلاثة, ستقلل تكلفة الطاقة إلى (0.82 دولار/كيلو وات ساعة) في نظام يحتوي على 30 خلية شمسية و 27 بطارية.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 Motivation

It is observed that with the scientific and technology progress, the increasing of human dependency on energy with its multi shapes especially, cheaper traditional energy resulting from hydrocarbons such as oil and coal. This resulted in increases in the emissions and pollutants in the atmosphere like CO and CO_2. This consequently, leads to increase in the global warming phenomena and to rise in the temperature of the Earth which leads to melt the ice and rise the sea level causing disappearing of many coastal cities. Therefore, there is a growing interest in renewable energy such as solar and wind power due to their pollution free, availability in all over the world. These facts make these energy resources attractive for many applications in various fields. But relying on one source of renewable energy either a standalone solar or wind power generation system cannot give us a reliable and continuous resource of electric power. This is due to many influence factors such as lack of solar energy at night, cloudy sky, or if the local wind speed less than the cut in wind speed of the wind turbine. This implies that in order to achieve high availability of energy, it is possible to use a hybrid system where two or more sources of renewable energy are exploited with the use of batteries to power the system in the absence of solar energy and wind energy together or incase of insufficient power generated by the hybrid system compared to the load demand.

1.2 Global Warming and Renewable Energy

As a result of burning coal and oil as fuel, the level of CO_2 has risen significantly in the last 100 years. It is estimated that CO_2 accounts for about 60% of the anthropogenic (or human-caused) greenhouse change, known as the enhanced greenhouse effect. Since CO_2 is one of the large gas molecules that trap long-wave radiation to warm the lower atmosphere by the so-called greenhouse effect, atmospheric scientists and meteorologists alike suggested that increase in the CO_2 might be causing a general warming of the 's climate). The consumption of the fossil fuels is responsible for the increase of the CO_2 in the atmosphere by approximately 3×10^{12} kg/year [1]. The major problem is the fact that a large amount, approximately 98% of CO_2 is dissolved in the water of the oceans (7.5×10^{14} kg in the atmosphere, 4.1×10^{16} kg in the ocean). The solubility of CO_2 decreases with the increasing temperature of water by approximately 3% degree Kelvin. If the average temperature of the oceans increases the CO_2 solubility equilibrium between the atmosphere and the oceans shifts toward the atmosphere and then leads to an additional increase in the greenhouse gas in the atmosphere. The world eco-system is suffering from air pollution and global warming. The issue is a central problem now for every evolving technology to be accepted by the global community. It is therefore necessary to develop new and eco-friendly technologies. The global system is being disturbed such that it is no longer tolerant of further unwanted technologies.

Renewable energy sources are expected to become economically competitive as their costs already have fallen significantly compared with conventional energy sources in the

medium term. Moreover, new renewable energy sources offer huge benefits to developing countries, especially in the provision of energy services to the people who currently lack them. Up to now, the renewable sources have been completely discriminated against for economic reasons. However, the trend in recent years favors the renewable sources in many cases over conventional sources.

The advantages of renewable energy are that they are sustainable, ubiquitous (found everywhere across the world in contrast to fossil fuels and minerals), and essentially clean and environmental friendly. The disadvantages of renewable energy are its variability, low density, and generally higher initial cost. For different forms of renewable energy, other disadvantages or perceived problems are pollution, odor from biomass, avian with wind plants, and brine from geothermal. In contrast, fossil fuels are stored solar energy from past geological ages. Even though the quantities of oil, natural gas, and coal are large, they are finite and for the long term of hundreds of years they are not sustainable. The world energy demand depends, mainly, on fossil fuels with respective shares of petroleum, coal, and natural gas at 38%, 30%, and 20%, respectively. The remaining 12% is filled by the non-conventional energy alternatives of hydropower (7%) and nuclear energy (5%). It is expected that the world oil and natural gas reserves will last for several decades, but the coal reserves will sustain the energy requirements for a few centuries. This means that the fossil fuel amount is currently limited and even though new reserves might be found in the future, they will still remain limited and the rate of energy demand increase in the world will require exploitation of other renewable alternatives at ever increasing rates. The desire to use renewable energy sources is not

only due to their availability in many parts of the world, but also, more empathetically, as a result of the fossil fuel damage to environmental and atmospheric cleanness issues. The search for new alternative energy systems has increased greatly in the last few decades for the following reasons:

1. The extra demand on energy within the next five decades will continue to increase in such a manner that the use of fossil fuels will not be sufficient, and therefore, the deficit in the energy supply will be covered by additional energy production and discoveries.

2. Fossil fuels are not available in every country because they are unevenly distributed over the world, but renewable energies, and especially solar radiation, are more evenly distributed and, consequently, each country will do its best to research and develop their own national energy harvest.

3. Fossil fuel combustion leads to some undesirable effects such as CO_2 emissions. The environmental problems including air pollution, acid rain, greenhouse effect, climate changes, oil spills, etc. It is understood by now that even with refined precautions and technology, these undesirable effects can never be avoided completely but can be minimized. One way of such minimization is to substitute at least a significant part of the fossil fuel usage by renewable energy.

1.3 Major Sources of Renewable Energy

1.3.1 Solar Energy

Solar energy comes from the Sun which is a sphere of intensely hot gaseous matter with a diameter $1.93\times10^{9}m$ and is, on the average $1.5\times10^{11}m$ from the Earth [2]. Figure (1.1) shows schematically the geometry of the composite result of the Sun-Earth relationships. The eccentricity of the Earth's orbit is such that the distance between the sun and the Earth varies by 1.7%. At a distance of one astronomical unit, $1.495\times10^{11}m$, the mean Earth-Sun distance, the Sun subtends an angle of 32°. The radiation emitted by the Sun and its spatial relationship to the Earth result in a nearly fixed intensity of solar radiation outside of the Earth's atmosphere.

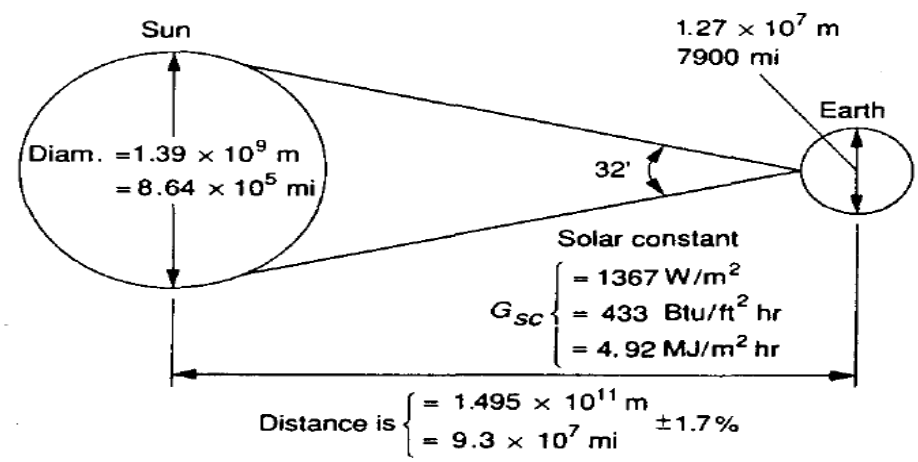


Fig. (1.1) Sun Earth relationships [2]

The solar constant, (G_{sc}) is the energy from the Sun, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation, at mean Earth-

Sun distance, outside of the atmosphere. Many studies have been done to calculate the value of solar constant and these studies recommend that the value of solar constant $G_{sc} = 1373\ W/m^2$ with probable error of 1 to 2%. However, areas on high altitudes or with substantial cloud cover do not receive a constant supply of solar energy, which is a problem that scientists are dealing with. So, solar energy is available throughout the world, although in varying amounts. The colors in the map in Figure (1.2) show the average available solar energy on the surface (data from 1991 to 1993). For comparison, the dark disks mark the land area required to supply the primary energy demand in the year 2010 [3]. Solar power systems installed in the areas defined by the dark disks could meet the world's current total energy demand.

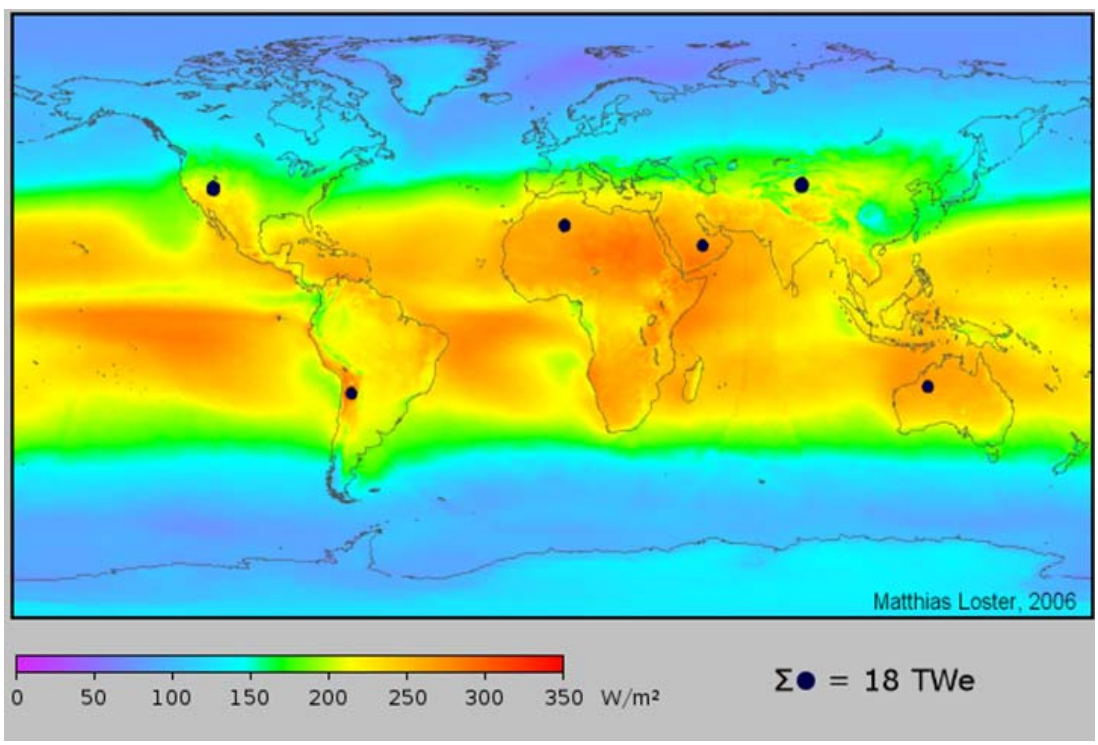


Fig. (1.2) the average available solar energy on the surface of the Earth [3]

Solar energy can be converted to various types of energy; mainly electricity (photovoltaic cells and heat engines), heat (hot water, building heat, cooking, lighting), light (skylights) and chemical (bio fuels and fossil fuels). There are direct and indirect as well as active and passive means of converting solar energy into each of the above types of energy. However, PV modules produce DC current, which has to be converted to AC current to be used in most of the modern day appliances. This is an additional cost which increases the per person cost of solar energy. The amount of solar energy intercepted by the Earth every minute is greater than the amount of fossil fuel the world uses every year. Hence as we can see, we have more than enough solar energy to power the entire human population. Direct energy production through this renewable source is pollution free. The wastes produced through bio fuels and Photovoltaic cells are manageable with the use of existing pollution controls. Even though the capital costs of setting up equipment powered by solar energy are high, the operating costs are low. The costs are also recovered within four to eight years of the initial set up [3].

1.3.2 Wind Energy

Wind is one of the nature's potential renewable energy resources. Wind can be harnessed to provide an environmentally friendly and reliable source of energy. Wind energy systems are reliable, cost-effective and environmentally friendly. Wind energy is the ideal power source for many applications. Wind energy systems are available in many sizes, from very small micro systems, which can be mounted on a pole, to more than 1.5 megawatt turbines that can supply energy to the electrical grid. Most stand-alone systems fall into one of three categories: micro systems (100 W or less), mini systems (100 W to 10 kW) and small systems (10 kW to 50 kW). Wind energy systems require a fairly constant wind. They are designed to "cut in" or begin operating, at speeds greater than15 km/h and "cut out" at very high wind speeds to protect themselves from damage. When calculating whether a given site has enough wind energy to effectively operate a wind energy system, the average annual wind speed and the number of days the wind is above the "cut in" point is very important. The wind, of course, is not always present with enough speed to power a wind energy system. This is why many systems are used in combination with another energy source such as solar panels or a diesel generator. Other types of wind energy systems are connected to batteries. When the wind falls below the cut in wind speed of the wind turbine, the batteries are used. When the wind is sufficient, the turbines charge the batteries. Some systems, such as mechanical water pumpers, do not need a backup power supply or batteries.

Initially, wind energy systems tend to cost more than conventional alternatives such as gasoline turbines, but over the long term they can provide inexpensive, low maintenance power. So, wind energy systems are a versatile and reliable alternative of producing energy using a renewable energy source. If wind conditions are right or high in a given area, a wind energy system can provide years of low maintenance and inexpensive power.

1.4 Objectives

The main objective of this thesis is to size and optimize a hybrid PV/wind power generation system applied in the Kingdom of Saudi Arabia. The hybrid system consists of photovoltaic modules and wind turbines. Battery bank is also used to cover the load in case the total power generated by the hybrid system is less than the load demand. Mathematical models for PV modules, wind turbines and storage batteries are developed. Then, a computer program by MATLAB is developed to find the optimum numbers of PV modules, wind turbines as well as storage batteries that is required to cover the load demand with the minimum cost and achieve optimal performance of the hybrid system.

While trying to achieve the main objective, weather data for a full year of the city of Dhahran in the Kingdom of Saudi Arabia including solar radiation, wind speed and ambient temperature are collected. In the photovoltaic model, the horizontal solar radiation should be converted to that on the tilted plane of the photovoltaic module. Also

in the wind turbine model, the wind speed of the weather data should be converted to the corresponding wind speed at hub height of the wind turbine

The specific objectives of this study are briefed in the following:

- To develop a computational model for hybrid PV/wind power generation system.
- To apply the model for the sizing optimization of hybrid PV/wind power generation system.
- To conduct an assessment of hybrid PV/wind power generation system in the Kingdom of Saudi Arabia.

1.5 The Configuration of a PV/Wind Hybrid System

The configuration of a PV/wind hybrid system considered is shown in Figure (1.3). Because of most of electric appliances use AC power supply, an inverter is used before the load. Diesel engine (optional) is used in case the total power generated by the hybrid system is less than the load demand and the charge capacity of the battery bank reach the minimum limit.

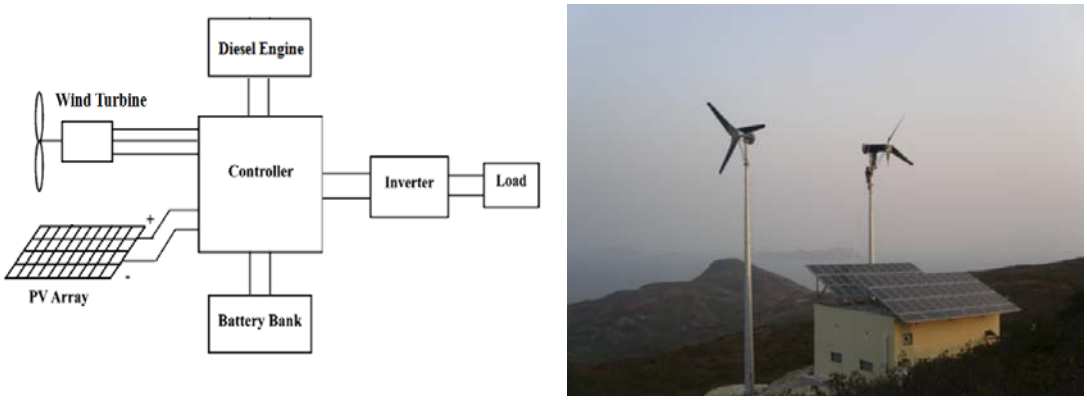


Fig. (1.3) Schematic of PV/wind hybrid system under study

1.6 Thesis Outline

The assessment and optimization for sizing of the feasibility of the hybrid PV/wind power generation system will be carried out according the following steps:

- The first step of the analysis is the development of the mathematical model that comprises all the required equations to model each component of the hybrid system (e.g. PV, wind, battery, etc…).

- The second step is to collect the required weather data of the location under study (solar radiation, wind speed and ambient temperature).

- The third step is to develop the computer code which can solve the developed the mathematical model.

- After that, the developed mathematical model and the computer code are validated with previous published work.

- The validated model is used to conduct the optimization sizing of the system under the weather conditions of Saudi Arabia at the selected location.

The remainder of this thesis is organized as follows:

Chapter two contains literature review. The mathematical models for each hybrid system component (PV Module, wind turbine, battery, diesel engine, modeling of system reliability and economical model) including finding the probability density functions for solar radiation and wind speed weather data are presented in chapter three. In chapter four, the developed mathematical model and computer code validated against previous published work. The validated mathematical model and computer code used to conduct the optimization sizing of the hybrid system under local weather conditions.

CHAPTER 2

LITERATURE REVIEW

The rapid depletion of fossil-fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources. As well, a growing interest in renewable energy resources has been observed, due to their pollution free, availability in all over the world, and continuity. These facts make these energy resources attractive for many applications. Of the many alternatives, photovoltaic and wind energy have been considered as promising toward meeting the continually increasing demand for energy. The wind and photovoltaic sources of energy are inexhaustible, the conversion processes are pollution-free, and their availability is free. In some cases, however a single energy source system, e.g., a standalone solar energy system, cannot provide a continuous source of energy due to the low availability during the no-sun period and the winter. This implies that in order to achieve the high energy availability required in some application such as: lighting, electrification of remote areas and telecommunications it is necessary to oversize the rating of the generating system (e.g., surface of the photovoltaic array, rating of wind turbine). On the other hand it is possible to use hybrid system where two or more renewable energy sources are exploited.

For creating a small scale demonstration system to study the feasibility and effectiveness of solar and wind power in addition to supply a small building through net metering, a grid-ties residential size hybrid system combining solar and wind power generation system was constructed at Frostburg State University by Soysal [5]. The study mainly concluded that in summer, the output energy of the system is mainly produced by the PV system; while in winter, the wind turbine output becomes greater. This is because the PV output decreases because of less sunlight available and shading by surrounding obstacles.

It has also been observed that the wind turbine contributes to the energy output of the system significantly in cloudy and windy days, when the PV output is not great.

In their work, Chedid and Rahman [6] employed a linear programming technique for sizing optimally hybrid wind-solar power systems with minimum average production cost of electricity while meeting the load requirements in a reliable manner. A controller for the system operations was designed to determine the energy available from each of the system components and for monitoring the environmental credit of the system. The controller gave details about the cost, unmet and spilled energies, and battery charge and discharge losses.

Shun and Ahmed [7] designed a low-cost hybrid ventilation device that utilizes both wind and solar energy as power sources. A commercially available wind driven turbine ventilator was used for the project. The turbine ventilator consisted of a cylindrically shaped rotating element which has several curved blades forming part of the rotating element. The blades extract energy from the prevailing wind and spin the rotating element, and also act to apply a motive force which results in exhaust air being centrifuged from the device. The solar powered ventilator used in the study consisted of a single stage axial fan driven by an electric motor which received power from a solar cell. The experimental test setup was formulated after considering testing procedures outlined in Australian Standards on the classification and performance testing of natural ventilators. Using wind tunnel testing, it was proved that the device had improved operational and performance benefits compared with conventional commercial roof top ventilators, particularly at zero to low wind speeds. Even under conditions of zero wind

and bad light, air extraction was possible, which represents a significant step forward in promoting the use of clean energy for the purposes of building ventilation.

Barley et al. [8] described an analysis of hybrid wind/photovoltaic (PV) system for providing electricity to about one-third of the non-grid connected households in Inner Mongolia. Based on a subjective trade-off between the cost of the system and the percent unmet load the sizing of the major components of the system was determined. Hybrid2 software in conjunction with a simplified time-series model was employed for the sizing calculations. Actual resource data for both wind speed and solar radiation from the region are processed so as to best represent the scenarios of interest. Small wind turbines of both Chinese and U.S. manufacture were considered in the designs. Among the several results presented by the study, it was shown that the addition of PV to the wind-only system, in conjunction with an increase of battery capacity, reduces the unmet load from 14% to 3.3%, with a cost increase of only 22%. The relative amount of PV in the indicated designs increases as the acceptable unmet load decreases and as the average wind speed decreases.

A methodology has been introduced for evaluating and segregating load requirements and characteristics to size hybrid energy source/storage elements for handling the types of loads for which they are best suited [9]. The presented methodology in the paper is general enough to be applied to any application with two or more source/storage elements, even without adequate knowledge of load profiles. The work focused on evaluating the suitability of a dual-source battery and ultra capacitor pack in place of the do-all single-battery solution that is being sought for hybrid electric applications. An

example battery and ultra capacitor combination for a midsize hybrid electric vehicle was used for demonstrating the general methodology. Average characteristics of a standard midsize passenger car were used to develop vehicle power load profiles. The paper concluded that future work based on load averaging developments should lead to (1) implementing load averaging in a real-time control system with real-world requirements taken into account, such as SOC control and gear selection for maximum engine operating efficiency, and (2) using optimization to adjust filter time constant settings and component sizing to obtain maximum fuel economy, minimum mass, and minimum volume.

Borowy and Salameh [10] developed a methodology for calculating the optimum size of a battery bank and the PV array for a standalone hybrid Wind PV system. As a load demand of the hybrid system, a load of a typical house in Massachusetts was used and the long term data of wind speed and irradiance recorded for every hour of the day for 30 years were used. For a given loss of power supply Probability, a different combination of the number of PV modules and the number of batteries were calculated and PV modules was calculated based on the minimum cost of the system. It was assumed that total cost of the system is linearly related to both the number of PV modules and the number of batteries and the minimum cost will be at the point of tangency of the line cost and the curve that represents the relationship between the number of PV modules and the number of batteries. The program for calculation of the number of batteries and PV modules was written in PASCAL programming language.

A novel method was introduced by Celik [11] for the purpose of optimally sizing an autonomous PV-wind hybrid energy system with battery storage on a techno-economic basis. The level of autonomy and the cost of the system were the targeted objectives of the study. As a case study, the design of a hypothetical system based on yearly Cardiff (UK) weather data was performed by applying the new and the existing similar techniques using Cardiff 1994 weather data. It was observed in the study that the worst month based scenarios lead to the least optimal systems in terms of techno-economics. It was also shown that even though the worst month's scenario provides a high level of autonomy (99%), the corresponding system cost turns out to be too high and that using different scenarios, the same level of autonomy (99%) could be obtained at less cost by the introduction of a third energy (auxiliary energy) supply. The study also concluded that the goodness of a sizing technique is largely site specific and that before any sizing method is used, the monthly solar radiation and wind speed distributions must be analyzed at the probable installation site.

A novel description of the production/consumption phenomenon has been proposed, and a new sizing procedure has been developed by Hocaoglu et al. [12]. Using this procedure, optimum battery capacity, together with optimum number of PV modules and wind turbines subject to minimum cost has been obtained with good accuracy. The difference and contribution of the proposed method is in the determination of the minimum supply size – versus – maximum battery size point. This point is found by initially assuming the charge of battery capacities to be infinity to calculate the optimum number of PV and wind turbine that can supply the load with desired reliability. After this sub-optimization step, a system with the smallest size of energy supply units is obtained. It is shown that

the battery size satisfying this case gives an upper bound for the battery capacity. Therefore, it is suggested that the global optimization can be achieved by gradually decreasing the battery size from this extrema, and running classical optimization procedures for the energy sources. The combination of battery cost and source costs on the overlaid plots as a function of battery number also gives an insight about how the optimal point could be achieved between a minimal (say, one) battery capacity and the obtained maximum battery. The method is tested, verified, and illustrated on the data obtained from Eskisehir region, Turkey. Besides the determination of the prescribed extremum point for the purpose of bounding the search space during the minimum cost evaluation, the approach also gives an insight about how the cost figures alter with respect to the number of batteries.

Vick et al [13] used a combination of wind and solar energy successfully to power an ultraviolet water purification system. The graphs contained in their paper could be used to determine the feasibility of powering other electrical loads. They showed that combining a 100-W solar-PV system with a 500-W wind turbine resulted in pumping and purifying enough water to satisfy the potable water requirements of 4000 people (16000 liters/day) at an estimated equipment cost of $4630. For the purpose of extending the battery lifetime, a controller dump load containing resistive elements was used to absorb the excess renewable energy which prevented overcharging the batteries of the system. The controller dump load also kept the wind turbine from spinning too fast because the wind turbine was always loaded. Reduced rotor speed also reduced the noise and extended the lifetime of the wind turbine.

Zhou et al [14] presented a simple mathematical approach to simulate the lead–acid battery behaviors in standalone hybrid solar–wind power generation systems. Several factors that affect the battery behaviors have been taken into account, such as the current rate, the charging efficiency, the self-discharge rate, as well as the battery capacity. Good agreements were found between the predicted results and the field measured data of a hybrid solar–wind project. It has been found that the battery state-of-charge has strong variations both monthly and hourly, but it is more affected by the PV power than by the wind power. The battery has also been demonstrated to be in good working states with 86.7% opportunities for the battery state-of-charge to remain higher than 0.5, and the over discharge situations seldom occurred throughout the studied year.

A research work has carried out by Nandi and Ghosh [15] on optimization of a wind–photovoltaic-battery hybrid system and its performance for a typical community load in Bangladesh. For feasibility and optimum sizing of the components simulation software, Hybrid Optimization Model for Electric Renewable (HOMER) has been used. The assessment criterions of the analysis were cost of energy (COE) used by the households, net present cost (NPC), excess energy, renewable factor and payback time. The assessment showed that least cost of energy (COE) is about (0.363 $/kWh) for a community using (169 kWh/day) with (61 kW) peak and having minimum amount of access or unused energy. Moreover, compared to the existing fossil fuel-based electricity supply, such an environment friendly system can mitigate about (25 Tons of CO_2 / year). The analysis also indicated that wind–PV battery is economically viable as are placement for conventional grid energy supply for a community at a minimum distance of about 17km from grid.

A computer-aided design of PV/wind hybrid System was developed by Ai et al [16]. A complete set of match calculation methods for optimum sizing of PV/wind hybrid system was presented. In this method, the more practical mathematical models for characterizing PV module, wind turbine and battery were adopted. According to local hourly measured meteorological data, load demand, the characteristic and price of the components and reliability requirement on power supply, the optimum configuration which meets the load demand with the minimum cost were determined by this method. Based on this method, a set of match calculation programs has been developed. Applying these programs to an assumed PV/wind hybrid system to be installed, two optimum configurations and their detailed operating situations are given.

Habib et al [17] presented an optimization procedure of a hybrid photovoltaic wind energy system which can be used to satisfy the requirements of a given load distribution (5 kW). The procedure was based on calculating the optimal percentage of power produced by each of the two separate systems that make up the hybrid system, namely solar and wind. The objective of the optimization procedure was to size a hybrid system that satisfies an annual specified load demand with the minimum cost. A hybrid solar/wind system with different PV array areas and multiple wind turbines of 18 kW rated power was considered. The study showed that the cost of the hybrid system depends largely on the solar/wind power ratio and the results indicated that the optimal solar/wind ratio that resulted in the minimum capital cost is 70%.

Diaf et al [18] presented a methodology to perform the optimal sizing of an autonomous hybrid PV/wind system. They have proposed mathematical models for characterizing PV

module, wind turbine and battery. They have also focused on optimization of sizing of the PV/wind system according to the loss of power supply probability (LPSP) and the levelized cost of energy (LCE) concepts. It has been found that the configuration with the lowest LCE gives the optimal choice. The methodology (simulation and optimal sizing) has been applied to a PV/wind hybrid system to be installed at a remote Island. The simulation results, for 0 LPSP as a desired criteria, show that in order to obtain a total renewable contribution (RC = 1), more than 30% of the energy production is unused unless the battery capacity is very large. On the other hand, while in a renewable contribution of about 85%, the energy excess percentage decreases to 5%, for a configuration with one wind turbine and below 15% for that comprising two turbines. The study concludes that a hybrid system comprising of wind, PV and battery storage has been found to be optimal from both the economical and technical point of view. The study also highlights that in order to reduce the energy excess, corresponding to the lowest LCE, the use of a third energy source (diesel) can be beneficial.

Hongxing et al [19] recommended an optimal design model for designing hybrid solar–wind systems employing battery banks for calculating the system optimum configurations and ensuring that the annualized cost of the systems is minimized while satisfying the custom required loss of power supply probability. The decision variables included in the optimization process are the PV module number, PV module slope angle, wind turbine number, wind turbine installation height and battery number. The proposed method has been applied to design a hybrid system to supply power for a telecommunication relay station. The research and project monitoring results of the hybrid project were reported, good complementary characteristics between the solar and wind energy were found, and

the hybrid system turned out to be able to perform very well throughout the year with the battery over-discharge situations seldom occurred. With a one year hourly measured field data, the monthly energy contribution of each component (PV module and wind turbine), the battery working states and the energy balance were investigated. The energy contributions from photovoltaic and wind turbines varied greatly from one month to the next, but good complementary characteristic between solar energy and wind energy were found.

A probabilistic approach for a Hybrid solar/wind power system was presented by Tina et al [20]. The approach is based on the convolution technique to assess the long-term performance of a hybrid solar–wind power system for both stand-alone and grid-linked applications. Analytical expressions were developed to obtain the power generated. The hybrid system and the load models employed enable the study period to range from one year to one particular hour-of-day, thus allowing the inclusion of the time-value of energy as appropriate in economic assessments. The work has shown by means of a case study, that a good evaluation of the long-term average performance of a hybrid system can be obtained through a statistical approach alternative to time step simulations. The amount of solar radiation that reaches the ground, besides on the daily and yearly apparent motion of the sun depends on the geographical location (latitude and altitude) and on the climatic conditions (e.g., cloud cover). Many studies have proved that cloudiness is the main factor affecting the difference between the values of solar radiation measured outside the atmosphere and on ly surface. To account for the difference between these two values, a daily clearness index (K_t) has been defined as the ratio of a particular day's total solar radiation (H_t) [MJ/m^2], to the extraterrestrial total solar radiation (H_o) [MJ/m^2]

for that day, both referred to a horizontal surface. He also defined an hourly clearness index (k_t) as the ratio of the irradiance on a horizontal plane, (I) [kW/m^2], to the extraterrestrial total solar irradiance (I_o) [kW/m^2]. Knowing the hourly clearness index (k_t), it is possible to determine the irradiance on a surface with inclination (β) to the horizontal plane, (I_T) [kW/m^2]. Since the PVS is usually equipped with a maximum power point tracker (MPPT) and the relationship between the maximum power per unit area of array surface available from PVS and (I_T) is linear. The wind speed distributions for selected sites as well as the power output characteristic of the chosen wind turbine are the factors that have to be considered to determine the WECS power output [19]. Since the wind speed (v) is a random variable, a long-term meteorological data is desirable to describe wind energy potential of the sites. In order to account the variability of wind speed, during the(jth) hour (j = 1,2,. . . , 24) of the (mth) month (m = 1,2,. . . , 12), it is assumed to be characterized by a Weibull distribution with a scale parameter (α_w) and a shape parameter (β_w). For a typical (WECS), the power output characteristic can be assumed in such a way that it starts generating at the cut-in wind speed (v_c), the power output increases linearly as the wind speed increases from (v_c) to the rated wind speed (v_R). The rated power (P_R) is produced when the wind speed varies from (V_R) to the cut-out wind speed (v_F) at which the (WECS) will be shut down for safety.

Nfah et al [21] introduced a configuration to produce electrical power from renewable energy hybrid system using solar/diesel/battery hybrid power systems which have been modeled for the electrification of typical rural households and schools in remote areas of the far north province of Cameroon. The hourly solar radiation received by latitude-titled and south-facing modules was computed from hourly global horizontal solar radiation

weather data. Assuming that maximum-power-point tracker (MPPT) is used and that the PV module is always working at the maximum-power point, the monthly energy production of the solar modules was computed. It has been demonstrated that the solar resource can be used to model solar/ diesel/battery hybrid power systems for the electrification of typical rural households and a secondary school with energy demands in the range 70–2585 kWh/yr. These results showed that there is a possibility to increase the access rate to electricity in the far north without recourse to grid extension or more thermal plants in the northern grid or more independent diesel plants supplying power to remote areas of the province. However, the hourly state of charge of the battery bank that determines the number of start/stop cycles of the diesel generator was not computed due to the lack of hourly load profiles. Also, the unit cost of energy produced by the modeled systems has not been computed. An economic analysis of power supply options involving grid extension, a conventional diesel generator plant, and solar/diesel/battery hybrid power system is yet to be done to encourage the use the solar/ diesel/battery hybrid power systems that have been modeled in this paper for far north Cameroon.

Wind/Diesel/battery hybrid power systems have been modeled for electrification of typical rural households and schools in remote areas of the Far North Province of Cameroon [22]. Two wind turbines with rated powers 180 W and 290W were used in sizing wind hybrid systems for typical rural households energy needs in the range 70–300 kWh per year. It was found that a wind/Diesel hybrid power system based on a combination of two wind turbines rated 290 W and a 5 kW single phase generator operating at a load fraction of 70% required only 106 generator hours/yr to supply 2585

kWh/yr or 7 kWh/day to a typical secondary school. The renewable energy fractions attained in feasible systems were in the range 70–100%.

Yang et al [23] developed the hybrid solar-wind system optimization sizing model (HSWSO), to optimize the capacity sizes of different components of hybrid solar-wind power generation systems employing a battery bank. The model consists of three main parts. These are system models for PV system, wind system and battery bank; the technical model developed according to the Loss of Power Supply Probability technique for system reliability evaluation; and the economic model developed based on the concept of the Levelised Cost of Energy for cost analysis. A case study is reported to show the importance of the (HSWSO) model for sizing the capacities of wind turbines, PV panel and battery banks of a hybrid solar-wind renewable energy system. A hybrid solar-wind system was simulated by running the model program, and its relationships with system configurations were also analyzed. The optimal configurations of the hybrid system were obtained in terms of different desired system reliability requirements and the Levelized Cost of Energy for cost analysis. The optimal configuration of the number of PV modules, the capacity of wind turbine, and the capacity of battery bank were found to be obtained technically and economically by using the model.

Nema et al [24] introduced a paper which aimed to review the current state of the design, operation and control requirement of the stand-alone PV solar–wind hybrid energy systems with conventional backup source like diesel pickup engine or grid. This Paper also highlighted the future developments, which have the potential to increase the economic attractiveness of such systems and their acceptance by the user. Solar energy

conversion system depends upon the solar cell and photovoltaic module. The total solar radiation thus estimated depends on position of sun in the sky, which varies from month to month. The wind turbine is characterized by non-dimensional performance as a function of tip speed ratio. For small-scale wind turbines, the cut-in wind speed is relatively smaller, and wind turbines can operate easily even when wind speed is not very high.

In Iraq, the electric power generated is not enough to meet the power demand of domestic and industrial sectors. So Dihrab and Sopian [25] proposed a hybrid system as a renewable resource of power generation for grid connected applications in three cities in Iraq. The proposed system was simulated using MATLAB solver, in which the input parameters for the solver were the meteorological data for the selected locations and the sizes of PV and wind turbines. The PV cell can directly convert the sunlight to DC power through the photoelectric phenomena. Usually the PV manufacturer supply their products with a data sheet that contains values of voltage and current for three conditions namely, the short circuit, the open circuit and the maximum power for a given set of reference condition. The reference solar irradiation and temperature is (I_{st}) = 1000 (W/m^2) and (T_{st}) = 25 (°C), respectively. In short circuit condition, the diode current is very small and the light current is equal to the short circuit current. Wind is a form of solar energy. It is caused by uneven heating of the atmosphere by the sun, irregularities of the Earth's surface, and rotation of the Earth. Wind flow patterns are modified by Earth's terrain, bodies of water, and vegetation. Human use this wind flow, or motion energy, for many purposes such as sailing, flying a kite, and even generating electricity. The amount of power transferred to a wind turbine is directly proportional to the area swept out by the

rotor, the air density, and the cubic power of the wind speed. The results showed that it is possible for Iraq to use the solar and wind energy to generate enough power for some villages in the desert or rural area. It is also possible to use such a system as a black start source of power during total shutdown time. Results also indicated that the preferred location for this system is in Basrah for both solar and wind energy.

De Soto et al [26] proposed a five parameter model that uses manufacturer's data, absorbed solar radiation and cell temperature together with semi-empirical equations to predict current-voltage curve. The model requires a one-time calculation of the five parameters (a_{ref}; ideality factor parameter, $I_{o,ref}$; diode reverse saturation current at SRC, $I_{L,ref}$; light current at SRC, $R_{s,ref}$; series resistance at SRC and $R_{sh,ref}$; shunt resistance at standard rating conditions SRC). These parameters depend on solar radiant energy and cell temperature. They are used in the model to calculate the parameters at other operating conditions since they are provided as functions of temperature. Results were compared with building integrated photovoltaic facility for four different cell technologies including single and poly crystalline silicon cells. Good agreement was recorded and thus the model is useful since it relies on small amount of input data that are typically given by manufacturers. It was also reported by the investigators that the model deviation with experimental data can be reduced when additional experimental data (I-V) at two radiation models are used to determine the reference parameters.

Jones et al [27] modeled the transient energy balance of PV cells based on climate variables. They considered both short and long wave radiation in addition to convection (free and forced) and electrical energy generation. Both convection and radiation from

the module surfaces are significant. Results were compared with measured data where the model was found to be effective in clear weather within 5 K of measured values 95% of the time. In transient data, the model responded qualitatively with slight increase in the predicted values.

For hybrid power generation systems utilizing photovoltaic and wind energy, a unit sizing optimization deterministic approach was investigated by Yokoyama, etc [28]. Using the weighing method, numerical solutions were obtained for minimizing the annual cost and energy consumption. The investigations accommodated two systems interconnected with and without electric power grid: allowing the reverse electricity flow into the grid. The tradeoff relationships between the two objectives of the study, in addition to the optimal sizing of device capacities were presented for some case studies.

A process was developed to evaluate the economic benefits from constructing and operating a wind energy project [29]. The process uses an economic input/output analysis in conjunction with Monte Carlo simulation. Process results estimate the number of jobs and amount of spending that will occur in the analysis region because of the construction and operation of a wind energy project. Results from the proposed process may be used to garner community and governmental support for projects. The National Renewable Energy Laboratory jobs, Economic Development and Impacts (JEDI) model, developed specifically for wind energy projects, is used. As there is uncertainty in some of the required input parameters, the Monte Carlo simulation allows the input parameters to be entered as a range. The results of the JEDI model with the Monte Carlo simulation analysis produce a distribution for jobs, salaries and wages, and economic output during

construction and operations. The results of the Monte Carlo simulation also provide a sensitivity analysis for each of the JEDI outputs. Two northern Arizona counties, Coconino County and Navajo County, were analyzed to demonstrate the process.

The Maximum Likely Estimation (MLE) method and the Method of Moments (MOM) for wind speed modeling were described by Zuwei et al [30]. The Weibull wind speed distribution models are fitted using the two methods and the wind data from a tall tower in the Midwestern United States, with seasonal wind speed variations also considered in the modeling. It turned out that both methods provide very similar results with comparable accuracy. The Monte Carlo simulation is used for obtaining expected wind energy production using a Weibull sampling technique.

A methodology is developed to estimate the chord distribution airfoil and blade twist along the radius of the blade by using axial and angular moment conservation equations, blade element theory and optimization processes [31]. This methodology takes into account the concept related with getting wind power for different chord blade values and selecting one that facilitates to get the maximum value for wind power. Simulation of power generation output was carried out by using a wind-speed probability distribution function (PDF) obtained from data collected at the Guajira region of Colombia.

By combining today's techniques of energy conversion and storage it is possible to construct energy supply systems based to a high degree of renewable sources [32]. At Oldenburg University a small laboratory building is in operation whose energy supply is covered by solar radiation, wind energy and to a small extent by conventional fuel. The authors report on simulation calculations for such systems using experimentally validated

models for converters and storage devices. In particular the influence of system parameters such as size of different converters and battery capacity on the renewable fraction and the energy payback time of the whole system is discussed.

Stand-alone photovoltaic power systems with different energy storage technologies have been studied by Li et al [33]. Due to the intermittent nature of solar energy, energy storage is needed in a stand-alone PV system for the purpose of ensuring/ascertaining continuous power flow. Specifically, the following combinations: photovoltaic/battery, photovoltaic/fuel-cell, and Photovoltaic/fuel-cell/battery have been modeled/optimally-sized/analyzed/compared. The results indicate that maximizing the system efficiency while minimizing system cost is a multi-objective optimization problem. A combination with photovoltaic/fuel-cell/battery has been found to give higher efficiency, lower cost, and less PV modules as compared to other configurations.

Ian et al. [34] attempted to explore the current practicalities of utilizing combined wind/PV (together with an energy storage system) power generation system for powering the cellular phone base stations (*total load = 4 kW, i.e. 35 MWh/year*). These stations are rural/remote (located in UK) where an electric supply is not available. The storage (10 days autonomy; i.e. 1 MWh) is required to bridge the gap between the energy being available, e.g. the wind blowing hard (or not), and the instantaneous load consumption. The study indicates that the load can be covered by a combination of 15 kW wind turbine (generates about 35 MWh/year, with an efficiency of 27%) and 25 m^2 PV array (generates about 3 MWh/year). The study concludes that short-term autonomy is best provided by a VRLA battery (lead–acid recombination batteries of the VRLA type). The

longer term intermittence of the wind demands a back-up power supply best provided by a diesel generator. The battery will minimize the start/run demand on the diesel engine, which in turn will minimize the required size of the battery storage capacity.

Divya et al. [35] have developed models for various types of wind generating units (WTGU) such as: fixed, semi-variable and variable speed types. The proposed models have been used to study the impact of wind speed and terminal voltage variation on the behavior of each type of WTGU. The study indicates that the real power output of all the types of WTGU (considered in the study) at any given wind speed does not change perceptibly even with significant changes in terminal voltage.

De Soto et al. [36] proposed a five parameter model that uses manufacturer's data, absorbed solar radiation and cell temperature together with semi-empirical equations to predict current-voltage curve. The model requires a one-time calculation of the five parameters (a_{ref}); ideality factor parameter, ($I_{o,ref}$); diode reverse saturation current at (SRC), ($I_{L,ref}$); light current at SRC, ($R_{s,ref}$); series resistance at (SRC) and ($R_{sh,ref}$); shunt resistance at (SRC). These parameters depend on solar radiant energy and cell temperature. They are used in the model to calculate the parameters at other operating conditions since they are provided as functions of temperature. Results were compared with building integrated photovoltaic facility for four different cell technologies including single and poly crystalline silicon cells. Good agreement was recorded and thus the model is useful since it relies on small amount of input data that are typically given by manufacturers. It was also reported by the investigators that the model deviation with

experimental data can be reduced when additional experimental data (I-V) at two radiation models are used to determine the reference parameters.

Jones et al. [37] modeled the transient energy balance of PV cells based on climate variables. They considered both short and long wave radiation in addition to convection (free and forced) and electrical energy generation. Both convection and radiation from the module surfaces are significant. Results were compared with measured data where the model was found to be effective in clear weather within 5 K of measured values 95% of the time. In transient data, the model responded qualitatively with slight increase in the predicted values.

Hongxing et al. [38] proposed a model to predict the PV module performance based on the module current voltage (I-V) curves. They introduced five parameters to account for the dependence of PV module performance on solar irradiation intensity and the module temperature. The five parameters are: three constant parameters related to nonlinear environment effects on the PV module in addition to series resistance of the module and ideality factor at maximum power point. Thus, the most important parameters, namely, the short circuit current, open circuit voltage, fill factor and maximum module power output can be determined with minimum input of the manufacturer's data. They validated the model using field measurements and a good agreement was reported for both sunny and cloudy conditions.

Hessami et al. [39] addressed a feasibility study of hybrid wind power systems by investigating the technical and economic feasibility of replacing diesel power generation with hybrid wind power systems in remote communities. The economic, technical and

environmental characteristics of eight different hybrid wind power systems were established and compared in respect to their performance in the isolated community of French Island. The obtained results demonstrated the economic and environmental superiority of the hybrid wind– diesel–battery system over all other studied systems. This system was found to have the lowest net present cost and cost per kWh among the modeled systems. Furthermore, the results clearly indicated that hybrid wind power systems are, in general, a feasible and preferable alternative to diesel power generation.

A general outline of a simulation model used to size and assess the performance a PV installation using DELPH5 programming language was presented by Benatiallah et al [40]. This program allows the user to determine at any moment the performance of the PV installation by comparing the PV electric energy produced and the required consumption load and. It also permits the optimization of the system relative to the factor of time. The program also allows the user to assess the electric power output for different site configuration and data as well as different energy consumption needs of the consumer.

Raquel et al. [41] compared two models to determine the size of grid units and dispatch in a wind-diesel power system with hydrogen storage. Both take as data one year time series of hourly wind speed and electricity demand, and their objective is to minimize cost. The first model was based on linear programming, generates as output a combination of capacities and a year time series for the dispatch variables. The second model runs a fixed dispatch rule over several capacity combinations and selects the cheapest option. The results illustrated the complex interdependence between unit sizing decisions and

dispatch policies in the presence of storage. It has seen that the choice of dispatch policies can have a significant impact on overall cost of hybrid systems. Under a good operation rule the contribution of renewable energy is higher in the optimal solutions.

A combined system which is produced electrical energy from both solar radiation via solar cells and wind energy by using wind turbine was studied by Ozdamar et al [42]. For wind energy, measurements of wind velocities at 12 m height were taken. Then, these values were calculated for 42 m by using Hellmann equation. After that, wind energy converted to the electrical energy. However, value of solar radiation from solar cells was taken at the optimum slope angle of collector which provided higher energy production for each 1 h during this application. Thus, obtained data from each system were used together for finding total energy. It can be seen from the results that wind and solar energy support each other. Also it can be seen that either just solar energy system or just wind energy system cannot satisfy constant load demands. Therefore, wind and solar energy systems can be used as a combined system to meet continuous energy demand.

Skunpong et al [43] presented a simple and practical method for PV sizing which takes very short time for zing PV system using HOMER software. The calculation focused on both PV stand alone and PV hybrid system. The simulation result showed that the PV system can supply power to the load demand without any shortage or unmet load and the PV system can cover the load even there were two continued low radiation days. Shen [44] investigated a size optimization of solar array and battery in a standalone photovoltaic (SPV) system. Based on the energy efficiency model, the loss of power supply probability (LPSP) of the (SPV) system was calculated for different size

combinations of solar array and battery. For the desired LPSP at the given load demand, the optimal size combination is obtained at the minimum system cost. One case study is given to show the application of the method in Malaysian weather conditions.

Al-Badi et al [45] utilized the average daily global solar radiation and sunshine duration data of 25 locations in Oman to study the economic prospects of solar energy. The study considered a solar PV power plant of 5-MW at each of the 25 locations. The global solar radiation varies between slightly greater than (4 kWh/m^2/day) at Sur to about (6 kWh/m^2/day) at Marmul while the average value in the 25 locations is more than (5 kWh/ m^2/day). The results showed that the renewable energy produced each year from the PV power plant varies between (9000 MWh) at Marmul and (6200 MWh) at Sur while the mean value is (7700 MWh) of all the 25 locations. The capacity factor of PV plant varies between 20% and 14% and the cost of electricity varies between 210 US$/MWh and 304 US$/MWh for the best location to the least attractive location, respectively. The study has also found that the PV energy at the best location is competitive with diesel generation without including the externality costs of diesel. Renewable energy support policies that can be implemented in Oman are also discussed.

Rehman et al. [46] performed a pre-feasibility of wind penetration into an existing diesel plant of a village in north eastern part of Saudi Arabia. For simulation purpose, wind speed data from a nearby airport and the load data from the village have been used. The hybrid system design tool HOMER has been used to perform the feasibility study. The results showed that the wind diesel hybrid system becomes feasible at a wind speed of 6.0 m/s or more and a fuel price of 0.1 $/L or more. Finally the authors recommended that

the wind data must be collected at the village at three different heights using a wind mast of 40m for a minimum of one complete year and then the hybrid system must be re-designed.

A methodology for optimal sizing of stand-alone PV/WG systems is presented by Koutroulis et al [47]. The purpose of the proposed methodology to suggest, among a list of commercially available system devices, the optimal number and type of units ensuring that the 20-year round total system cost is minimized subject to the constraint that the load energy requirements are completely covered, resulting in zero load rejection. The proposed method has been applied for the design of a power generation system which supplies a residential household. The simulation results verify that hybrid PV/WG systems feature lower system cost compared to the cases where either exclusively WG or exclusively PV sources are used.

Belfkiraet et al [48] presented a methodology of sizing and optimization of a stand-alone hybrid wind/PV/diesel energy system. The approach made use of a deterministic algorithm to suggest, among a list of commercially available system devices, the optimal number and type of units ensuring that the total cost of the system is minimized while guaranteeing the availability of the energy. The collection of 6 months of data of wind speed, solar radiation and ambient temperature recorded for every hour of the day were used. The mathematical modeling of the main elements of the hybrid wind/PV/diesel system is exposed. A deterministic algorithm was used to minimize the total cost of the system while guaranteeing the satisfaction of the load demand. A comparison between

the total cost of the hybrid wind/PV/diesel energy system with batteries and the hybrid wind/PV/diesel energy system without batteries was presented.

Mansouri et al [49] presented a study of a structure composed of a wind turbine, a speed multiplier and an asynchronous generator coupled to the infinite power network through a line of energy transfer electric. After modeling of the global system, the behavior of the proposed structure in steady states and in transient regimes was studied. The results showed that if the wind speed changes too much variation, this will cause a violent variation of power and result in step out operation of the generator from the power system. A control strategy to reduce the power variations by introducing feed forward control combined with conventional feedback control was proposed.

Shafiqur Rehman and Al-Hadhrami [50] presented a PV/diesel hybrid power system with battery backup for a village being fed with diesel generated electricity to displace part of the diesel by solar using HOMER program in a small village Rowdat Ben Habbas located in the north eastern part of the Kingdom. It was found that a PV array of 2000 kW and four generators of 1250, 750, 2250 and 250 kW; operating at a load factor of 70% required to run for 3317 h/yr, 4242 h/yr, 2820 h/yr and 3150 h/yr, respectively; to produce a mix of 17,640 MWh of electricity annually and 48.33 MWh per day. The cost of energy (COE) of diesel only and PV/diesel/battery power system with 21% solar penetration was found to be 0.190$/kWh and 0.219$/kWh respectively for a diesel price of 0.2$/l.

The thorough literature survey sited above for the modeling analysis and optimization system show that it is a promising approach to electrify remote areas. However, the

modeling approach differ from one article to another and there is no a standard approach that can give a reliable results. Some models just used the raw weather data for one year and some have used the statistical weather data for prediction and imposing the probability density function. Moreover, there is no single article that model and analyze hybrid wind-solar power generation system in Saudi Arabia in the Gulf area except that reference in Iraq [25]. So this lack in the literature about modeling wind-solar system for Saudi Arabia motivated the present work.

CHAPTER 3

THE MATHEMATICAL MODEL

The mathematical model developed during the present work to simulate the hybrid PV-wind-diesel electric power generation system to electrify an off-grid load, consists of a separate mathematical model for each component of the system. These models were integrated together so as to satisfy a given load. In this regard, the mathematical model for the PV array consists of the main equations of PV module along with solar data of the required location. The wind turbine mathematical model is basically developed from the manufacturer data. Equations for the battery and diesel engine as well as the inverter are also included. To obtain reliable results, the probability function of the solar and wind weather data is imposed and used to calculate the power output of the solar PV array and the power output of the wind turbine. Integrating all equations to produce the power output of the hybrid system as well as the charging and discharging of the batteries with the required load, make us able to estimate the required number and size of the batteries required to satisfy the load. Sensitivity analysis for the sizing of the PV modules, wind turbine and battery size was carried out to optimize the system for the LEC. The details of the developed mathematical model are given here under.

3.1 Mathematical Model of PV Array

The operating voltage and current determine the power output of the PV array depending on the light intensity falling on the PV module, ambient temperature and the manufacturer characteristic properties of PV module.

The hourly total power output of PV array will be:

$$P_{PV} = n_{pv} V_{PV} \; i_{PV} \; F_c \; F_o \tag{3.1}$$

Assuming that maximum power point tracker (MPPT) is used and the PV module is always working at the maximum power point. The formulas for calculating the optimum operating point current and voltage under arbitrary conditions have the following forms [16]:

$$i_{PV} = i_{SC} \left(1 - C_1 \left[\exp\left(\frac{V_{PV} - \Delta V}{C_2 V_{OC}} \right) - 1 \right] \right) + \Delta i \tag{3.2}$$

Where

$$C_1 = \left(1 - \frac{i_{mp}}{i_{SC}} \right) \exp\left(-\frac{V_{mp}}{C_2 V_{OC}} \right) \tag{3.3}$$

$$C_2 = \frac{V_{mp} / (V_{OC} - 1)}{\ln\left(1 - i_{mp} / i_{SC}\right)} \tag{3.4}$$

$$V_{PV} = V_{mp} \left[1 + 0.0539 \log\left(\frac{I_T}{I_{st}} \right) \right] + \beta_o \Delta T \tag{3.5}$$

$$\Delta V = V_{PV} - V_{mp} \tag{3.6}$$

$$\Delta i = \alpha_o \left(\frac{I_T}{I_{st}} \right) \Delta T + \left(\frac{I_T}{I_{st}} - 1 \right) i_{SC} \tag{3.7}$$

$$\Delta T = T_{cell} - T_{st} \tag{3.8}$$

$$T_{cell} = T_A + 0.02 I_T \tag{3.9}$$

For the meanings of the symbols in above equations, refer to the nomenclature. The same remarks can be applied to other equations in this thesis.

While calculating the hourly output of PV module, the average hourly solar radiation on horizontal surface (I) which usually comes from weather stations, has to be converted to that on the PV module (I_T). Assuming that combination of the diffuse and ground-reflected radiation is isotropic. The summation of the diffuse radiation from the sky and the ground- reflected radiation on the tilted surface is the same regardless of orientation, and the total radiation on the tilt surface is the summation of the beam contribution calculated as ($I_b R_b$) and the diffuse on the horizontal surface, (I_d). A surface tilted at angle (β) from the horizontal has a view factor to the sky which is given by $(1+\cos\beta)/2$. (If the diffuse radiation is isotrobic, this is also (R_d), the ratio of diffuse on the tilted surface to that on the horizontal surface). The surface has a view factor to the ground which is $(1-\cos\beta)/2$.

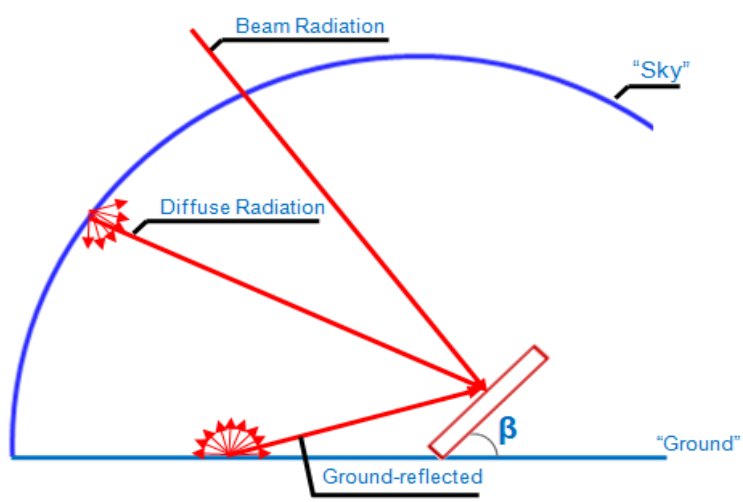


Fig. (3.1) Beam, diffuse, and ground-reflected radiation on a tilted surface [2]

So the total solar radiation on the tilted surface for an hour as the sum of three terms as the following [2]:

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2} \right) + I\,\rho_g \left(\frac{1-\cos\beta}{2} \right) \tag{3.10}$$

Where (R_b) is the ratio of beam radiation to that on a horizontal surface and can be defined as

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\cos(\phi-\beta)\cos\delta\sin\omega + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega + \sin\phi\sin\delta} \tag{3.11}$$

Where (θ) is the angle of incident which is between the beam radiation on a surface and the normal to that surface, (θ_z) is zenith angle which is between the virtical and the line to the sun.

To find beam contribution ($I_b R_b$) and the diffuse on the horizontal surface (I_d), we should calculate the extraterrestrial radiation on a horizontal surface for an hour period between hour angles ω_1 and ω_2 which define an hour (where ω_2 is the larger).

$$\begin{aligned} I_o = {} & \frac{12\times 3600\ G_{sc}}{\pi}\left(1+0.033\cos\left(\frac{360\ n}{365}\right)\right) \\ & \times \left(\cos\phi\ \cos\delta\ (\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2-\omega_1)}{180}\sin\phi\ \sin\delta\right) \end{aligned} \tag{3.12}$$

And (δ) declination of the sun (deg) from:

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \tag{3.13}$$

Where (n) is the day of the year.

After calculating hourly clerence index $k_T = \frac{I}{I_o}$, we can calculate beam and diffuse components of hourly radiation from [2]:

$$\frac{I_d}{I} = \begin{cases} 1 - 0.09\ K_T & for \rightarrow k_T \leq 0.22 \\ 0.9511 - 0.1604\ K_T + 4.388\ K_T^2 \\ \qquad -16.638\ K_T^3 + 12.336\ K_T^4 & for \rightarrow 0.22 < k_T \leq 0.8 \\ 0.165 & for \rightarrow k_T > 0.8 \end{cases} \tag{3.14}$$

So, the diffuse and beam radiations can be calculated from:

$$I_d = \frac{I_d}{I} \times I \qquad and \qquad I_b = \left(1 - \frac{I_d}{I}\right) \times I \tag{3.15}$$

Now we can substitute equations from (3.11) to (3.15) back into equation (3.10) to find the hourly total solar radiation on the tilted surface (I_T) and use the result to calculate the voltage, current and the output power of the PV module.

3.1.1. Probability Density Function for the Solar Radiation

The monthly average daily solar radiations for the period 1986 to 1993 (except 1989 and 1991) are collected by Elhadidy and Shaahid [4]. They showed that the radiation level is

high during the summer months (May to Aug.) as compared to other months. The overall average solar radiation is 5.84 (kWh/m^2).

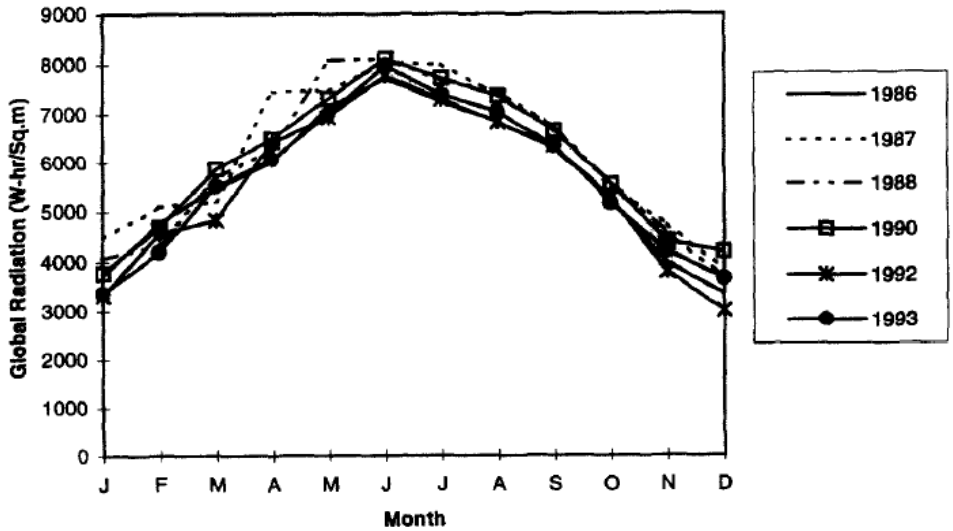


Fig. (3.2) monthly averaged daily global radiation at Dhahran during 1986-1993 [4]

Although, they showed that the variation of solar radiation between the years is minimal and the influence of this variation is small in Dhahran, a probabilistic study has been done for a complete year data (2008). The solar radiation probability distribution functions were calculated for each hour of a typical day in every month. Therefore, solar radiation will be described in terms of statistical methods and its distribution assumed to be a Weibull distribution. So, the probability density function (pdf) is given by [10]:

$$f(v) = \frac{k}{c}\left(\frac{I}{c}\right)^{k-1} \exp\left(-\left(\frac{I}{c}\right)^{k}\right) \qquad (3.16)$$

Where:

c - Scale factor, unit of solar radiation

k - Shape factor, dimensionless.

I – solar radiation

An example of the solar radiation probability density function is shown in Figure (3.3).

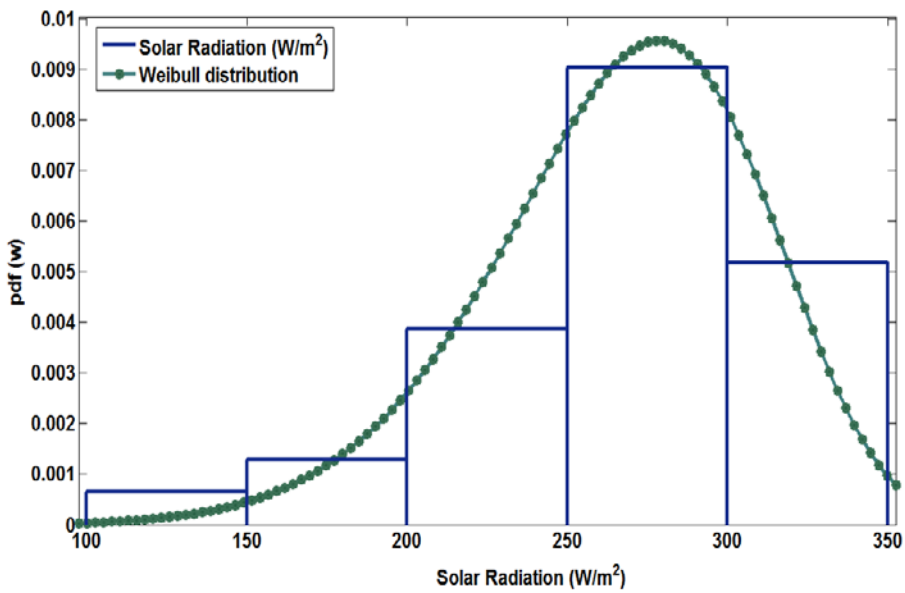


Fig. (3.3) Dhahran solar radiation histogram matched with Weibull probability density function plot for a typical day in January at 9:00 am

After calculating the probability density function for the solar radiation for each hour on a typical day in each month the average power output from a PV module was calculated using the following equation in the integral form [10]:

$$P_{pv,avg} = \int_{0}^{\infty} P_{pv} \; f(s) \; ds \qquad (3.17)$$

Where: ($f(s)$) is a probability density function for solar radiation given by (3.16), (P_{pv}) is the output power of the PV modules given by (3.1)

3.2 Mathematical Model of Wind Turbine

The hourly output of the wind turbine is determined by average hourly wind speed at the hub height and output characteristic curve of the wind turbine which is given by the manufacturer. Because wind speed near to ground changes with height according to the power law and wind power is proportional to the third power of wind speed, the hub height has great influence on the output of the wind turbine.

When calculating the output of wind turbine, the measured data of average hourly wind speed must be converted to the corresponding values at the hub height. The most commonly used formula is power law, expressed as [16]:

$$\frac{v}{v_o} = \left(\frac{z}{z_o}\right)^{\alpha} \tag{3.18}$$

Where (v) is the wind speed at desired height (z), (v_o) is wind speed at the reference height (z_o), (α) is the ground surface friction coefficient. According to many authors, the typical value of (1/7), corresponding to low roughness surfaces and well exposed sites, is used [14]. The hourly output of wind turbine can only be calculated accurately by using the characteristic curve of its own. The characteristic equation of wind turbine is obtained by fitting the practical output characteristic curve using least squares method. In order to guarantee the fitting accuracy, three or more binomial expressions have been developed for many wind turbines (Appendix 3).

$$P_w(v) = \begin{cases} 0 & for \rightarrow \quad v < v_c \\ a_1 v^n \ldots \; b_1 v^2 + c_1 v + d_1 & for \rightarrow \; v_c \le v < v_1 \\ a_2 v^n \ldots \; b_2 v^2 + c_2 v + d_2 & for \rightarrow \; v_1 \le v < v_2 \\ a_3 v^n \ldots \; b_3 v^2 + c_3 v + d_3 & for \rightarrow \; v_2 \le v < v_f \\ 0 & for \rightarrow \quad v > v_f \end{cases} \tag{3.19}$$

3.2.1. Probability Density Function for the Wind Speed

The wind speeds are generally higher in summer months (May to Aug.) in Dhahran as compared to other months [4]. This clearly reflects that such wind turbine would produce appreciably more energy during summer months as compared to the other months. The overall average wind speed is 5.42 m/s and the weather data show that there is considerable variation of monthly average wind speed of the same month from one year to another. These variations show how the monthly energy output from wind turbines would be subjected to considerable differences.

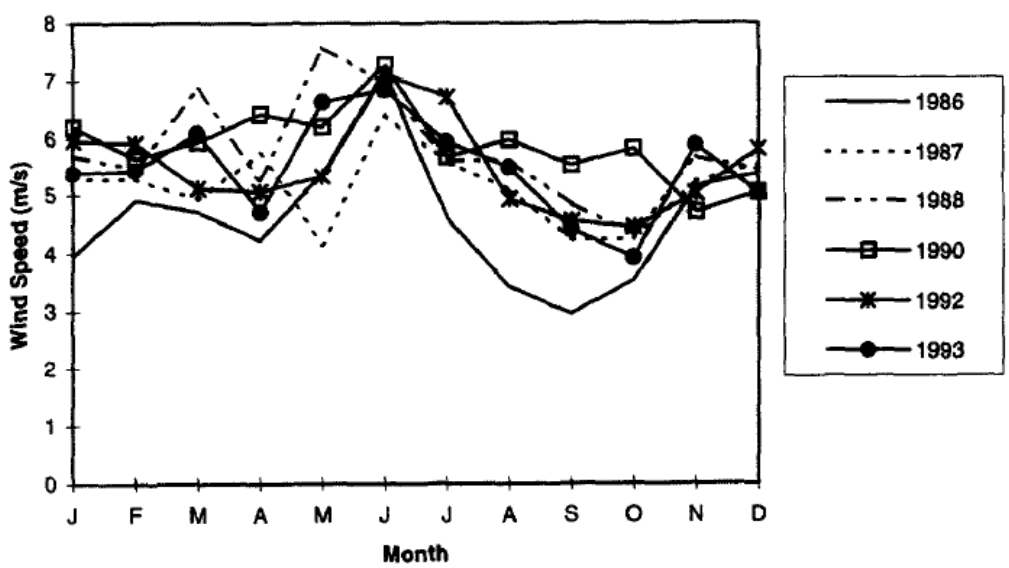


Fig. (3.4) monthly averaged wind speed at Dhahran during 1986-1993 [4]

Therefore wind speed should be described in terms of statistical methods and its distribution assumed to be a Weibull distribution. Hence the probability density function (pdf) is given by [10]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{3.20}$$

Where: c - Scale factor, unit of speed

k - Shape factor, dimensionless.

v - Wind speed.

The wind speed distribution functions were calculated for each hour of a typical day in every month. An example of the wind speed probability density function is shown in Figure (3.5).

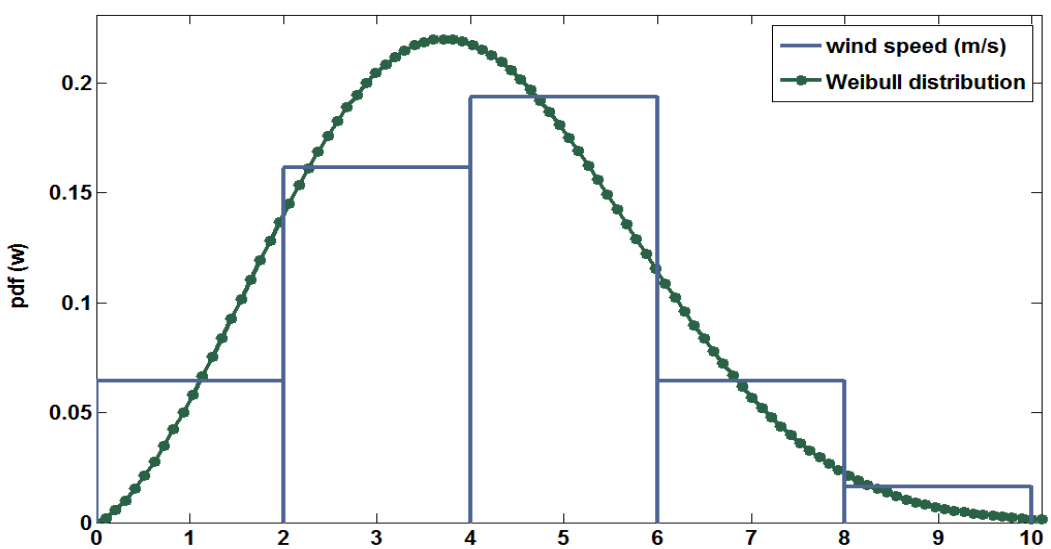


Fig. (3.5) Dhahran wind speed histogram matched with Weibull probability density function plot for a typical day in January at 9:00 am

Once distribution functions for wind speed were calculated for every hour of a typical day for each month, the average power output for every hour of the typical day in each month can be easily calculated using the following equation [10]:

$$P_{w,avg} = \int_{0}^{\infty} P_w \; f(v) \; dv \tag{3.21}$$

Where: ($f(v)$) is a probability density function for wind speed given by (3.20), (P_w) is the output power of the wind turbine given by (3.19)

3.3 Mathematical Model of Battery

At any hour the state of battery is related to the previous state of charge and to the energy production of the hybrid system and consumption situation of the system during the time from (*t-1*) to (*t*). During the charging process, when the total output of PV modules and wind turbines is greater than the load demand, the available battery bank capacity at hour (t) can be described by [16], [18]:

$$C_B(t) = C_B(t-1).(1-\sigma) + \left(P_T(t) - \frac{P_L(t)}{\eta_{inv}} \right) \eta_{Batt} \tag{3.22}$$

Where: ($P_T(t)$) is the total output power generated by the hybrid system at hour (t) which is calculated from:

$$P_T(t) = n_{pv} P_{pv} + n_w P_w \tag{3.23}$$

On the other hand, when the load demand is greater than the available power generated by the hybrid system, the battery bank is in discharging state. Therefore the charge capacity of battery bank at the time (t) can be expressed as:

$$C_B(t) = C_B(t-1).(1-\sigma) + \left(\frac{P_L(t)}{\eta_{inv}} - P_T(t) \right) \tag{3.24}$$

During discharging process, the battery discharging efficiency (η_{Batt}) was set equal to one and during charging, the efficiency (η_{Batt}) is 0.65–0.85 depending on the charging current. (σ) is the self-discharge rate of the battery bank. The manufacturer documentation gives a self-discharge of 25% over 6 months for a storage temperature of 20 C^o, that is to say 0.1% per day.

At any time, the charge capacity of battery bank is subject to the following constraints

$$C_{B\min} \le C_B(t) \le C_{B\max} \tag{3.25}$$

Where ($C_{B\max}$) and ($C_{B\min}$) are the maximum and minimum allowable storage capacity, respectively. Here, the maximum charge quantity of battery bank ($C_{B\max}$) takes the value of nominal capacity of battery bank (C_{Batt}) and the minimum charge quantity of battery bank ($C_{B\min}$) is determined by the maximum depth of discharge (DOD).

$$C_{B\max} = C_{Batt} \tag{3.26}$$

$$C_{B\min} = (1 - DOD).C_{Batt} \tag{3.27}$$

According to the specifications from the manufacturers, the battery's lifetime can be prolonged to the maximum if DOD takes the value of 30–50%.

3.4 Mathematical Model of Diesel Engine

In order to obtain the lowest levelized cost of energy (LCE) value and avoid system fail, the use of a third energy source (diesel) could be beneficial for the system (optional). Although using of any fossil fuel source of energy will lead to produce pollutants into the local atmosphere but it is necessary to use a diesel engine to cover the load in case the power generated from the hybrid system is less than the load. This can be happened because of bad weather conditions (dusty or cloudy weather) or in case the wind speed is less than the cut in speed of the wind turbine. The following table gives the specifications of the used diesel engine.

Table (1) specifications of the used diesel engine

Size (kW)	Slop (F_1) (L/hr/kW output)	Intercept coeff. (F_o) (L/hr/kW rated)	Operating and mentenance cost ($/hr)	Diesel price ($/L)	Cost ($)
2.6	0.32	0.13	0.04	0.2	900

Diesel engine will be used in case the power generated from the hybrid system is less than the load requirements and the battery bank reaches the minimum limit (C_{bmin}). So the power that should be covered by the diesel engine will be

$$P_{gen} = (P_L / \eta_{inv}) - P_T \qquad (3.28)$$

The following equation gives the generator's fuel consumption in (L/hour) as a function of its electrical output:

$$\dot{m}_d = F_o P_{dr} + F_1 P_{gen} \tag{3.29}$$

Where (F_o) is the fuel curve intercept coefficient in (L/hr/kW rated), (F_1) is the fuel curve slope in (L/hr/kW output), (P_{dr}) is the rated capacity of the generator in (kW), and (P_{gen}) is the electrical output of the generator in kW. The amount of CO_2 production in (kg/year) can be found from:

$$CO_2(production) = P_{gen} \cdot \left(Diesel(hours)\right) \cdot \left(1.35 \frac{Ib}{kWh}\right) \cdot \left(0.454 \frac{kg}{Ib}\right) \tag{3.30}$$

3.5 Modeling of system reliability

Modeling a hybrid PV/wind system is considered as the first step in the optimal sizing procedure. In this study, more accurate mathematical models for characterizing PV module, wind turbine and battery were proposed. The second step consists to optimize the sizing of a system according to the loss of power supply probability (LPSP) and the levelized cost of energy (LCE) concepts. The loss of power supply probability (LPSP) for a considered period (*T*) can be defined as the ratio of all the (LPS (t)) values over the total load required during that period. The technical model for hybrid system sizing is developed according to the LPSP technique. This can be defined as [18]:

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_L(t)} \Delta t \tag{3.31}$$

Where (LPS) is loss of power supply for an hour (t) when the battery reach the minimum allowable capacity can be expressed as follows

$$LPS(t) = P_L(t)\Delta t - (P_T \Delta t + C_B(t-1) - C_{B\min})\eta_{inv} \tag{3.32}$$

Where (Δt) is the step of time used for the calculations (in this study Δt=1 hour). During that time, the power produced by the PV and wind turbines is assumed constant. So, the power is numerically equal to the energy within this time step. Moreover, for the analysis we can introduce two more concepts: The first one is the renewable contribution (RC) defined as the ratio of the load supplied by the hybrid PV/wind system during a given time period over the total load during the same period. According to the (LPSP) it can be expressed as follows [18]:

$$RC(T) = 1 - LPSP \tag{3.33}$$

The second concept is the energy excess percentage, which is defined as the wasted energy divided by the total energy produced by the PV and wind turbines during the considered period.

$$EXC(T) = \frac{WE(T)}{P_T(T)} \tag{3.34}$$

In case the battery capacity reaches a maximum value, ($C_{B\max}$), the control system stops the charging process. The wasted energy (WE (T)), defined as the energy produced and not used by the system, for an hour t is calculated as follows:

$$WE(t) = P_T(t)\Delta t - \left(\frac{P_L(T)}{\eta_{inv}} \Delta t + \left(\frac{C_{B\max} - C_B(t-1)}{\eta_{cha}} \right) \right) \tag{3.35}$$

For a given LPSP value and a defined period, many configurations can technically meet the required reliability demand of power supply. The optimal configuration can be identified finally from this set of configurations by achieving the lowest LCE.

3.6 Modeling of System Economics

Since more concerns are given to the lowest energy cost in such projects, an economic sizing model is developed for the hybrid PV/wind power generation system according to the levelized cost of energy (LCE) concept.

The levelized cost of energy is defined as:

$$LEC = \frac{(C_{tot}/n) + C_{run}}{\sum P_L} \tag{3.36}$$

Where: (n) is the system life in years, ($\sum P_L$) is the summation of the load demand the hybrid system in (kWh), (C_{run}) is the running cost of the hybrid system including the

running cost of the diesel engine, (C_{tot}) is the total present value of actual cost of all system components including the replacement cost of the hybrid system components, which can be expressed as follows:

$$C_{tot} = C_{pvT} + C_{windT} + C_{battT} + C_{dieselT} \tag{3.37}$$

$$C_{pvT} = n_{replace} n_{pv} C_{pv} \tag{3.38}$$

$$C_{windT} = n_{replace} n_{wind} C_{wind} \tag{3.39}$$

$$C_{bettT} = n_{replace} n_{batt} C_{batt} \tag{3.40}$$

$$C_{dieselT} = n_{replace} C_{diesel} \tag{3.41}$$

$$C_{run} = \dot{m}_d C_{Ld} + C_{om} \tag{3.42}$$

Where: ($n_{replace}$) is replacement number of any hybrid system component during the system live. (C_{pv}) the sum of present value of capital and maintenance costs of the PV module, (C_{wind}) the sum of present value of capital and maintenance costs of the wind turbine, (C_{batt}) is the sum of present value of capital and replacement costs of the battery and (C_{diesel}) is the sum of present value of capital and replacement costs of diesel engine. ($\dot{m}_d$) is the fule consumption during the full year (L/year). (C_{Ld}) is the cost of one liter of diesel and (C_{om}) is the operation and maintenance cost in the full year.

3.7 Computational Procedure

The algorithm of the computer program used to solve the mathematical model is presented in Figure (3.6). The algorithm input data set consists of hourly solar radiation on horizontal surface, hourly mean values of ambient temperature, wind speed, the load power requirements during the year and specifications of the hybrid system components. The first step is to calculate the solar radiation on the tilted surface of PV module. Next, the output powers of single PV module and wind turbine are calculated. Then, for each configuration of the hybrid system components, the total output power is calculated. After that, if the total output power at specific hour is grater then the load demand, the battery bank is in charging state. If the total output power is less than the load demand, then the battery bank is in discharging state. In both situations, the charge capacity of battery bank is subject to maximum and minimum allowable storage capacity constraints and the loss of power supply probability is calculated. For the given LPSP value of the whole year, many configurations can meet this reliability demand of power supply. The configuration with the lowest levelized cost of energy LCE is taken as the optimal one from the set of configurations, which guarantee the required LPSP and give the minimum levelized cost of energy.

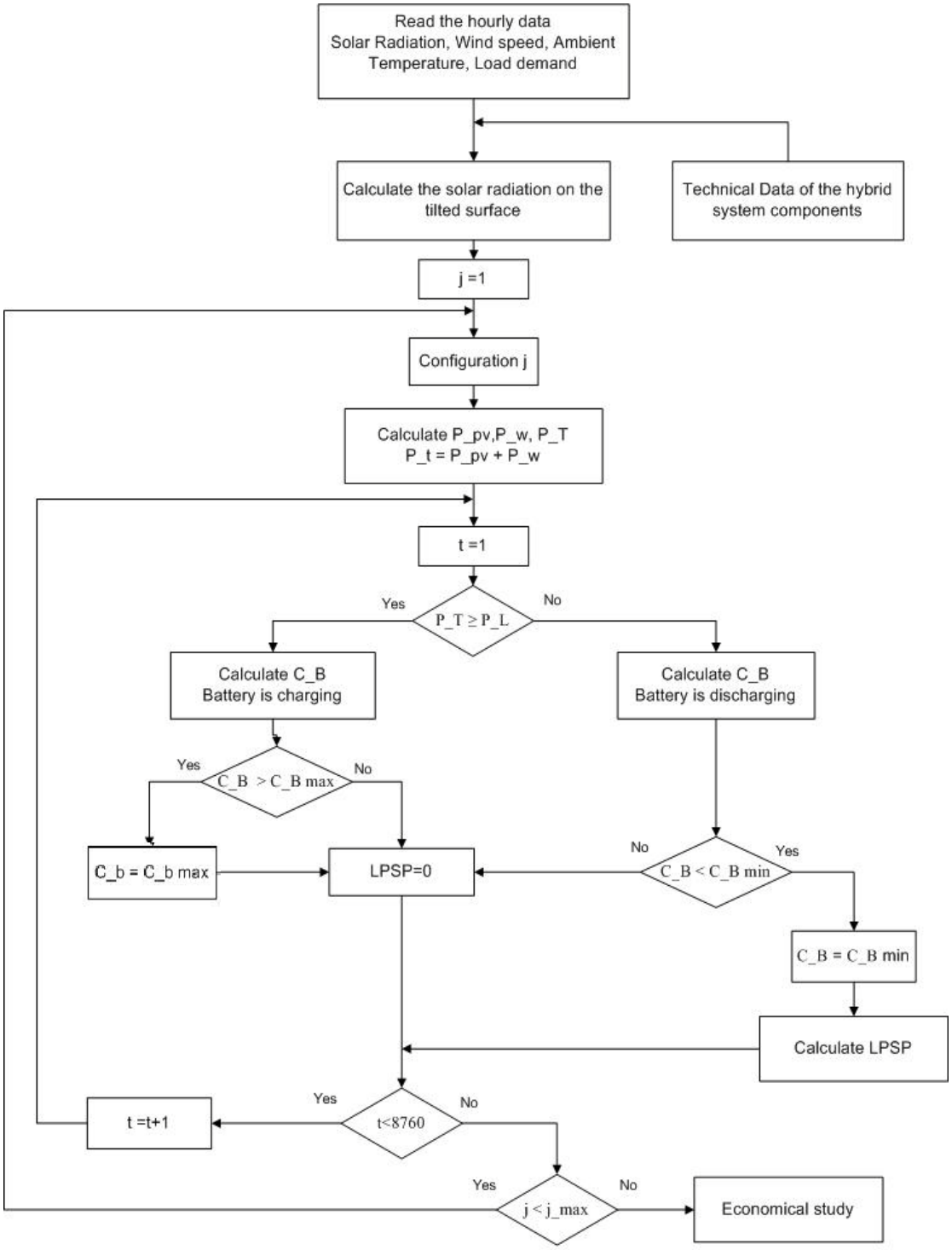


Fig. (3.6) Flowchart diagram of the hybrid PV\wind power generation system

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Validation

4.1.1 Validation against previous work

To ensure the validity and the dependency of the developed mathematical model and the computer code, the results obtained by the present code are validated against previous published work by Daif et al [18]. The developed methodology in [18] has been applied to design a standalone hybrid PV/wind system in order to power supply residential household located in the area of the Laboratory CNRS Ajaccio (Corsica Island) (41° 55′ N, 8° 44′ E).

For validation purpose, the same components of hybrid system and the hourly load profile of [18] have been used and the parameters of these components listed in Table (2).The characteristic curves of the used wind turbines are in the Appendix (3). Unfortunately, we don't have the same weather data of [18] location. An attempt has been done to communicate with the author to provide the weather data but he didn't response. Also we tried to use Homer software to generate the hourly solar radiation and wind speed (Appendix I) but the data were not consistent (compare Appendix 1 and Fig. 4.1) .So, weather data of Dhahran city, KSA for full year (2008) have been used for validation [provided by the Research Institute of King Fahd University of Petroleum and Minerals] and some differences in the simulation results will be expected. Figure (4.1) and Figure (4.2) show the weather data (solar radiation, wind speed and ambient temperature) of [18] location and Dhahran respectively.

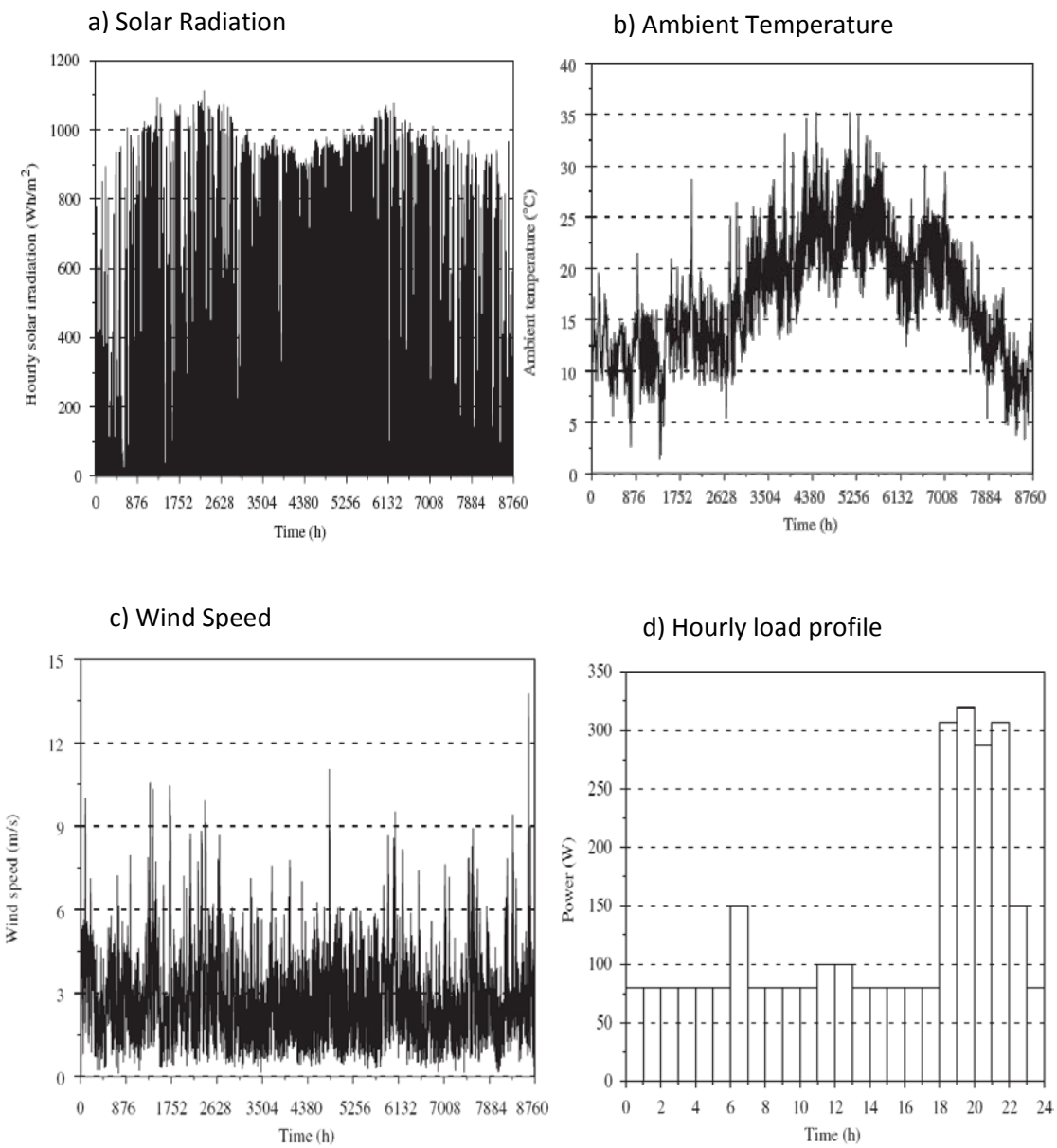
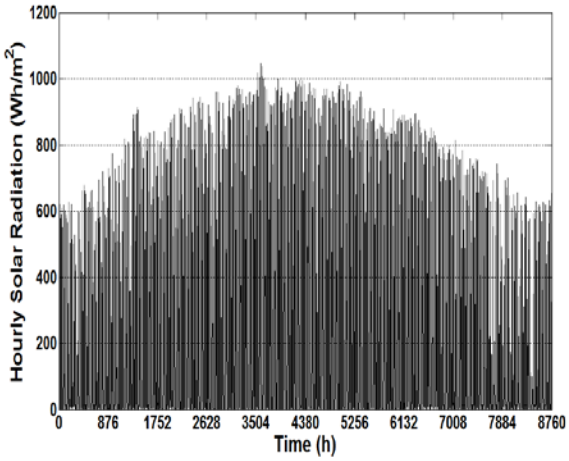


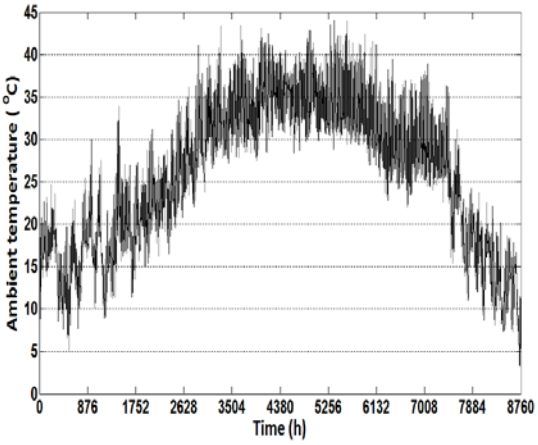
Fig. (4.1) Hourly values of meteorological parameters at Ajaccio

(41° 55′ N, 8° 44′ E) [18]

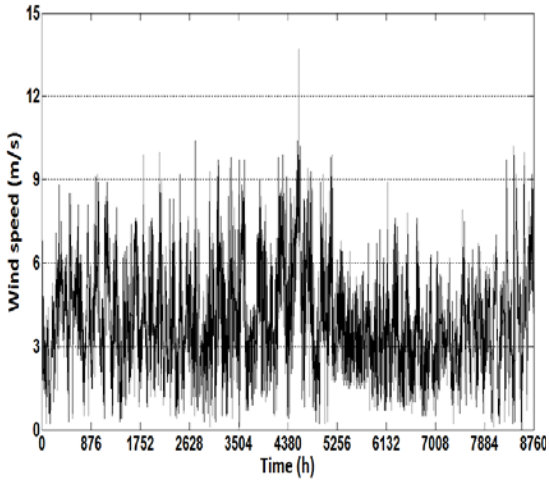
a) Solar Radiation



b) Ambient Temperature



c) Wind Speed



d) Hourly load profile

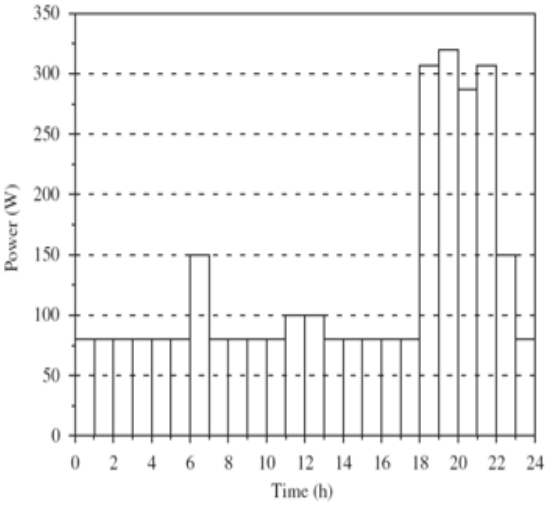


Fig. (4.2) Hourly values of meteorological parameters for Dhahran (2008)

Table (2) parameters of the hybrid system components used for validation a) Photovoltaic modules parameters, b) Wind turbines parameters, c) Battery Parameters [18]

a) Photovoltaic modules parameters

Model No.	P_{mp}(W)	V_{mp}(V)	I_{mp}(A)	V_{oc}(V)	I_{sc}(A)	A (m^2)	Price($)
BP350	50	17.3	2.89	21.8	3.17	1.018	350
BP3125	125	17.6	7.1	22.1	7.54	1.018	598

b) Wind turbines parameters

Model No.	Power rated(W)	V_{ci}(m/s)	V_r(m/s)	V_{co}(m/s)	Price($)
WT 600	600	2.5	12	25	1500
BWCXL 1000	1000	2.5	12	25	2500

c) Battery Parameters

Model No.	Nominal capacity (Ah)	Voltage (V)	Minimum charge	Price ($)
Concorde(PVX-890 T)	102	12	20	208
Concorde(PVX-2120L)	253	12	20	465

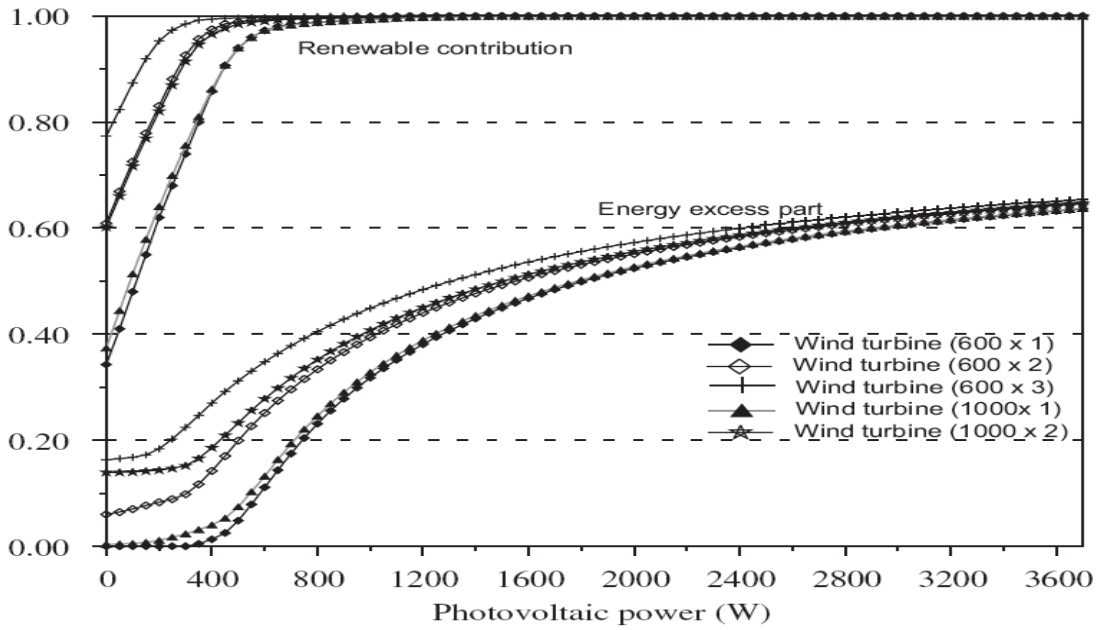
4.1.1.1 Results of Validation I

The system reliability is developed in terms of the concept of loss of power supply probability (LPSP). For this purpose, several simulations have been made by considering different combinations taking into account, the power of PV and wind turbines and the capacity storage. In (Figure (4.3), (a) [18] results, (b) validation results), the variation of the renewable contribution and the energy excess part as a function of the PV power for different wind turbine sizes are presented. According to the results obtained, the energy excess part increases with increasing wind turbine number. This increase is inversely proportional to the photovoltaic power. Therefore, in the range of the PV power varying from (0 to 450 W); the energy excess percentage is nearly zero for configuration including one wind turbine and increase significantly with increasing wind turbine number. In addition, we can observe that the configurations including one wind turbine, and whatever its power, lead to the same energy excess. Good qualitative agreements between [18] results and validation results can be demonstrated taking into account the used weather date is different.

An interesting conclusion from (Figure (4.4), (a) [18] results, (b) validation results) states that the renewable contribution trend is a linear function of the power generated and is independent of the battery capacity. This fact is valid even for the large battery capacity. Quantitative and qualitative validated results can be observed from this figure. To obtain a total renewable contribution (RC = 1), more than 30% of the PV and wind energy production is unused unless the battery capacity is very large which leads to increase the

total cost of the hybrid system. As it can be seen in (Figure (4.5), (a) [18] results, (b) validation results), the LCE curve has two linear parts. In the first part (below a storage battery of 500 Ah), a sharp decrease in the cost is observed, which is mainly due to the decrease of PV power. In the second part, for a storage capacity of battery greater than 500 Ah, the LCE increases gradually with increasing the storage capacity. This increase is due to the short life of battery and with increasing the number of batteries leads to raise the minimum limit of the storage capacity of the battery bank which needs more power from the hybrid system and this leads to increase the levelized cost of energy (LCE).

a) Results of [18]



b) Present calculation results for Dhahran (2008)

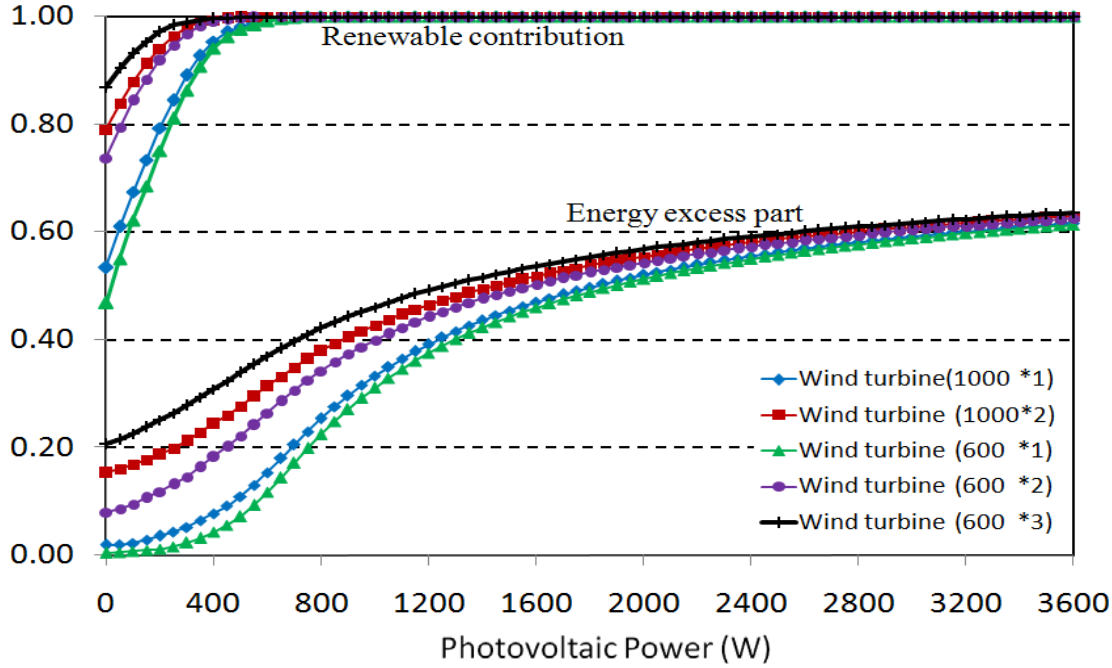
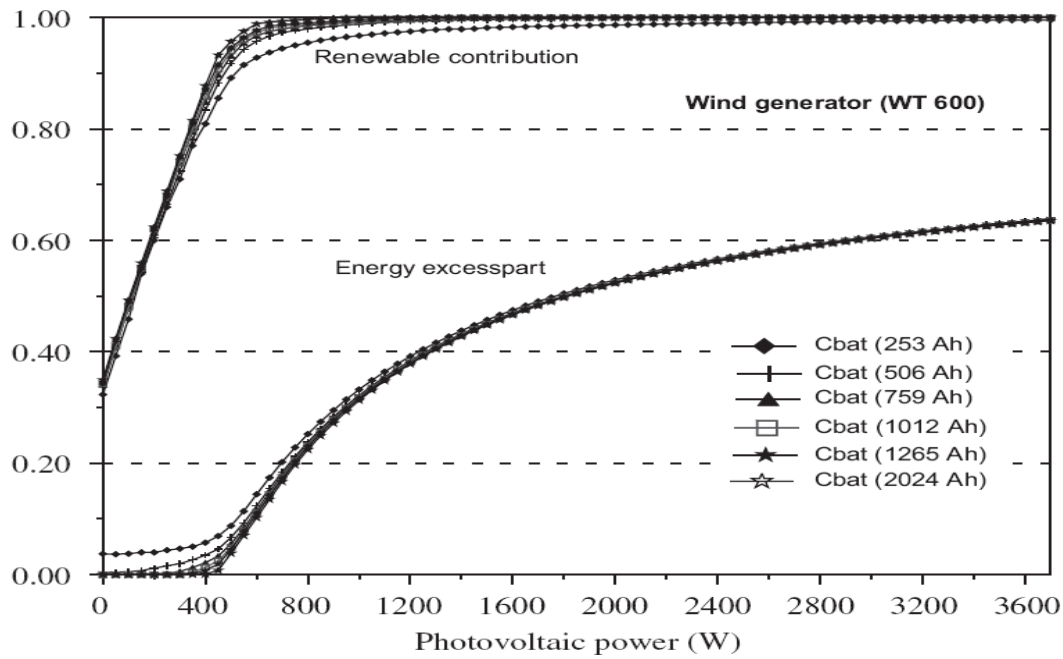


Fig. (4.3) Renewable contribution and energy excess part as a function of PV power for different wind turbines (1012 Ah of capacity storage)

a) Results of [18]



b) Present calculation results for Dhahran (2008)

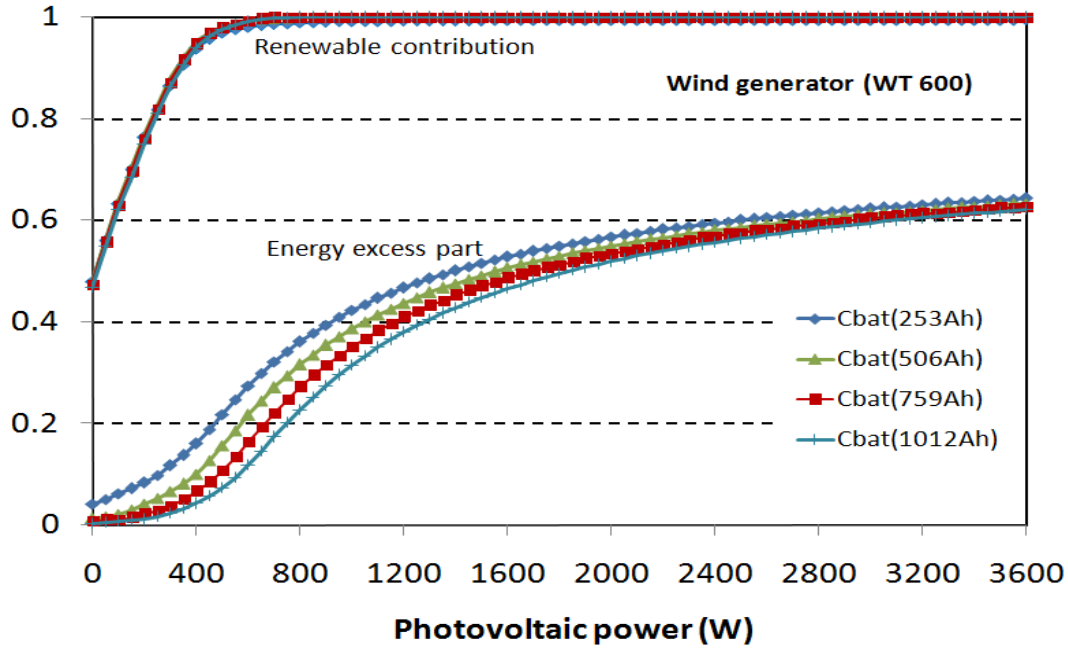
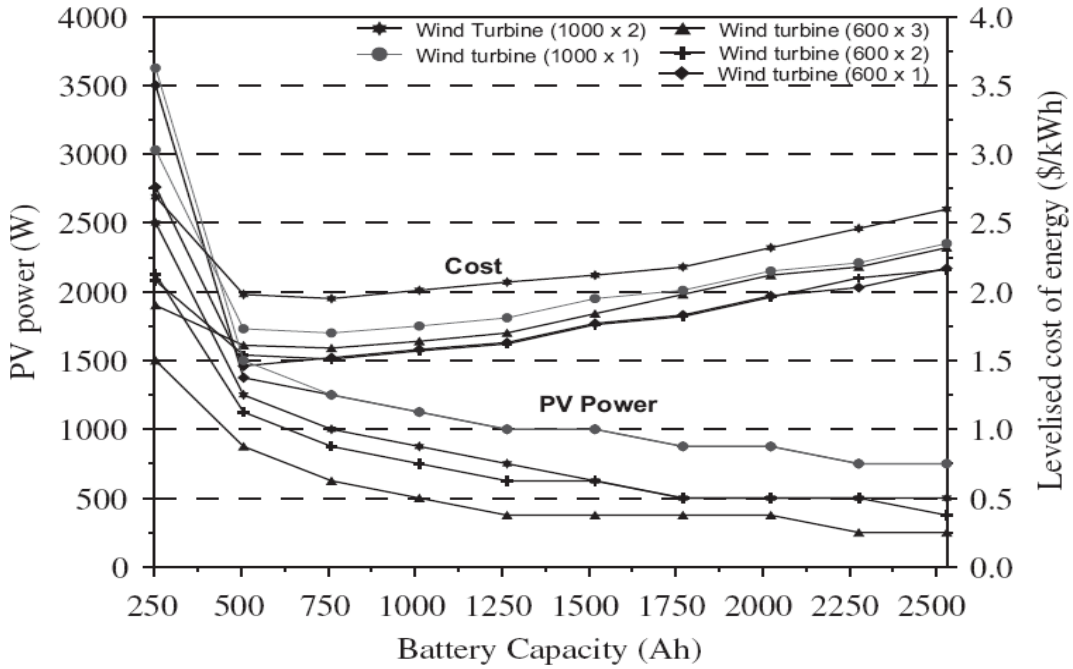


Fig. (4.4) Renewable contribution and energy excess part as a function of PV power

a) Results of [18]



b) Present calculation results for Dhahran (2008)

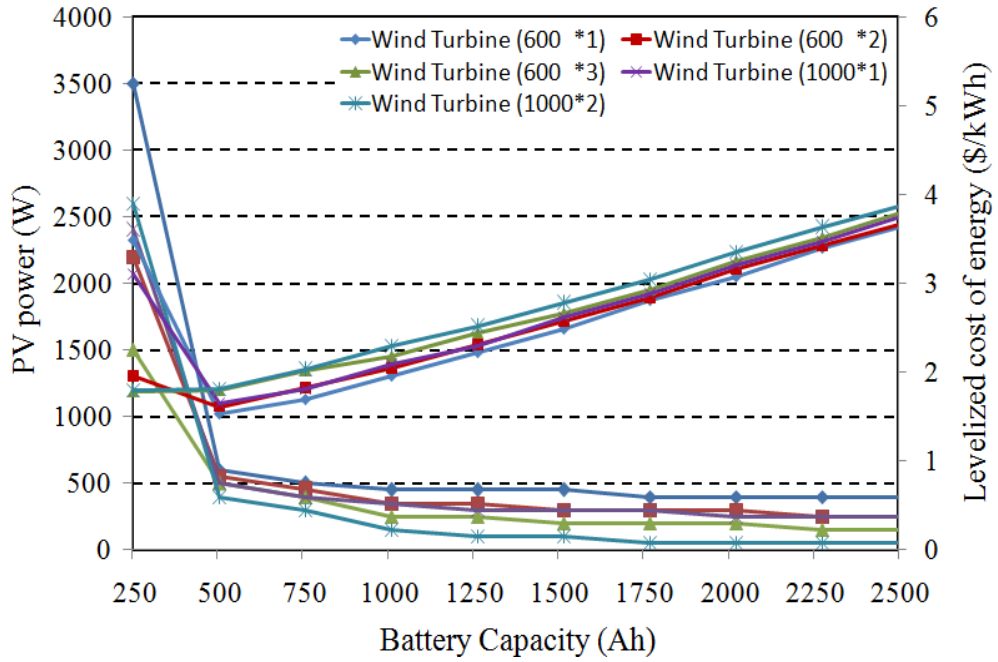


Fig. (4.5) Comparison of levelized costs of energy for different configurations at (LPSP= 0)

4.1.2 Validation against HOMER Software

The developed mathematical model and computer code also validated against Homer software. The hybrid PV/wind power generation system has been used to power supply specific load requirements for a typical house located in Dhahran city [Latitude 26° 17′ North, 50° 9′ East]. For validation purpose the same components of the hybrid system have been used in both Homer and the developed Mat-lab code. The Parameters of these components are listed in table (3). The schematic diagram of the PV/wind/battery hybrid system used for validation is depicted in Fig. (4.6).

The main input data include; solar radiation, wind speed and load data; technical specifications and cost data of photovoltaic modules, wind turbines, converter and batteries. Figure (4.7) shows the weather data (solar radiation, wind speed) and hourly load profile for a typical house.

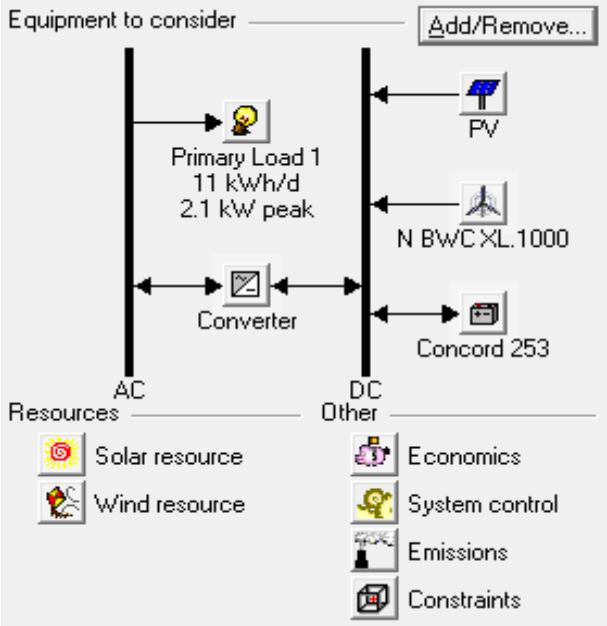
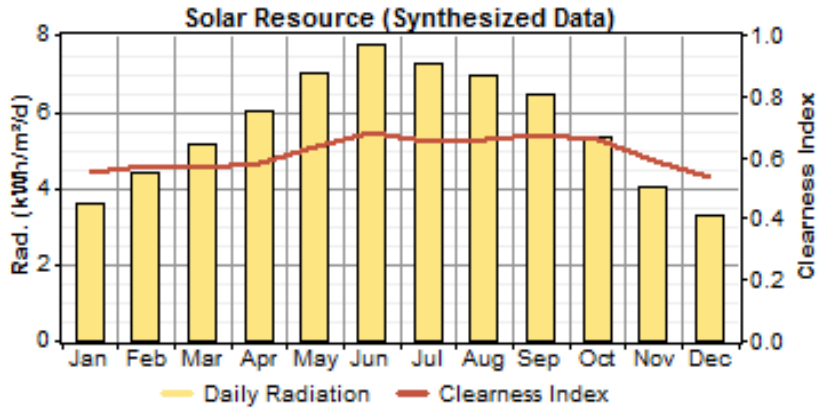
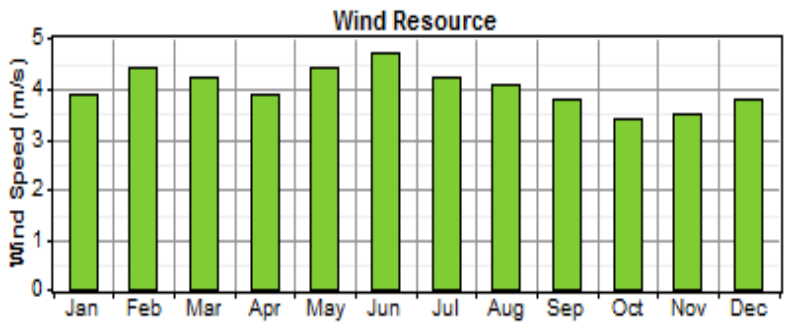


Fig.(4.6) The schematic diagram of the PV/wind/battery hybrid system

a) Monthly mean daily global solar radiation at Dhahran (KSA)



b) Monthly mean wind speed at Dhahran (KSA)



c) Hourly load profile for typical house

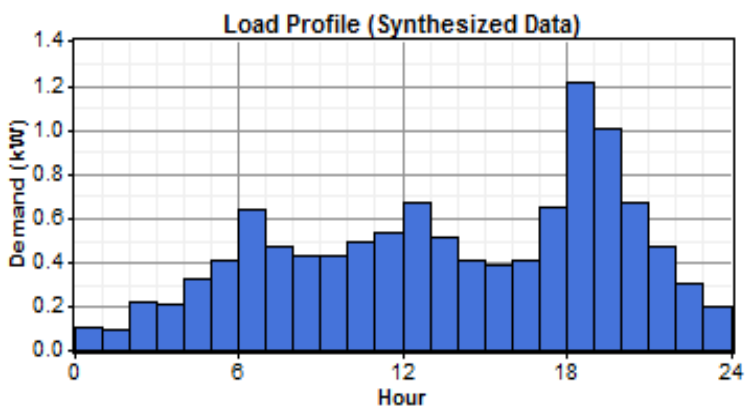


Figure (4.7) Monthly mean weather data (solar radiation and wind speed) at Dhahran city (KSA) and hourly load profile for a typical house

Table (3) Parameters of the hybrid system components used for validation against HOMER

Parameters of the chosen PV module :

Model No.	Max. power output (W)	Max. power voltage (V)	Max. power current (A)	Open circuit voltage (V)	Short circuit current	Price($)
BP350	50	17.5	2.9	21.8	3.2	350

Parameters of the chosen Wind turbine:

Model No.	Rated power (W)	Rated wind speed (m/s)	Cut-in wind speed (m/s)	Cut-off wind speed (m/s)	Price($)
BWCXL1000	1000	11	2.5	25	2500

Parameters of the chosen battery:

Model No.	Nominal capacity (Ah)	Voltage (V)	Minimum charge	Price ($)
Concord (2120L)	253	12	20%	465

4.1.2.1 Results of Validation II

Based on the above inputs (the weather data and the parameters of the hybrid system components), many simulations have been made using both Homer program and the developed Matlab code. Two cases have been investigated; the first one using one wind turbine and the second one using two wind turbines. The target in both cases was to find the optimum configuration of PV power and the number of batteries that give the minimum levelized cost of energy and met the load requirements. The simulation number of Homer in both cases with one and two wind turbines were 1302. With one wind turbine using the developed computer code the simulation number was 420 whereas with two wind turbines it was 290 and every single simulation reflects the whole hours in the full year that is to say 8760 hours. It is important to mention here that the battery numbers in Homer start from 0 to 20 whereas in the simulations using the developed computer code it start from 5 to 20 batteries. Table (4) shows Homer Program results with [a) one wind turbine, b) wind turbines]. Figure (4.8) shows the simulation results using the developed Matlab code [a) one wind turbine, b) two wind turbines]. Table (4 [a]) and Figure (4.8 [a]) show that the optimum configuration with one wind turbine was (2.4 W PV power and 10 batteries) with (0.794 $/kWh). With two wind turbines the same optimum configuration has been achieved (1.9 W PV power and 8 batteries) using both Homer Program and the developed Matlab code with (0.71 $/kWh).

Table (4) Homer program results with one and two wind turbines

a) Homer Program results with one wind turbine

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	XL1kW	Concord ..	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
2.4	1	10	2	$ 24,700	731	$ 31,877	0.794	1.00
2.6	1	9	2	$ 25,635	658	$ 32,094	0.800	1.00
2.8	1	8	2	$ 26,570	585	$ 32,312	0.805	1.00
2.3	1	11	2	$ 24,465	804	$ 32,360	0.806	1.00
2.5	1	10	2	$ 25,400	731	$ 32,577	0.812	1.00
2.7	1	9	2	$ 26,335	658	$ 32,794	0.817	1.00
2.9	1	8	2	$ 27,270	585	$ 33,012	0.823	1.00
2.4	1	11	2	$ 25,165	804	$ 33,060	0.824	1.00
2.6	1	10	2	$ 26,100	731	$ 33,277	0.829	1.00
2.8	1	9	2	$ 27,035	658	$ 33,494	0.835	1.00
2.3	1	12	2	$ 24,930	877	$ 33,543	0.836	1.00
3.0	1	8	2	$ 27,970	585	$ 33,712	0.840	1.00
2.5	1	11	2	$ 25,865	804	$ 33,760	0.841	1.00
2.7	1	10	2	$ 26,800	731	$ 33,977	0.847	1.00
2.2	1	13	2	$ 24,695	950	$ 34,025	0.848	1.00
2.9	1	9	2	$ 27,735	658	$ 34,194	0.852	1.00
2.4	1	12	2	$ 25,630	877	$ 34,243	0.853	1.00
2.6	1	11	2	$ 26,565	804	$ 34,460	0.859	1.00
2.8	1	10	2	$ 27,500	731	$ 34,677	0.864	1.00
2.3	1	13	2	$ 25,395	950	$ 34,725	0.865	1.00

a) Homer Program results with two wind turbines

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	XL1kW	Concord ..	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
1.9	2	8	2	$ 22,770	585	$ 28,512	0.710	1.00
2.1	2	7	2	$ 23,705	512	$ 28,729	0.716	1.00
1.8	2	9	2	$ 22,535	658	$ 28,994	0.722	1.00
2.0	2	8	2	$ 23,470	585	$ 29,212	0.728	1.00
2.2	2	7	2	$ 24,405	512	$ 29,429	0.733	1.00
1.7	2	10	2	$ 22,300	731	$ 29,477	0.734	1.00
1.9	2	9	2	$ 23,235	658	$ 29,694	0.740	1.00
2.1	2	8	2	$ 24,170	585	$ 29,912	0.745	1.00
2.3	2	7	2	$ 25,105	512	$ 30,129	0.751	1.00
1.8	2	10	2	$ 23,000	731	$ 30,177	0.752	1.00
2.5	2	6	2	$ 26,040	439	$ 30,346	0.756	1.00
2.0	2	9	2	$ 23,935	658	$ 30,394	0.757	1.00
2.2	2	8	2	$ 24,870	585	$ 30,612	0.763	1.00
1.7	2	11	2	$ 22,765	804	$ 30,660	0.764	1.00
2.4	2	7	2	$ 25,805	512	$ 30,829	0.768	1.00
1.9	2	10	2	$ 23,700	731	$ 30,877	0.769	1.00
2.6	2	6	2	$ 26,740	439	$ 31,046	0.774	1.00
2.1	2	9	2	$ 24,635	658	$ 31,094	0.775	1.00
1.6	2	12	2	$ 22,530	877	$ 31,143	0.776	1.00

For comparison purpose, the following tables give the simulation results at the optimum configuration with one and two wind turbines using Homer and the developed computer code. It can be observed that very good agreements have been achieved between Homer results and the results of the developed computer code and the differences are negligible in both cases with one and with two wind turbines.

Table (5) Comparison between the results of Homer Software and the developed computer code

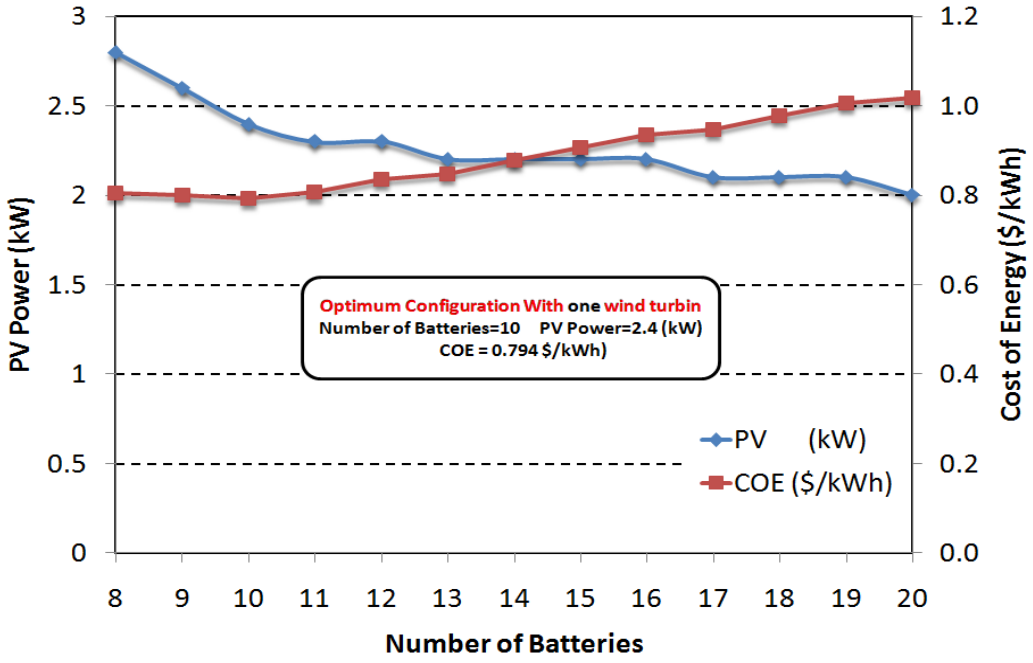
a) Present results with one wind turbine (optimum configuration)

Optimum configurations	No. of Wind turbines	PV (kW)	No. of Batteries	Initial Capital cost ($)	Operating Cost ($/Yr)	Total Net Present cost ($)	Cost of energy ($/kWh)	Renewable Fraction
Homer Results	1	2.4	10	24700	731	31877	0.79400	1.000
Present Results	1	2.4	10	24700	730.05	31876.81	0.7942	0.9911
Difference	0	0	0	0	0.05	0.002	0.0002	0.0089

b) Present results with two wind turbines (optimum configuration)

Optimum configurations	No. of Wind turbines	PV (kW)	No. of Batteries	Initial Capital cost ($)	Operating Cost ($/Yr)	Total Net Present cost ($)	Cost of energy ($/kWh)	Renewable Fraction
Homer Results	2	1.9	8	22770	585	28512	0.7100	1.000
Present Results	2	1.9	8	22770	584.04	28511.45	0.7104	0.9934
Difference	0	0	0	0	0.96	0.55	0.0004	0.0066

a) Results of validation with one wind turbine



b) Results of validation with two wind turbines

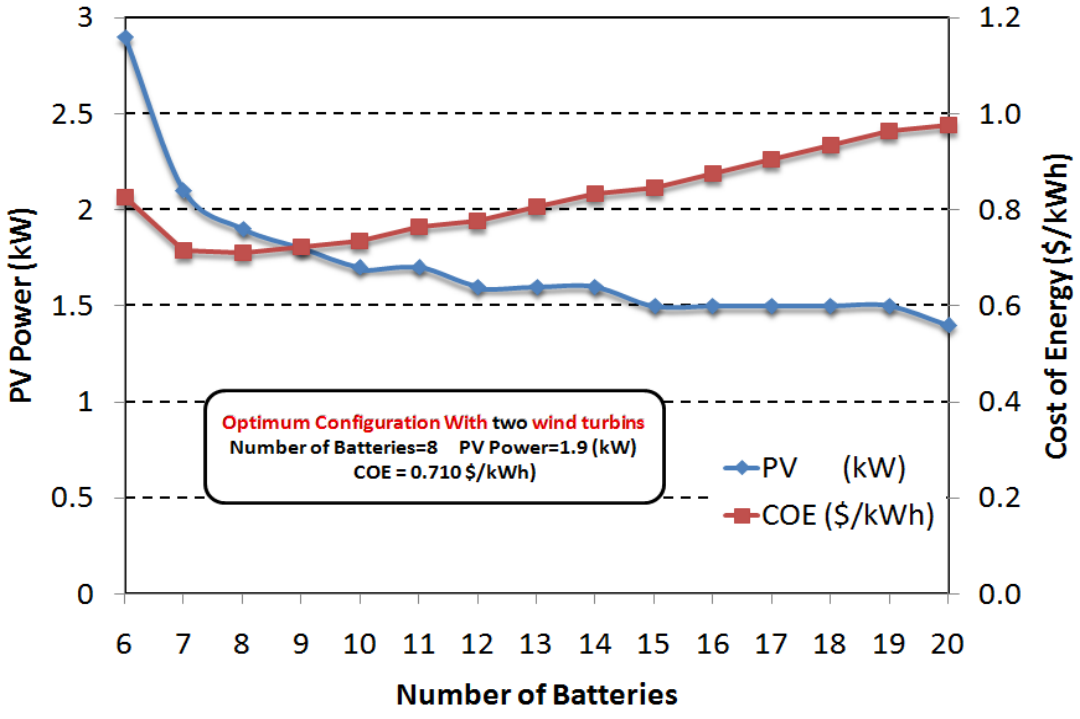


Fig (4.8) Results of validation with one and two wind turbines

4.2 Simulation Analysis under Saudi Arabia Weather Conditions

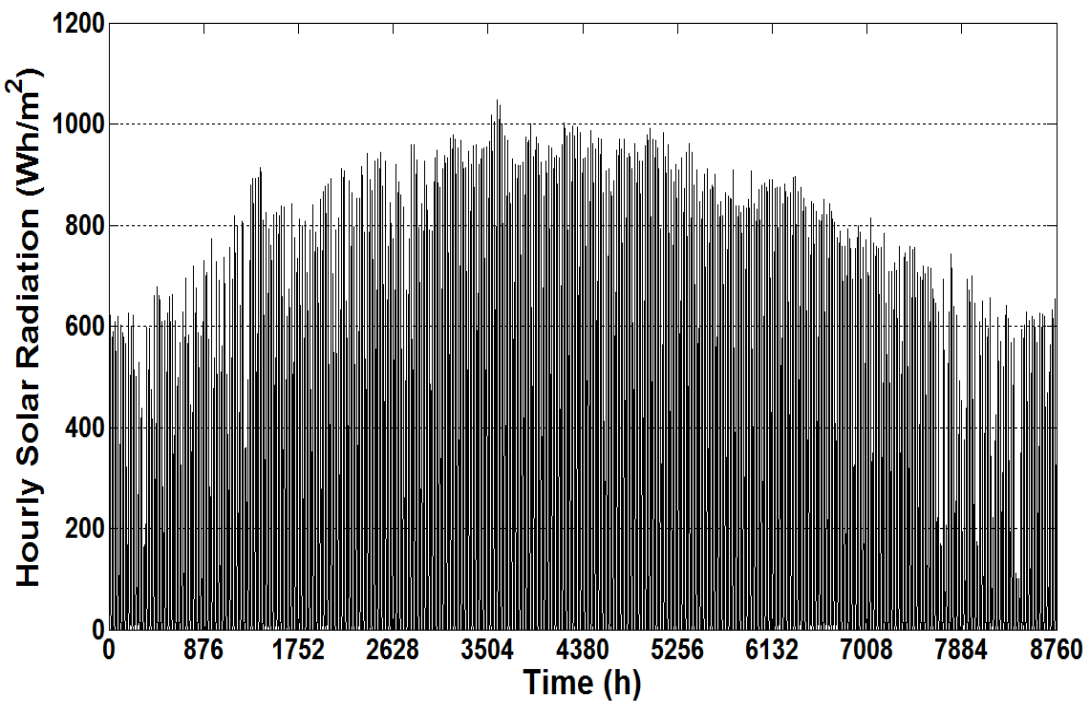
The validated mathematical model and the computer code have been applied to design a standalone hybrid PV/wind power generation system in order to power supply a residential household located in the area of Dhahran city (Latitude 26° 17′ North, 50° 9′ East) in the kingdom of Saudi Arabia.

The simulations were conducted using the raw weather data of Dhahran city for the year (2008), [provided by the Research Institute of King Fahd University of Petroleum and Minerals], with imposing the probability density function on it. The simulation code that impose the probability density function (PDF) of the weather data was developed in a general form such that it can handle any weather data and impose on it its pertinent probability density function (PDF). A subroutine in the simulation code was developed to estimate the (PDF) for the weather data of a given location using the weather data cumulative over years. This subroutine was developed using MATLAB software in general way such it can estimate the (PDF) for weather data over any number of years. The more the number of data points the more accurate and reliable the estimation of (PDF) is.

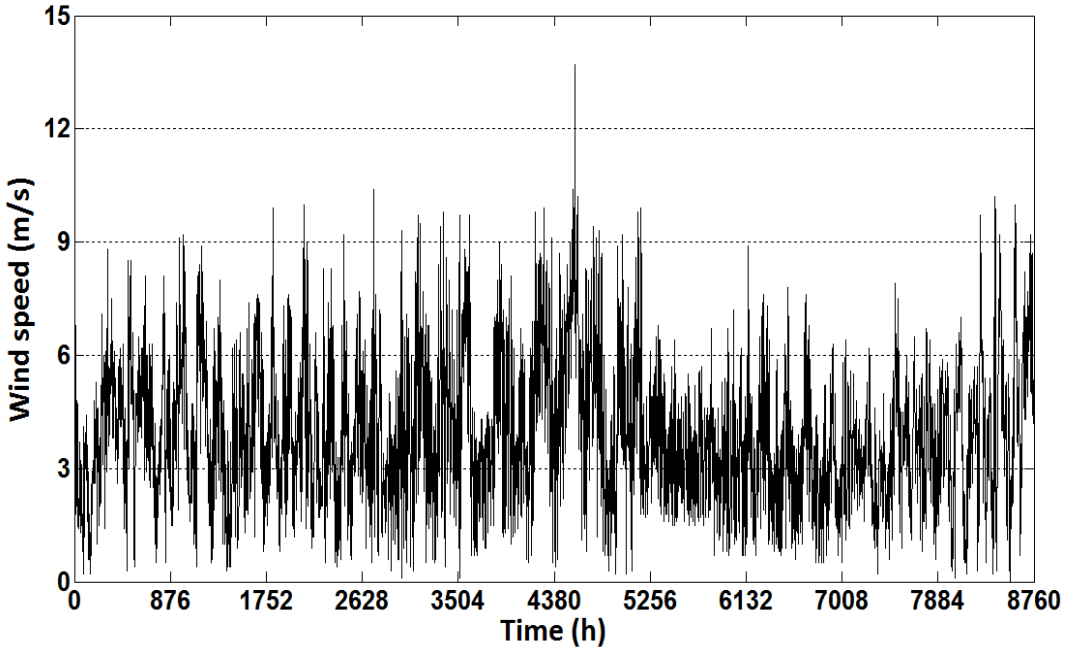
In the present work, the (PDF) was developed only for the data of (2008) since it was the only available data. This data is used here for the purpose of explaining the approach and the methodology of using the (PDF) predict the output of the hybrid system. First, a

typical load for a house is chosen. Next, a hybrid system was designed and consists of (1- PV modules, 2- Wind turbines, 3- Batteries and 4- Diesel engine (optional). Then, the hybrid system was optimized in light of the system components specifications, cost and load requirement. The optimization function was the levelized cost of energy (LEC). Hourly global solar radiation on horizontal surface, as well as hourly mean values of wind speeds and ambient temperature are given in Figure (4.9).

a) Solar radiation on horizontal plane



b) Wind speed



c) Ambient temperature

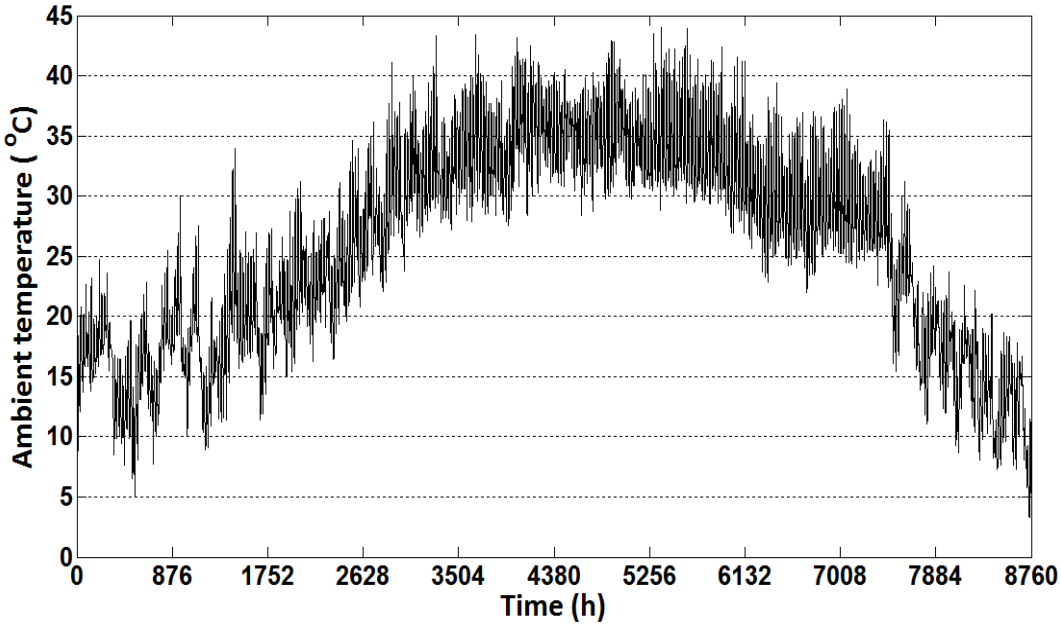


Fig. (4.9) Hourly values of meteorological parameters for Dhahran (2008)

The developed method was used to calculate the optimum number of batteries and PV modules that give the minimum cost. The parameters of the hybrid system components are listed in Table (6). Hummer (H2.7) wind turbine of rated power 500W was considered. The rated power of a PV module used was 50W. The capacity of a single battery used was (100 Ah) and the selected battery has a round-trip efficiency of 0.85% and 80% of the depth of discharge. The calculation of the optimum number of photovoltaic modules and batteries was based upon a Loss of Power Supply Probability (LPSP) [10], and levelized cost of energy (LCE) [18] concepts. Loss of Power Supply Probability can be defined as the long-term average fraction of the load that is not supplied by a stand-alone system. A (LPSP) of 0 means the load will be always satisfied and the (LPSP) of 1 means that the load will never be satisfied. The (LPSP) was specified as one day over 10 years (0.000274). The load of a typical house with average (473 W) and peak (1231 W) was used. The load profile is shown in Figure (4.10).

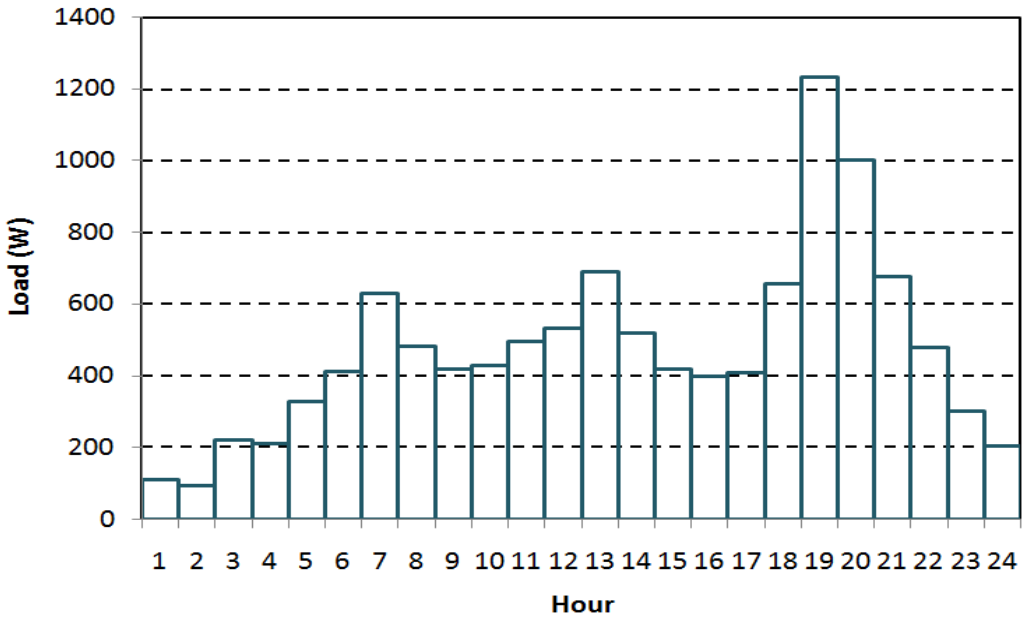


Fig. (4.10) Hourly load profile of a typical house

Table (6) Parameters of the hybrid system components used for simulation

Parameters of the chosen PV module :

Model No.	Max. power output (W)	Max. power voltage (V)	Max. power current (A)	Open circuit voltage (V)	Short circuit current	Price($)
BP350	50	17.3	2.89	21.8	3.17	350

Parameters of the chosen Wind turbine:

Model No.	Rated power (W)	Tower height (m)	Rated wind speed (m/s)	Cut-in wind speed (m/s)	Cut-off wind speed (m/s)	Blade diameter (m)	Price($)
H2.7-500W	500	6	7	3	20	2.7	500

Parameters of the chosen battery:

Model No.	Nominal capacity (Ah)	Voltage (V)	Minimum charge	Price ($)
TOYO GFM-100	100	2	20%	100

Using the developed mathematical model and the computer code, series of possible combinations of the number of PV modules and batteries has been calculated. It is necessary to determine a PV/battery combination that yields a minimum cost of the system. The system total cost equation is linearly related to both the number of PV modules and the number of batteries. The inclination of the line that expresses the cost equation depends on the cost of single battery over the cost of single PV module ($-C_{batt}/C_{PV} = -\beta/\alpha$) [10]. The minimum cost will be at the point of tangency (S) of the cost line and the curve that represents the relationship between the number of PV modules and the number of batteries for the desired (LPSP). Figure (4.11) give us an example of optimization procedure used to find the optimum configuration that gives the minimum levelized cost of energy (LCE) and achieve the desired level of loss of power supply probability (LPSP).

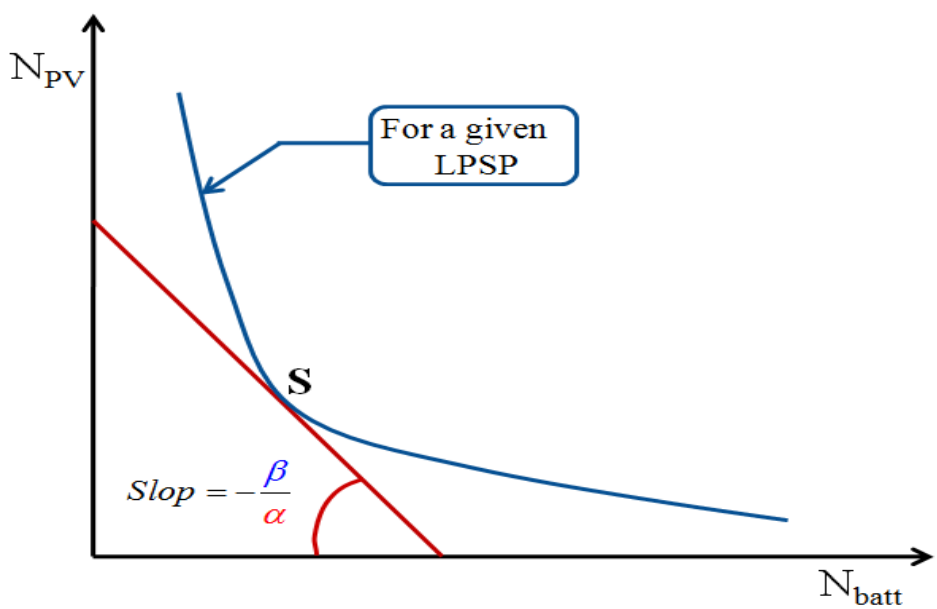
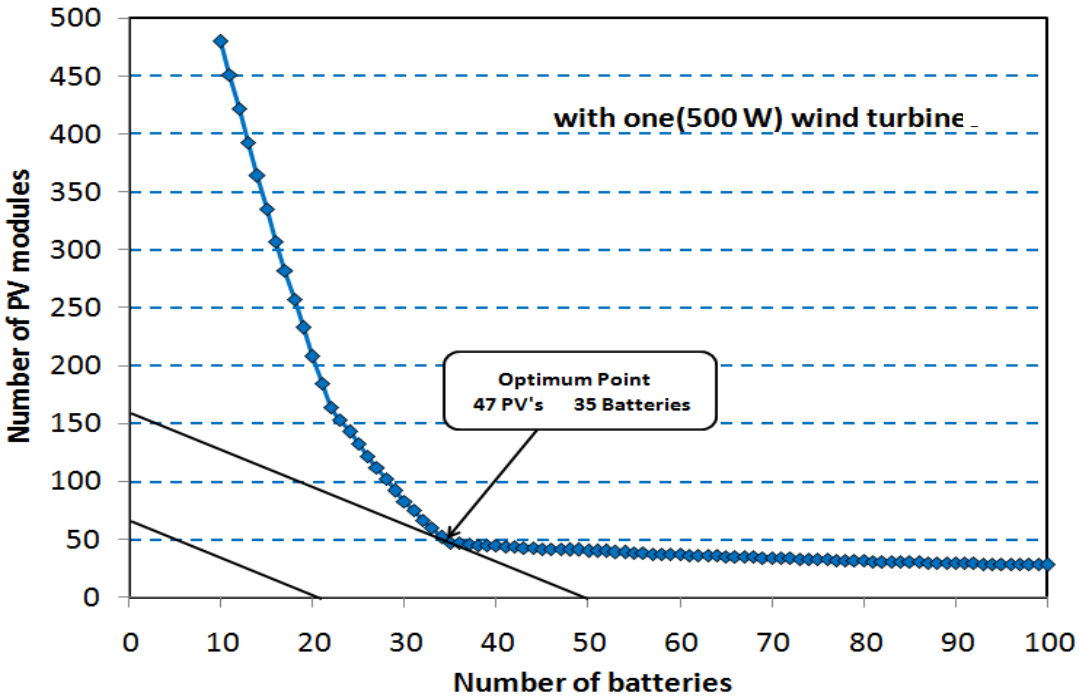


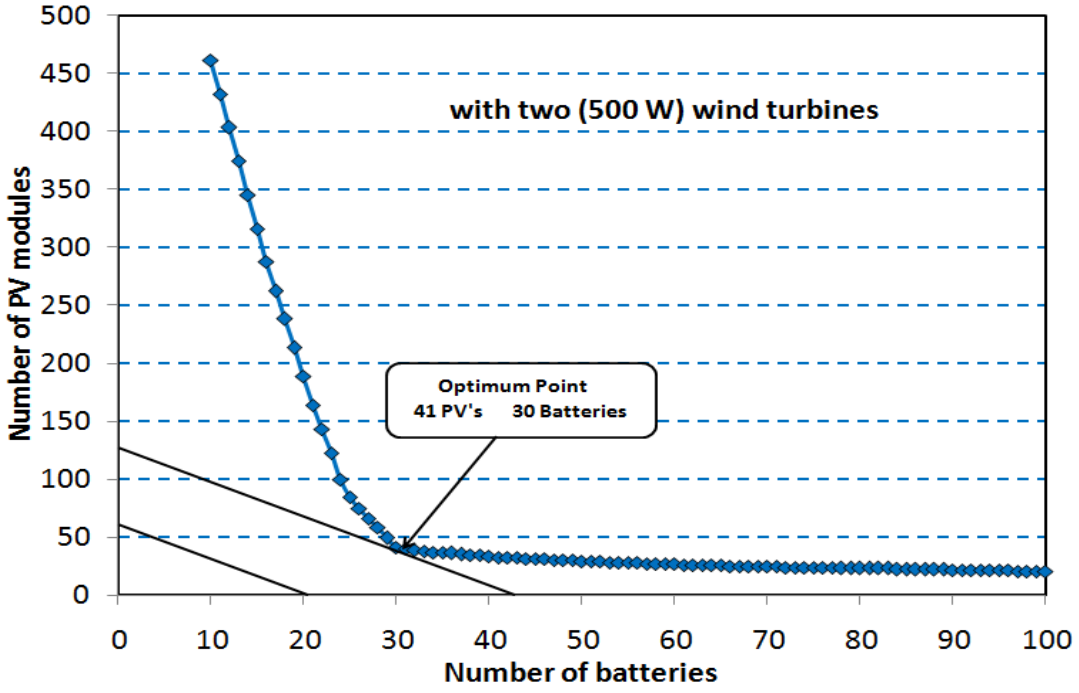
Fig.(4.11) Plot of Number of PV modules versus Number of Batteries for a given LPSP.

So, for a given unit cost of batteries and PV modules, optimum solutions that minimize the cost of the system were found with one, two and three wind turbine. Plots of the number of PV modules versus the number of batteries for a given LPSP are shown in (Fig. 4.12). On the same plots, the cost function lines are shown. The optimum numbers of PV modules and batteries from the point of tangency with one (500 W) wind turbine are 47 and 35 respectively, as indicated in (Fig. 4.12 [a]) with (1.0513 $/kWh). Increasing the number of the wind turbines to be two (500 W) wind turbines, will decrease the levelized cost of energy (LCE) of the hybrid system to be (0.93 $/kWh) at the optimum point with 41 PV modules and 30 batteries Fig. 4.12 [b]). Further increasing the number of wind turbines to be three will leads to reduce the levelized cost of energy to be (0.82 $/kWh) with 34 PV modules and 27 batteries Fig. 4.12 [c]). Two domains can be identified, if the number of batteries are less than the number of batteries of the optimum points, the variation of PV power versus the capacity battery is important, and become gradual after these points. This can be explained because with low storage capacity, the system needs more PV power to meet the load with the desired LPSP. A summary for these results that the optimum points for the desired LPSP is listed in Table (7). These points give the economical optimal configurations with the lowest levelized cost of energy. It has been remarked that increasing the number of wind turbine will reduce the levelized cost of energy and reflect good contribution of both wind and solar energies for the desired reliability.

a) With one (500 W) wind turbine



b) With two (500 W) wind turbine



c) With three (500 W) wind turbine

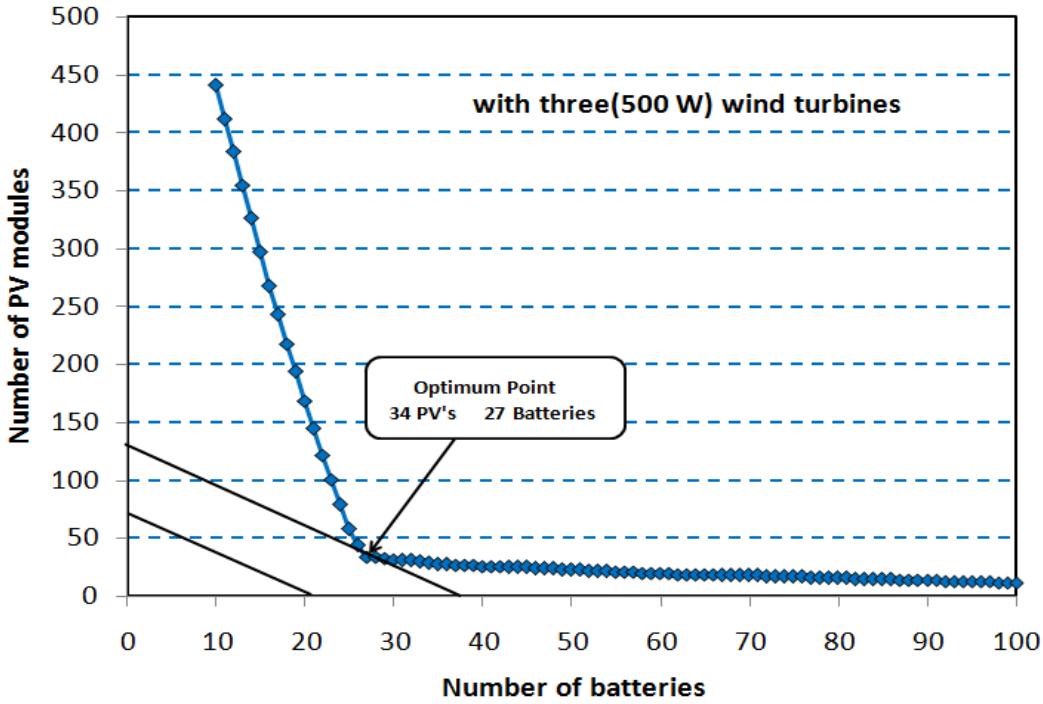


Fig.(4.12) Plots of the number of PV modules versus the number of batteries for a given (LPSP = 0.000274) with the optimum configurations

Table (7) Optimum configurations that give the minimum cost for specific LPSP with one, two and three (500 W) wind turbines.

Optimum Points (LPSP=0.000274)	**One (500 W) WT**	**Two (500 W) WT**	**Three (500 W) WT**
N_PV	47	41	34
N_Batt	35	30	27
Cost ($/kWh)	1.05	0.93	0.82

Figure (4.13) gives a cumulative conclusion of the simulation results for the optimum solution of the PV/battery configurations that give the minimum levelized cost of energy with one, two and three wind turbines. In this figure, the different configurations, which meet the same reliability of power supply, are expressed by plotting the trade-off curve between the number of PV modules and the number of batteries for each wind turbine. In the same figure, the simulation results representing the levelized costs of energy for different combinations satisfying an (LPSP of 0.000274) are presented. This figure illustrates different combinations of PV, wind and battery storage capacities and their corresponding kWh costs for each wind turbine. The results yield only one combination for the optimum solution, where the cost of kWh energy is a minimum for each wind turbine. As it can be seen from Figure (4.13), the (LCE) curves have two linear parts. In

the first part (below the optimum points), a sharp decrease in the cost is observed, which is mainly due to the decrease of PV power. In the second part, (after the optimum points) the LCE increases gradually with increasing the storage capacity. This increase is due to the short life of battery as well as increasing the number of batteries leads to raise the minimum limit of the batteries capacity which more PV need power to achieve the desired reliability.

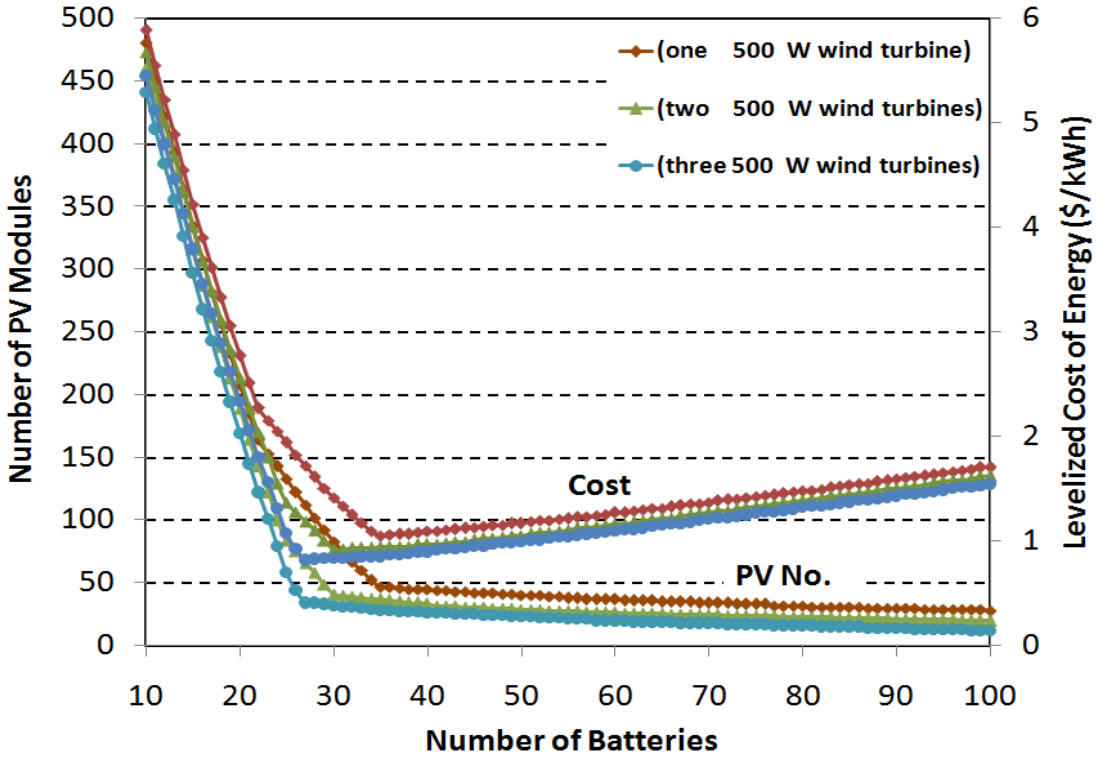


Fig.(4.13) Comparison of levelized costs of energy for different configurations with (LPSP=0.000274)

Since the concept of loss of power supply probability criteria is used to evaluate the reliability of the hybrid PV/wind power generation system, it is useful to compare it with the levelized cost of energy (LEC), Figure (4.14). This has been done at optimum point's number of batteries with changing the number of PV modules for each wind turbine. As shown in this figure, the levelized cost of energy is increasing with decrease the loss of power supply probability. This is due to high cost of the system components that gives high contribution of renewable energy. It is demonstrated from this figure that, increasing the number of wind turbines leads to achieve small values of loss of power supply probability which mean high contribution of renewable energy.

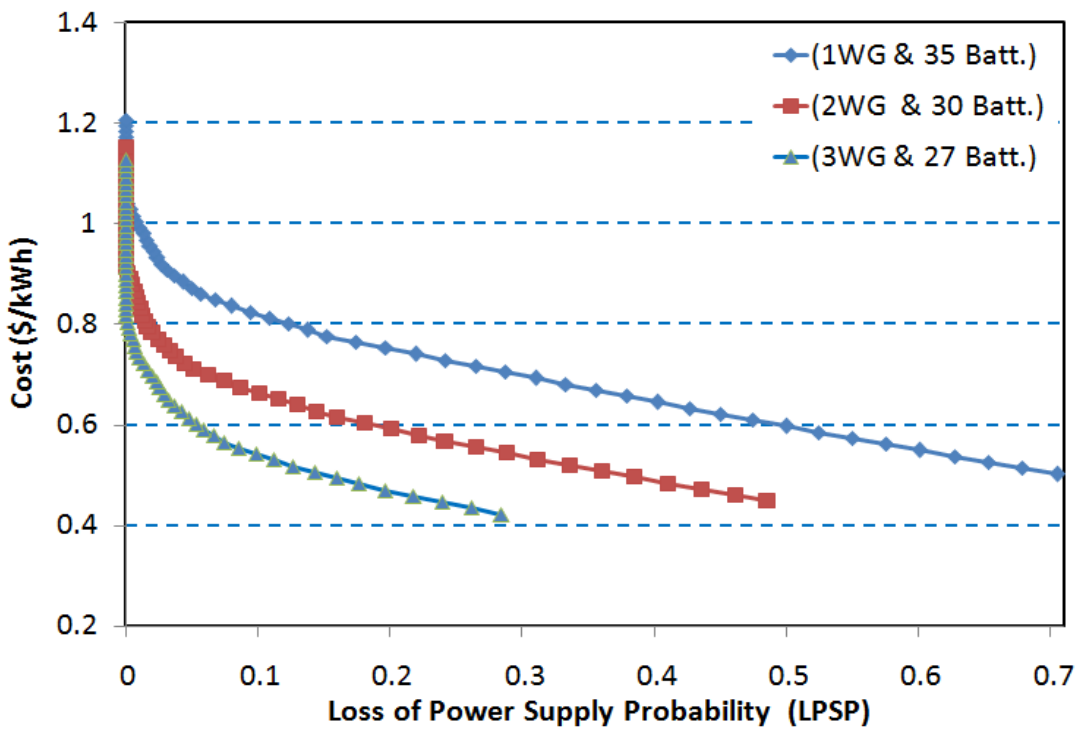
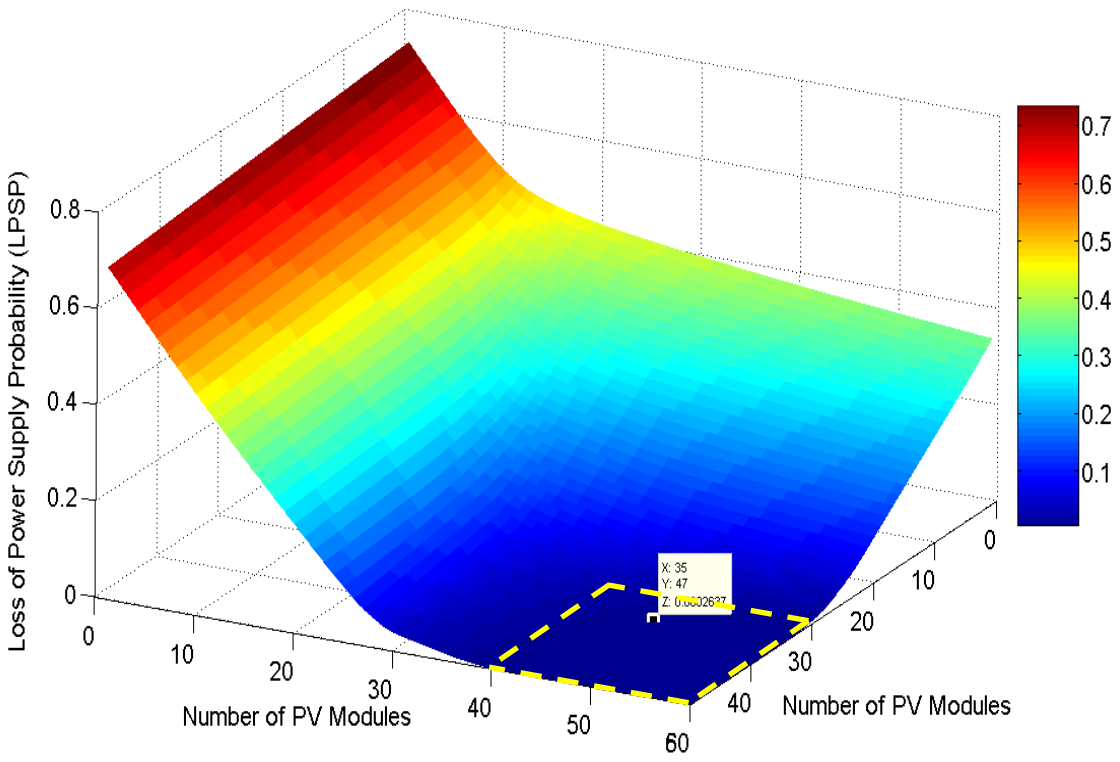


Fig.(4.14) Relation between Loss of Power supply probability and levelized cost of energy at optimum points number of batteries and changing the number of PV modules

Contour of constant loss of power supply probability (LPSP) with one (500 W) wind turbine is presented in Figure (4.15). It is clear from 3D contour that increasing the number of PV modules and number of batteries leads to achieve zero level of loss of power supply probability. The optimum point is shown in this figure with 47 PV modules and 35 batteries at LPSP = 0.000274 level is very close to zero LPSP level which means that the renewable contribution is very high.



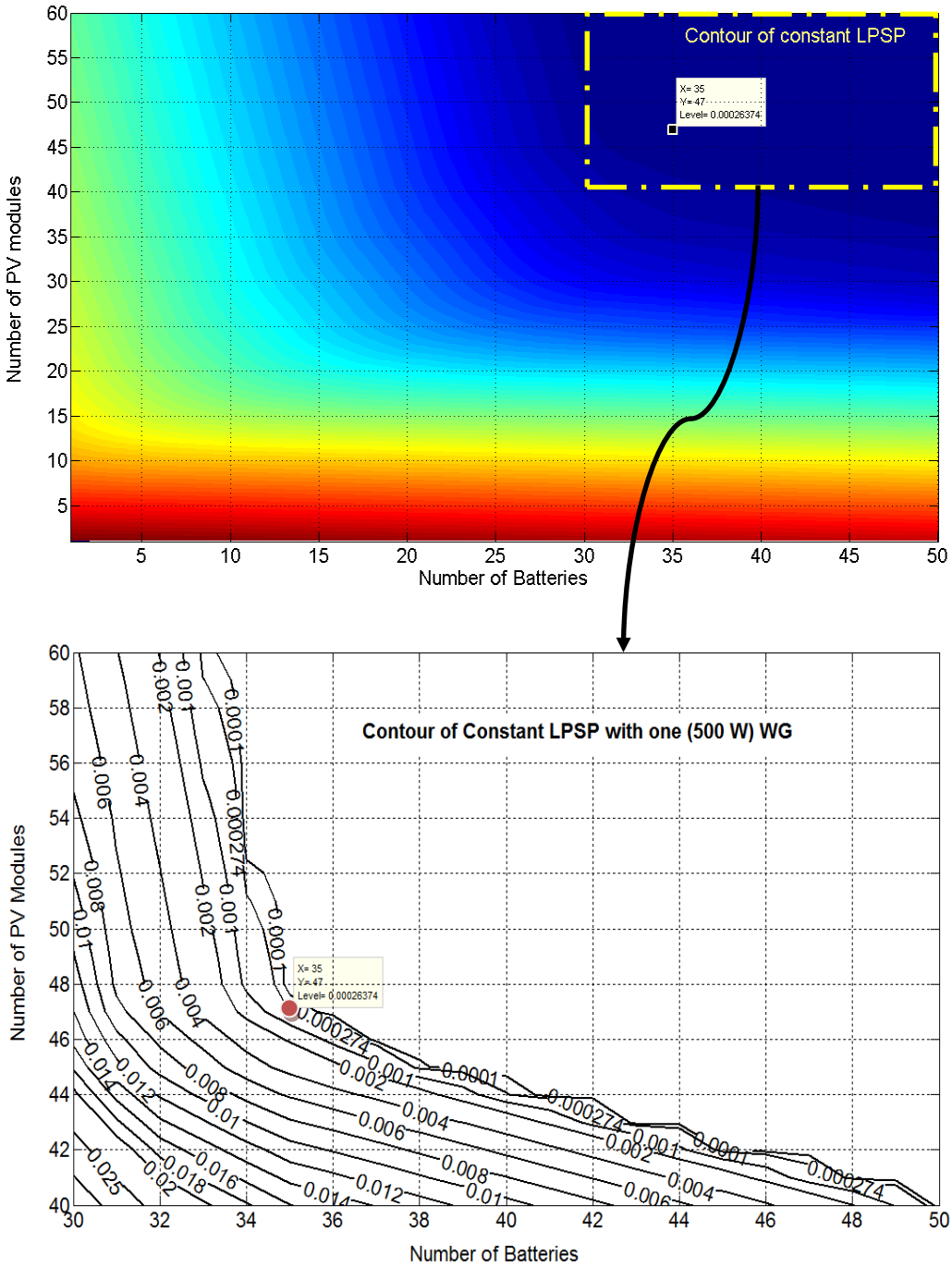
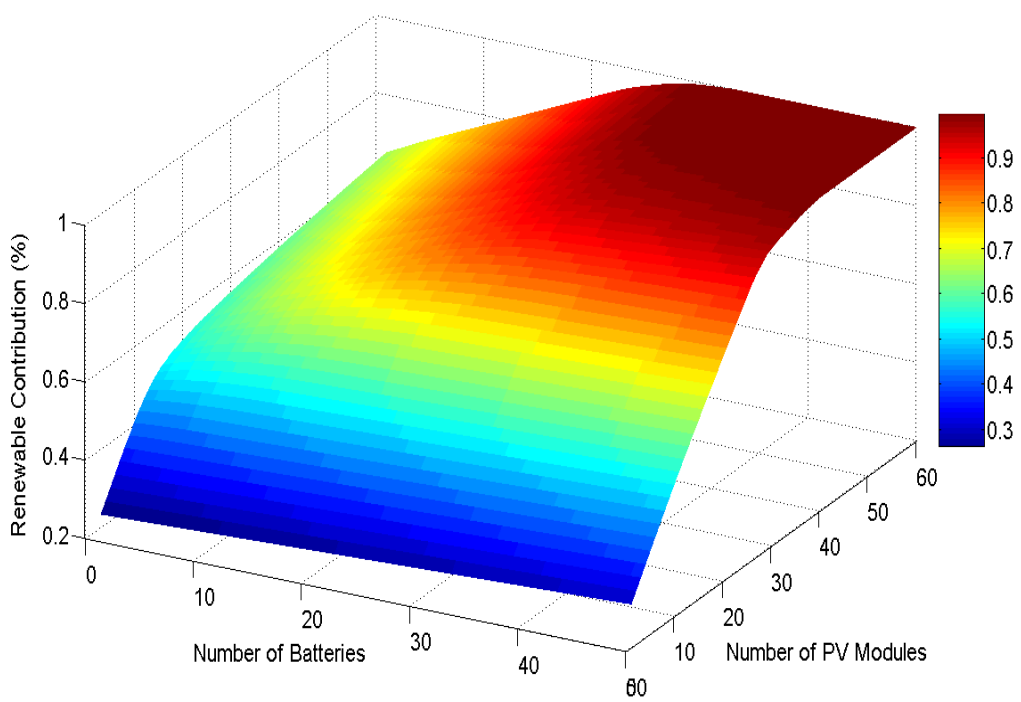


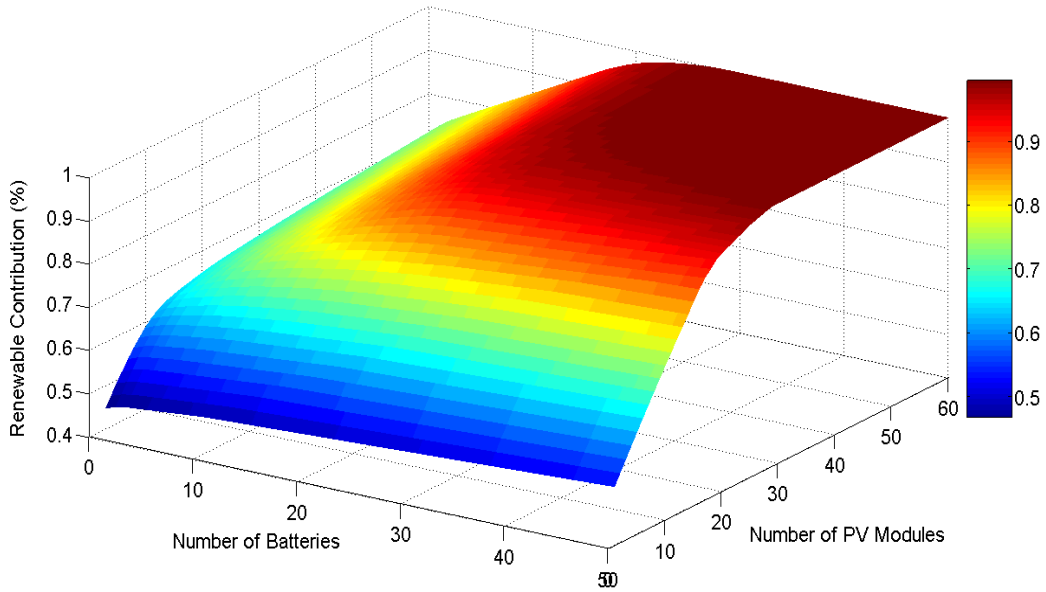
Fig.(4.15) Contour plots of constant LPSP for different configurations of PV modules and batteries with one (500 W) wind turbine.

3D contours of the renewable energy contribution for deferent configuration of PV modules and batteries with one, two and three wind turbines are shown in Figure (4.16). By comparing the results we conclude that the wind energy contribution is very important. Because of increasing the number of wind turbines, we can achieve high contribution of renewable energy and reduce the levelized cost of energy. The renewable energy contribution will be 100% with one wind turbine starting from more than 35 batteries and more than 45 PV modules whereas with two wind turbines we can achieve 100% renewable energy contribution starting from more than 25 batteries and more than 35 PV modules. With three wind turbines the same level of energy contribution can be achieved starting from more than 20 batteries and more than 25 PV modules.

a) With one (500 W) wind turbine



b) With two (500 W) wind turbine



c) With three (500 W) wind turbine

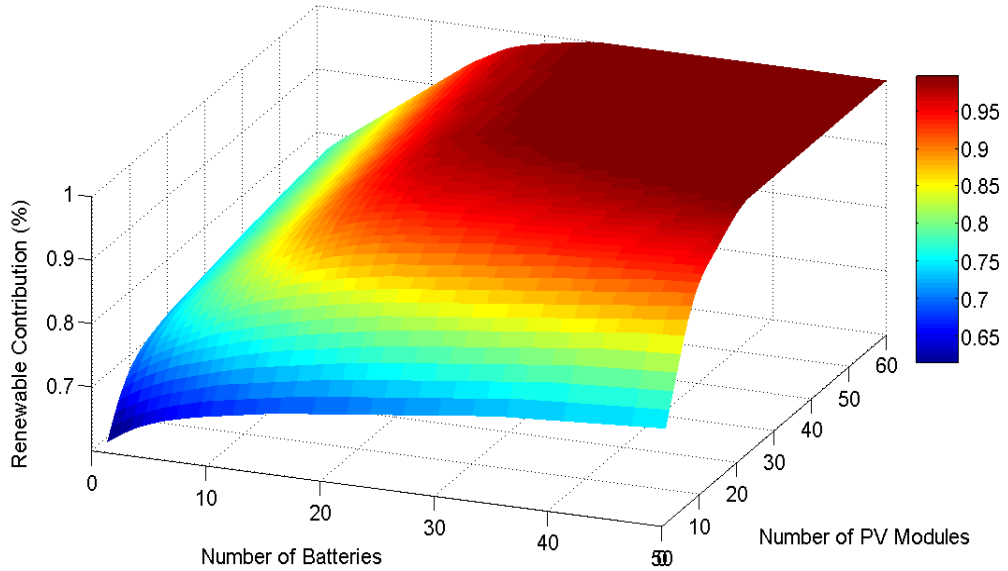
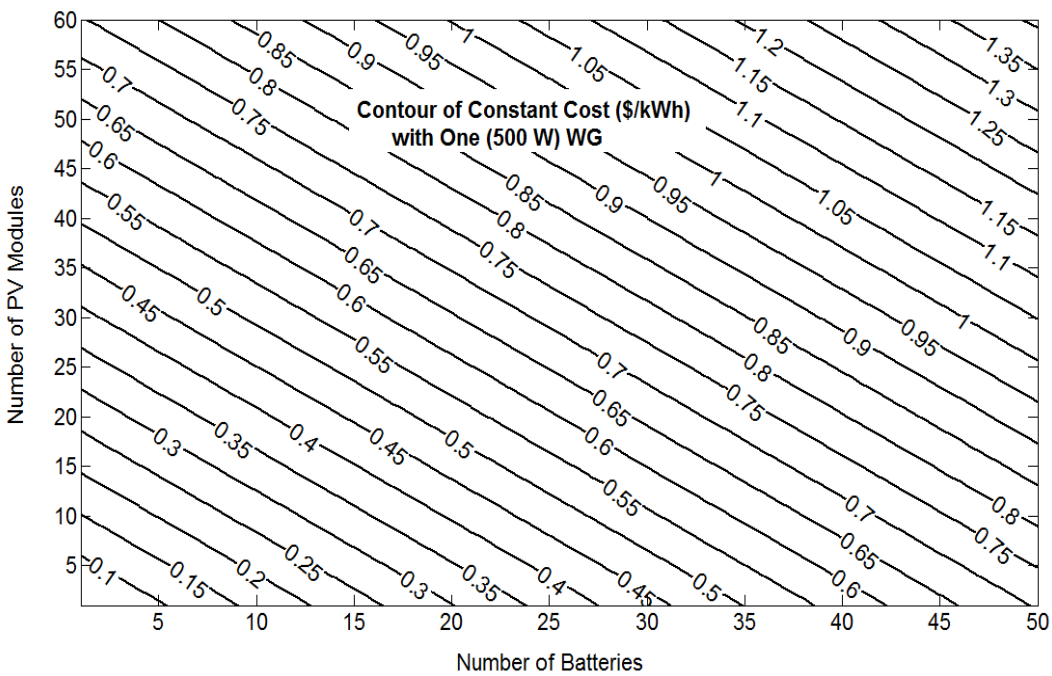


Fig. (4.16) 3D plots of renewable contribution for different configurations of PV modules and batteries

In order to obtain the lowest LCE value and avoid system fail, the use of a third energy source (diesel) could be beneficial for the system. Although using of any fossil fuel source of energy will lead to produce pollutants into the local atmosphere but it is necessary to use a diesel engine to cover the load in case the power generated from the hybrid system is less than the load. This can be happened because of bad weather conditions (dusty or cloudy weather) or in case the wind speed is less than the cut in speed of the wind turbine. With one (500 W) wind turbine, the simulation results of the levelized cost of energy with and without (2.6 kW) diesel engine are shown in figure (4.17). This figure shows that the cost is increasing with the diesel engine due to calculating the capital and running costs of the diesel engine but the load is always satisfied.

a) Without diesel engine



b) With (2.6 kW) diesel engine

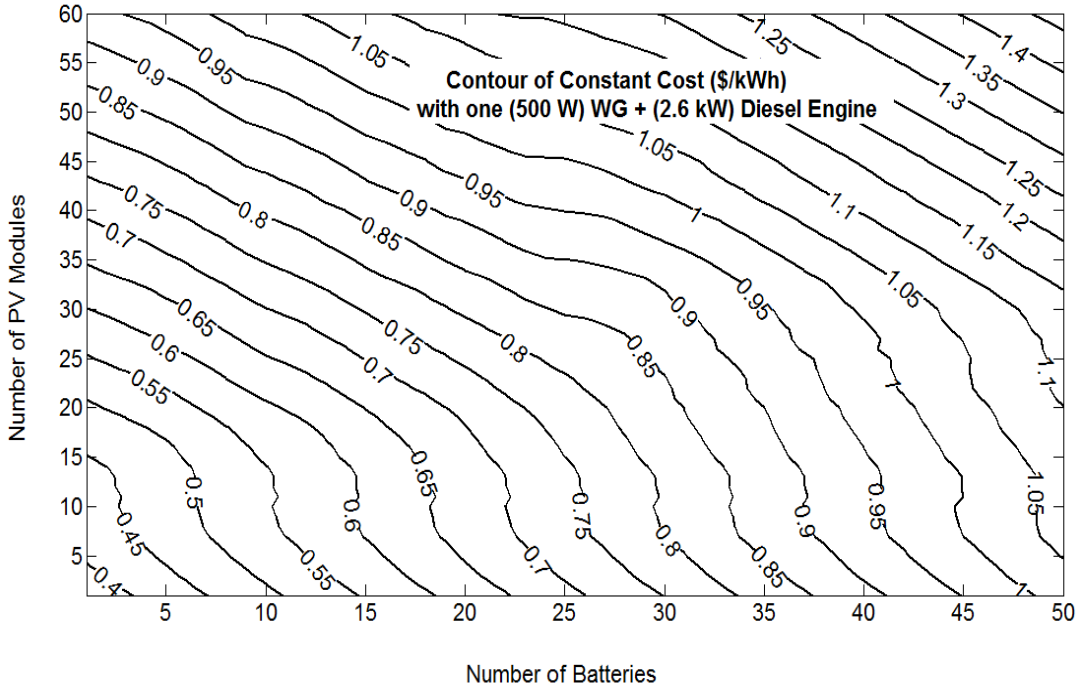
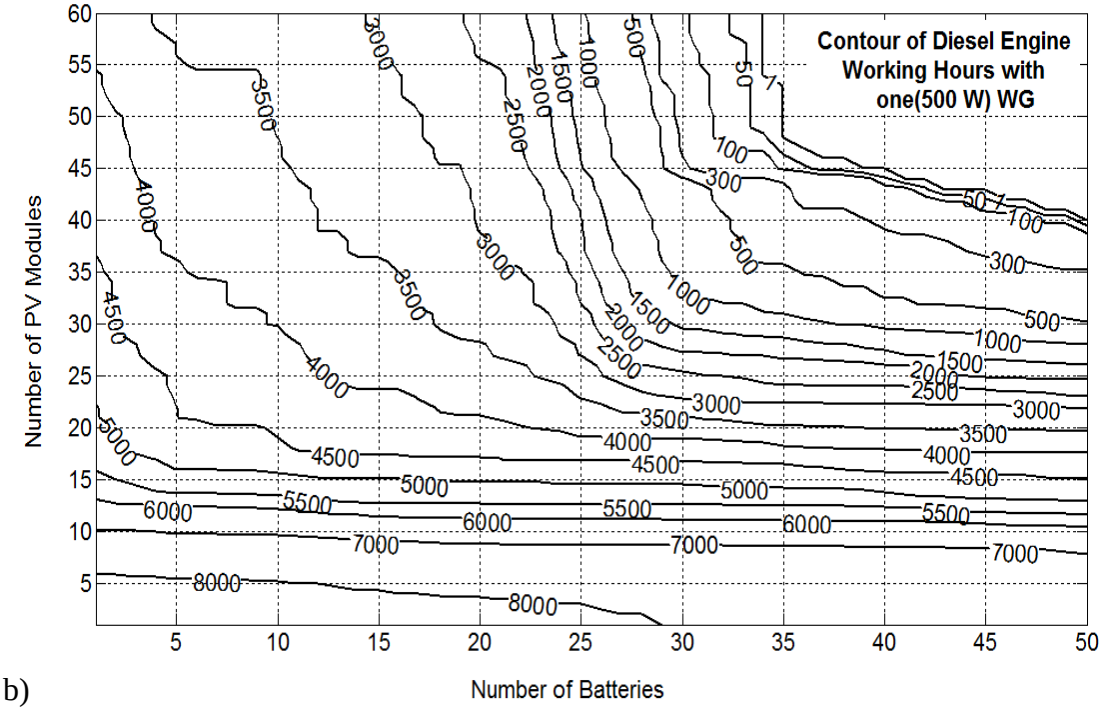


Fig. (4.17) Contour of constant cost ($/kWh) with one (500 W) wind turbine

Contours of diesel engine working hours during the whole year and CO_2 production are presented in Figure (4.18). Increasing the number of PV modules and the number of batteries leads to avoid using the diesel engine but this will increase the total cost of the system. With more than 35 batteries and more than 45 PV modules we can achieve zero working hours of the diesel engine and zero CO_2 production with levelized cost of energy (LCE) between 1.1 to 1.4 $/kwh. We can reduce this high cost by using he diesel engine and reduce the number of PV modules and batteries but this will leads to produce CO_2 to the local atmosphere.

a)



b)

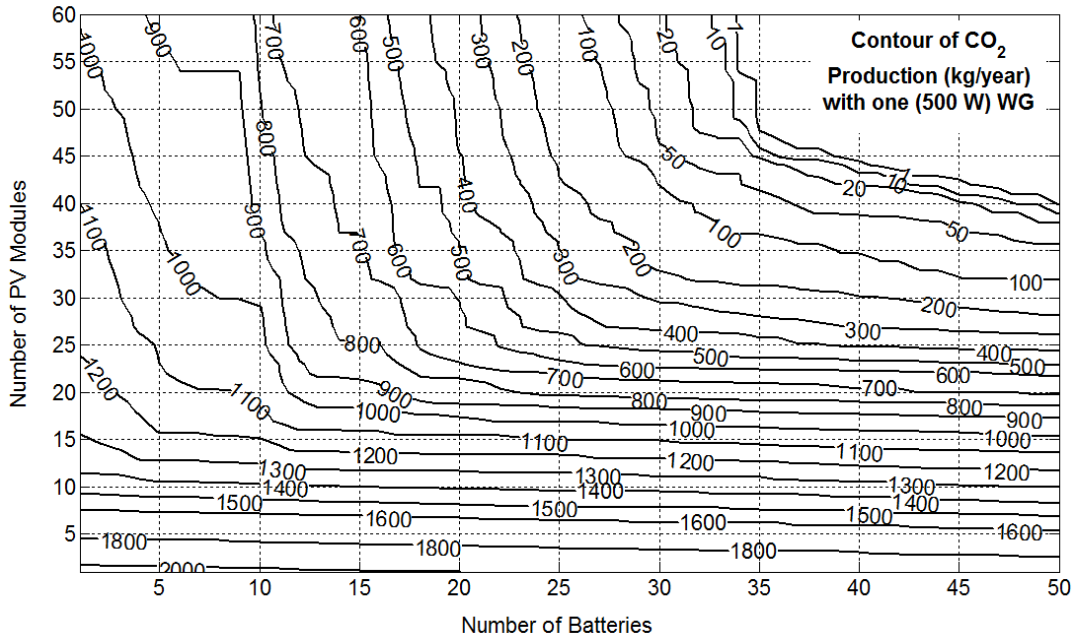


Fig. (4.18) Contour of a) diesel engine working hours and b) CO_2 production with one (500 W) wind turbine and one (2.6 kW) diesel engine

CONCLUSIONS

- A mathematical techno-economical modal have been developed to analyze and optimize an off grid hybrid PV/wind power generation system.

- The model includes the option of adding diesel engine to the system.

- The mathematical model includes the development of probability density function for both solar radiation and wind speed.

- A computer code has been developed to solve the mathematical model using MATLAP Platform.

- The developed mathematical mode l and computer code have been validated using published work and with spatial runs with the well known HOMER software.

- The validated code has been used to analyzed and optimize the hybrid PV/wind power generation system for a typical off grid house in the eastern province of the Kingdome of Saudi Arabia.

- The simulation results showed that for a house with a typical nominal load (473 W average) and for almost zero loss of power supply probability (LPSP) using a system comprises one wind turbine, the optimum number of PV module and

batteries are 47 and 35 respectively and the levelized cost of energy is (1.05 $/kWh).

- With two wind turbine the optimum configuration includes 41 PV modules and 30 batteries with (0.93 $/kWh).

- Further increasing the number of wind turbine to three, will reduce the levelized cost of energy to (0.82 $/kWh) with 30 PV modules and 27 batteries.

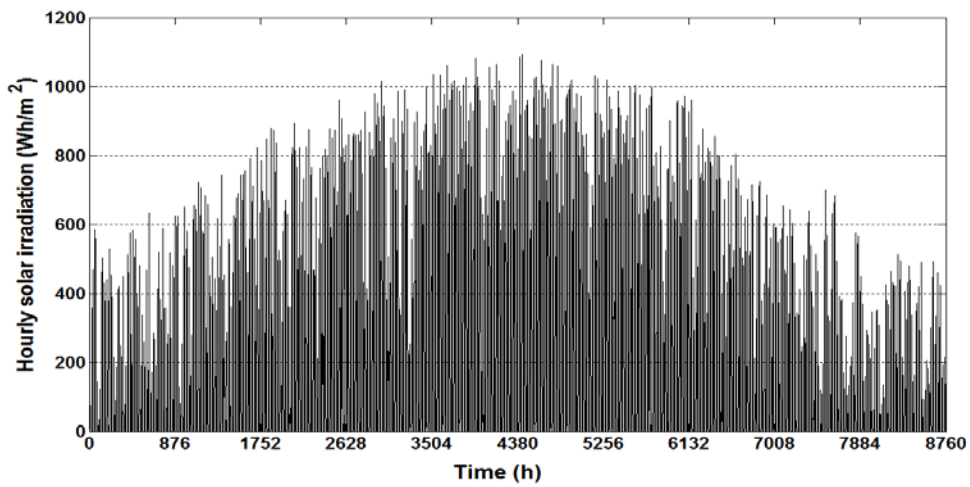
- The mathematical model and computer code were developed in a general manner such that it can simulate any location.

APPENDICES

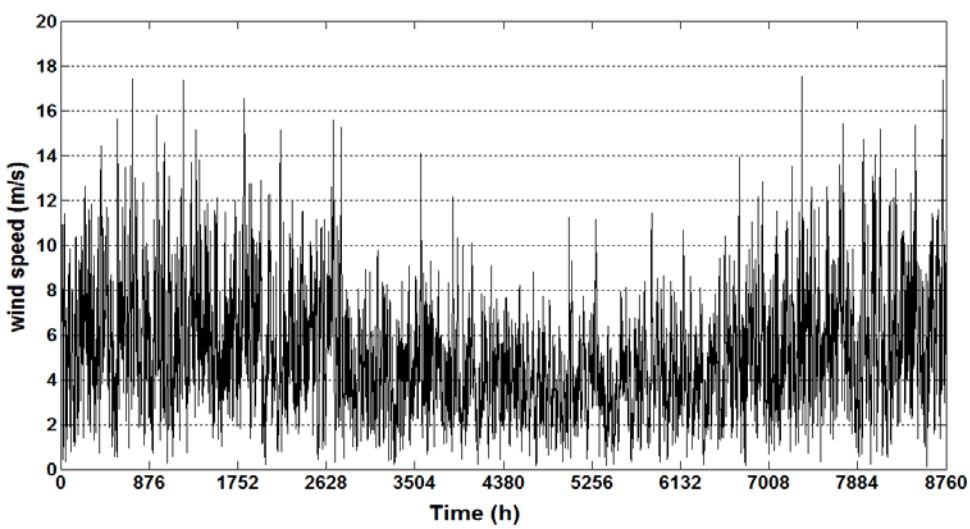
Appendix 1. How to Get the Solar Weather Data from HOMER Software via Internet

Hourly Values of Meteorological Parameters (Solar Radiation and wind speed) of Ajaccio [Latitude (41° 55’ North), Longitude (8° 44’ East)]

a) Solar radiation

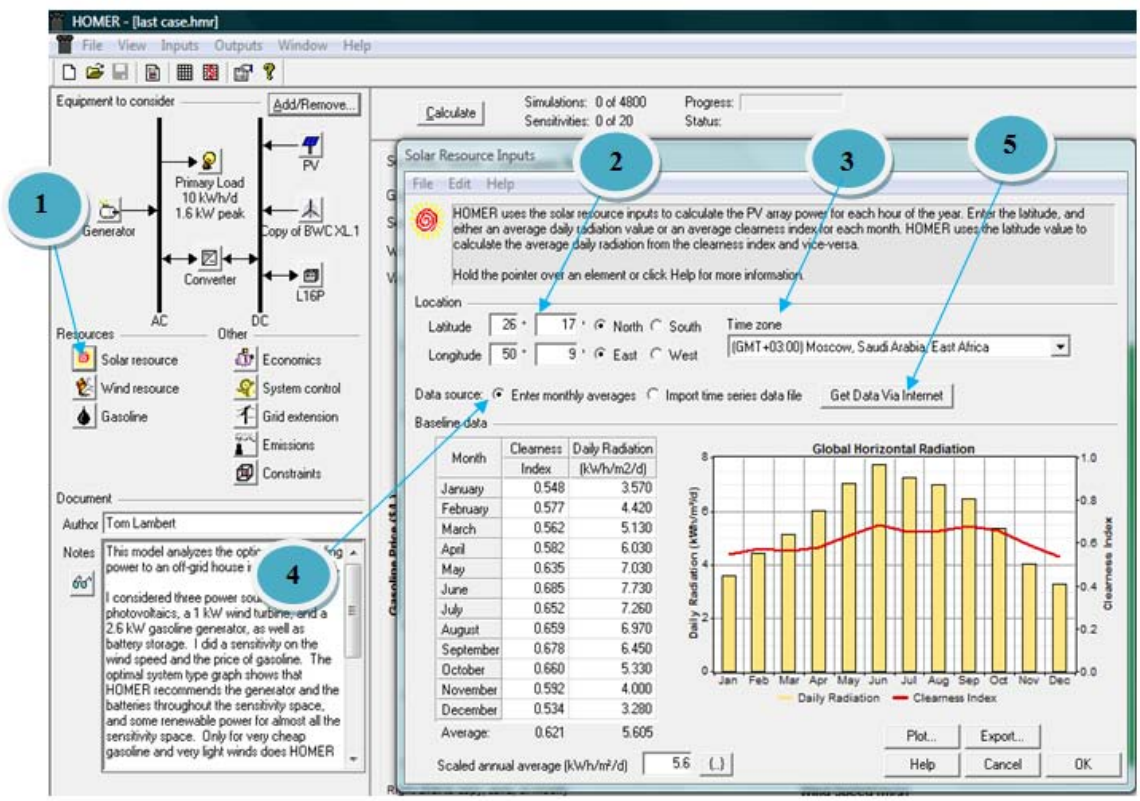


b) Wind speed

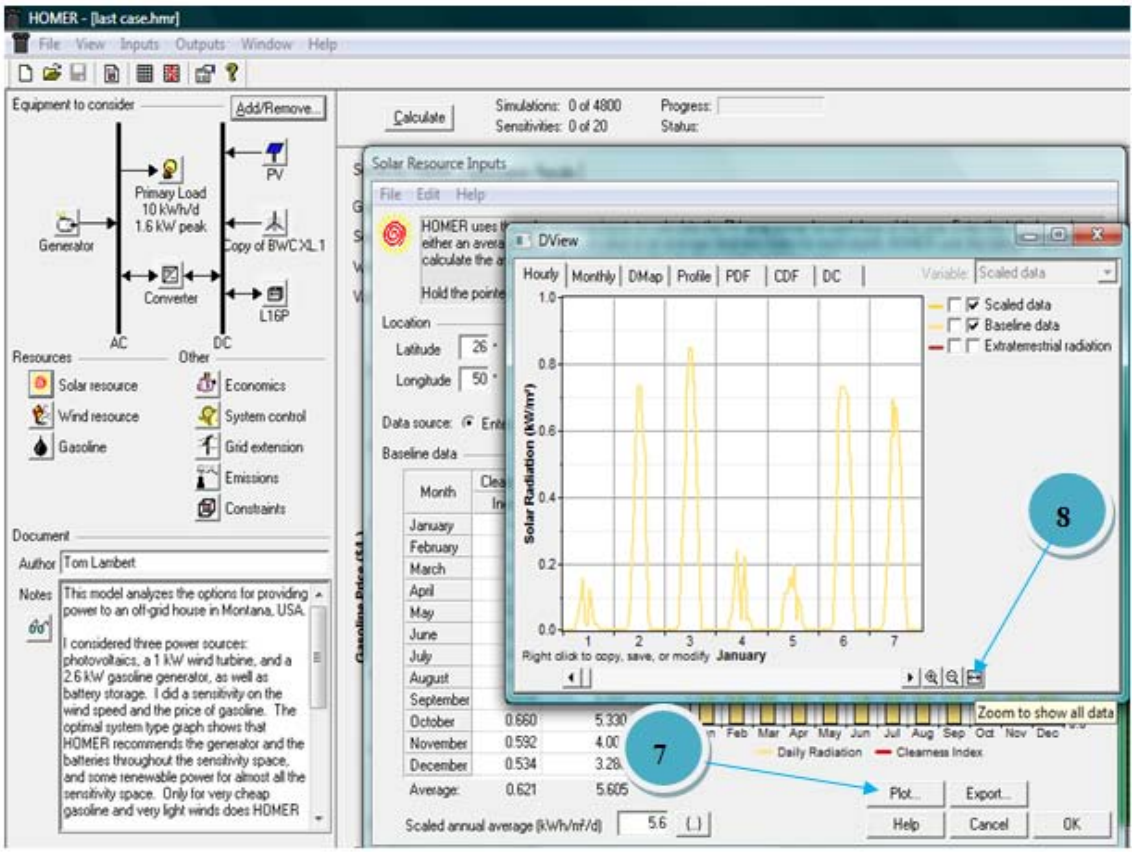


We can get the solar weather data as 22-year Average for any location from (HOMER) using the following steps:

1. On the left click solar resource.
2. In the solar resource window we should specify the longitude and the latitude of the location under interest (in our situation for validation purpose it is Ajaccio Latitude (41° 55′ North), Longitude (8° 44′ East)].
3. In the same window specify the time zone of the location.
4. Choose Enter monthly averages
5. Click Get Data Via Internet (Homer will ask you to register in Nasa website You have to put your Email and specify a password)
6. Homer will give you Monthly Averaged Radiation Incident On A Horizontal Surface



7. If you need the Hourly Averaged Solar Radiation (In our case we need the hourly data for simulation) click plot.
8. In Dview window Homer will give you one week solar radiation. Clicks zoom to show all data.

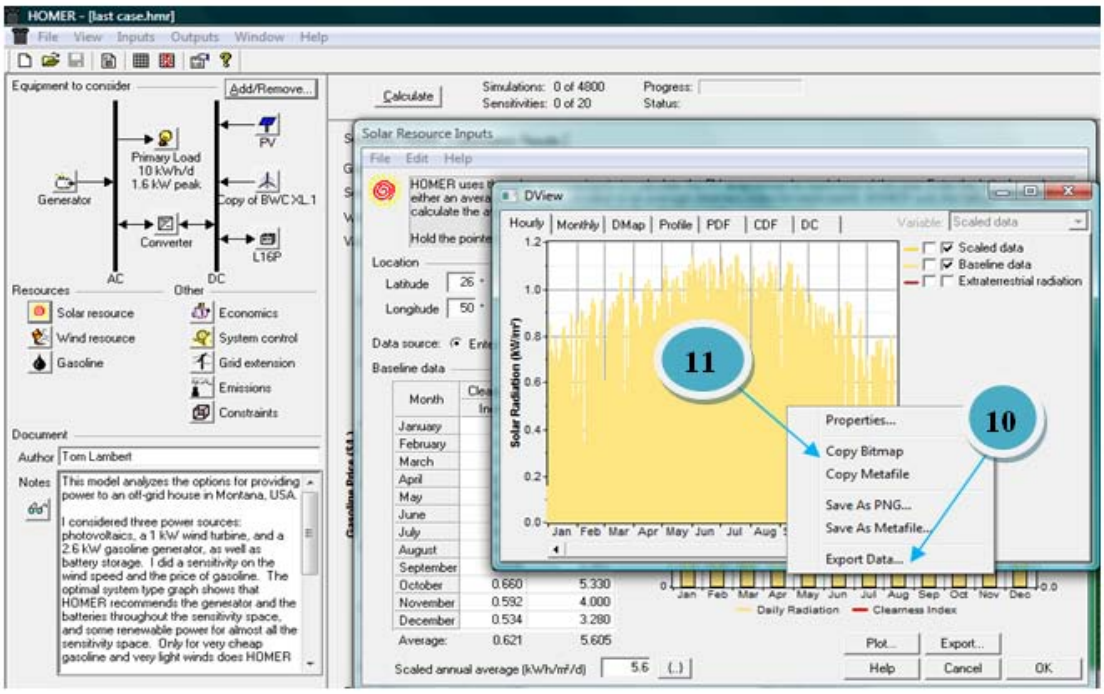


9. HOMER will give the full year Hourly Averaged Solar Radiation.

10. To export the full year data to read by any program for simulation purposes (right click on the curve and pick export data)

11. Also you can copy the figure from the same window.

12. The same steps can be done to find wind speed



Appendix 2. How to calculate the probability density function for wind speed or solar radiation using MATLAB:

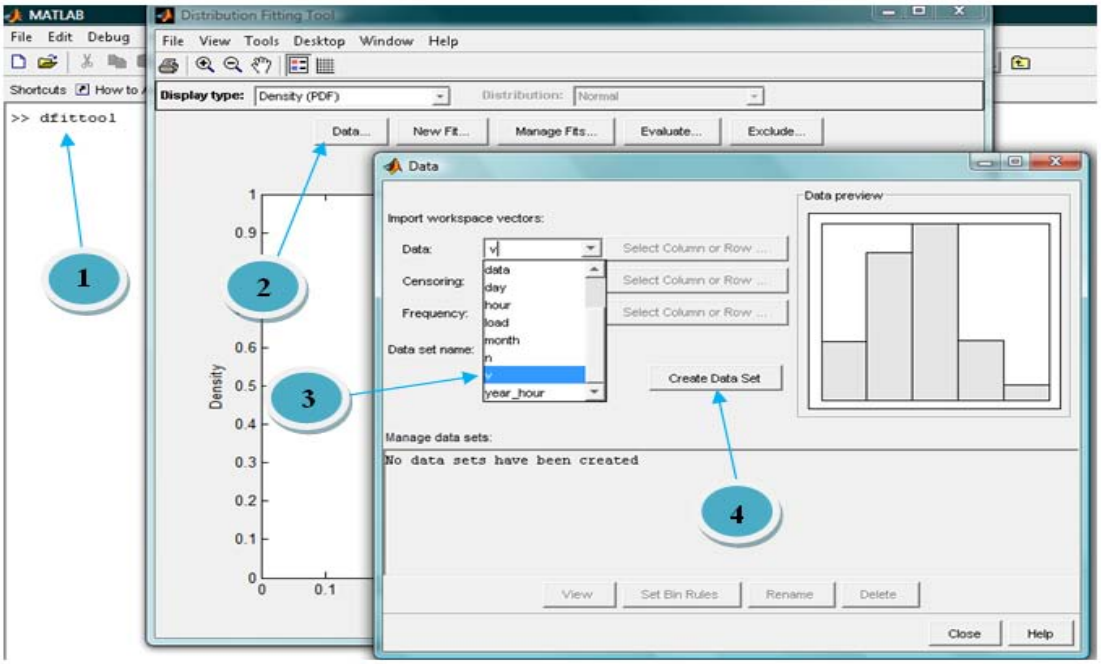
We can calculate the probability density function for any data by (Mat-lab) using the following steps:

1- In the command window of Mat-lab type (dfittool) to open the Distribution Fitting Tool Window.

2- In the Distribution Fitting Tool Window Click (Data).

3- Choose the variable you want to create the probability density function.

4- Click (Create Data Set).

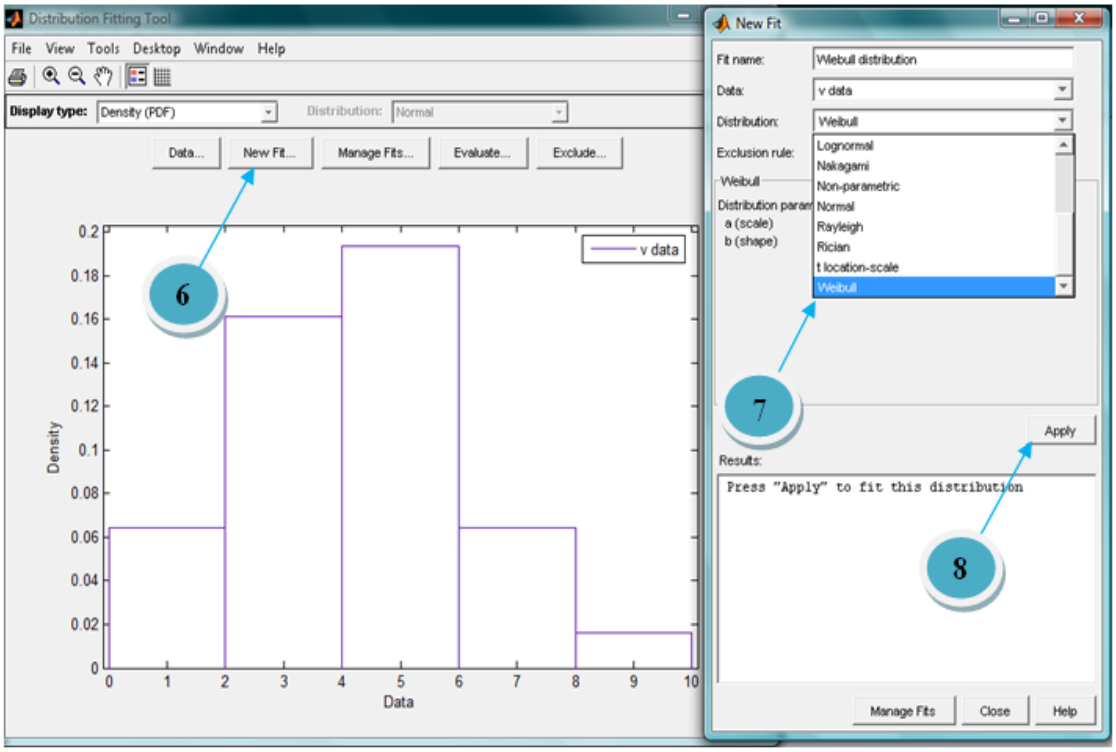


5- The histogram of the selected data will be created in the Distribution Fitting Tool Window.

6- In the Distribution Fitting Tool Window click (new fit).

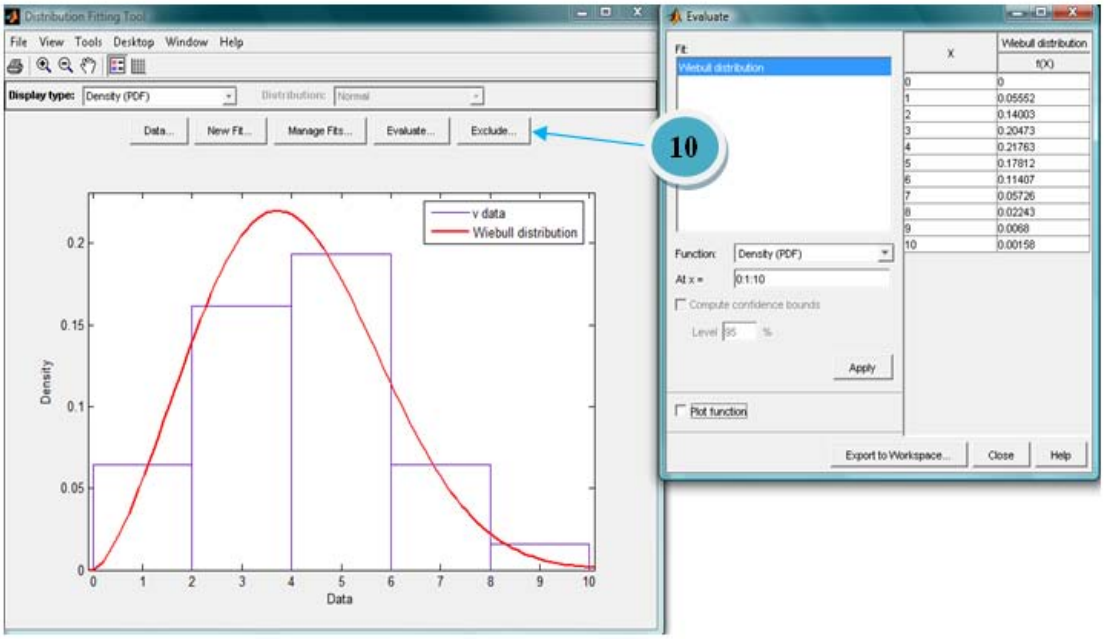
7- In the New Fit Window and from the drop-down list you can choose the distribution which gives the best fitting of the selected data e.g. Wiebull or Normal distribution.

8- Click (apply).



9- The selected distribution will be shown on the histogram of the selected data.

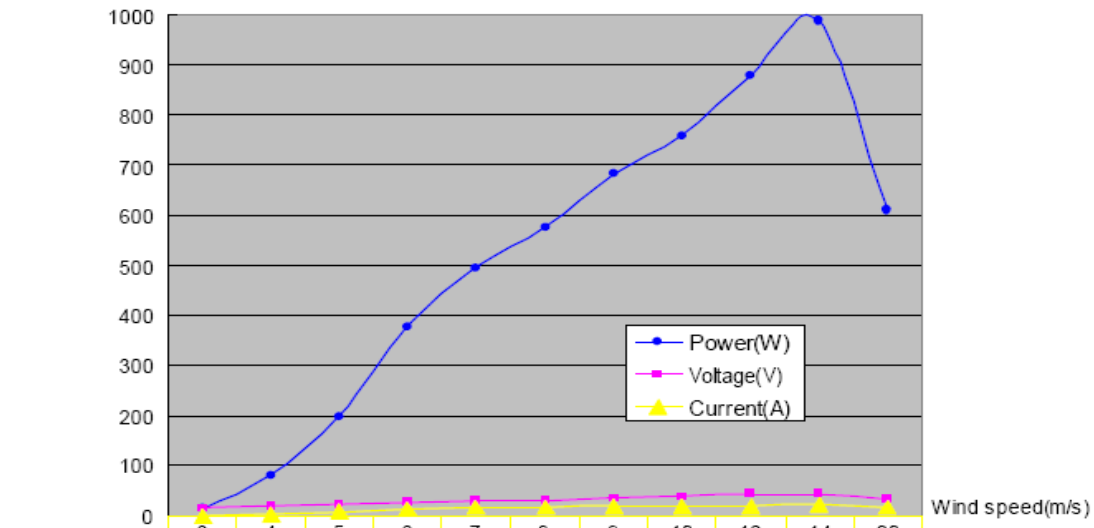
10- To evaluate the selected distribution click (Evaluate) in the Distribution Fitting Tool Window.



Appendix 3. Characteristic curves of Some Wind Turbines.

1-Wind Turbine (Hummer 500W)

The characteristic curve of Hummer 500W Wind turbine and the equation used in the program:



Wind speed(m/s)	3	4	5	6	7	8	9	10	12	14	20
Power(W)	14.4	80	198	378	495	576	684	760	880	989	612
Voltage(V)	18	20	22	28	30	32	36	40	44	46	34
Current(A)	0.8	4	9	13.5	16.5	18	19	19	20	21.5	18

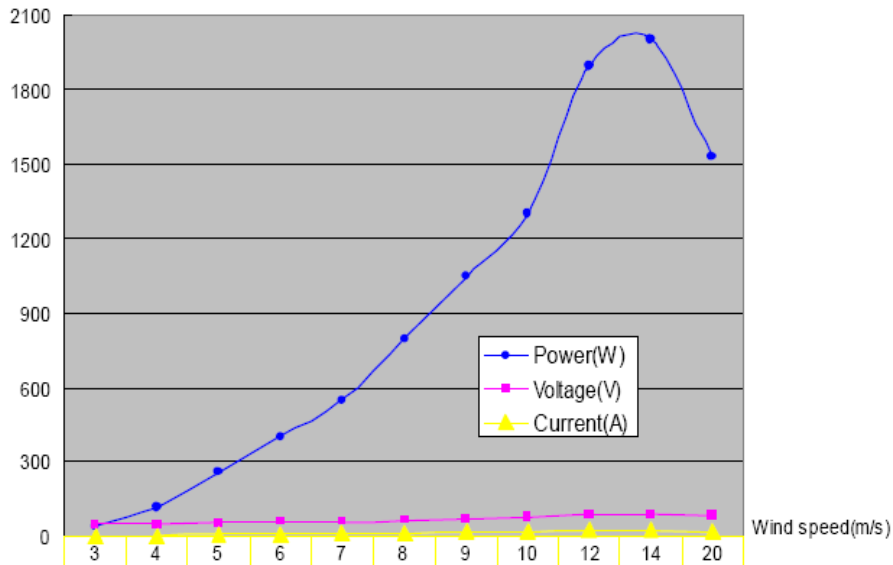
$$P(v)=\begin{cases} 0 & for \rightarrow \quad v<3 \\ 5.6083\,v^4+102.55\,v^3-660.4\,v^2+1875.45\,v-1983 & for \rightarrow \quad 3\le v<7 \\ 0.49\,v^4-20.35\,v^3+304.26\,v^2-1873.85\,v+4499.25 & for \rightarrow \quad 7\le v<14 \\ -62.83\,v+1868.67 & for \rightarrow \quad 14\le v\le 20 \\ 0 & for \rightarrow \quad v>20 \end{cases}$$

Specification

Rated power(W)	500
Maximum output power（W）	1000
Charging voltage (V)	DC 24
Blade quantity	3
Blade material	GRP
Blade diameter（m）	2.7
Start-up wind speed (m/s)	3.0
Rated wind speed (m/s)	7.0
Rated rotating rate (r/min)	600
Wind energy utilizing ratio (Cp)	0.48
Generator output	Single-phase frequency conversion AC
Output AC frequency (Hz)	0~300
Rated charging current (A)	15
The maximum charging current (in a short time)(A)	25
Generator efficiency	>0.78
Guy tower diameter(mm)	Φ76*2000*3 (3pcs)
Tower height(m)	6
Generator weight (kg)	6.5
Battery 12V 150Ah/200Ah	2pcs
Noise Index	LAeq=29 dBA 5m bebind turbine@5m/s gusting

2-Wind Turbine (Hummer 1000 W)

The characteristic curve of Hummer 1000 W Wind turbine and the equation used in the program:



Wind speed(m/s)	3	4	5	6	7	8	9	10	12	14	20
Power(W)	40	120	260	400	550	792	1050	1300	1892	2000	1530
Voltage(V)	50	50	52	57.14	61.1	66	70	76.5	86	90.9	80.53
Current(A)	0.8	2.4	5	7	9	12	15	17	22	22	19

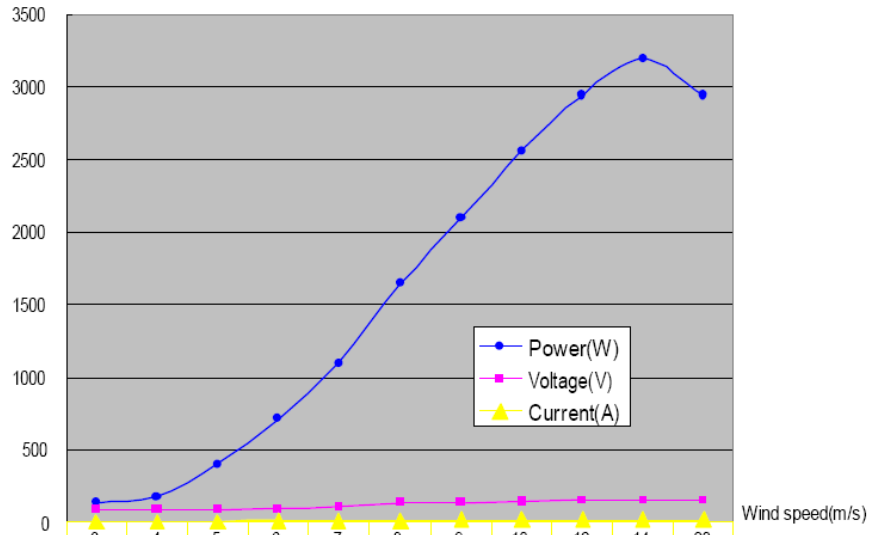
$$P(v) = \begin{cases} 0 & for \rightarrow \quad v < 3 \\ -0.154\, v^4 + 4.17\, v^3 - 24.38\, v^2 + 137.46\, v - 255.82 & for \rightarrow 3 \le v < 12 \\ 0.49\, v^4 - 20.35\, v^3 + 304.26\, v^2 - 1873.85\, v + 4499.25 & for \rightarrow 12 \le v \le 20 \\ 0 & for \rightarrow \quad v > 20 \end{cases}$$

Specification

Rated power(W)	1000
Maximum output power（W）	2000
Charging voltage(V)	DC 60
Blade quantity	3
Rotor blade material	GRP
Rotor blade diameter（m）	3.1
Start-up wind speed (m/s)	3.0
Rated wind speed (m/s)	9.0
Rated rotating rate (r/min)	500
Wind energy utilizing ratio (Cp)	0.45
Generator output	Single-phase frequency conversion AC
output AC frequency (Hz)	0~400
Rated charging current (A)	15
The maximum charging current (in a short time)(A)	30
Generator efficiency	>0.8
Guy tower diameter(mm)	Φ89*2000*3.5（4pcs）
Tower height(m)	8
Weight of generator (kg)	15
Battery 12V 150Ah/ 200Ah	5pcs
Noise Index	LAeq=30 dBA 5m bebind turbine@5m/s gusting

3-Wind Turbine (Hummer 2000 W)

The characteristic curve of Hummer 2000 W Wind turbine and the equation used in the program:



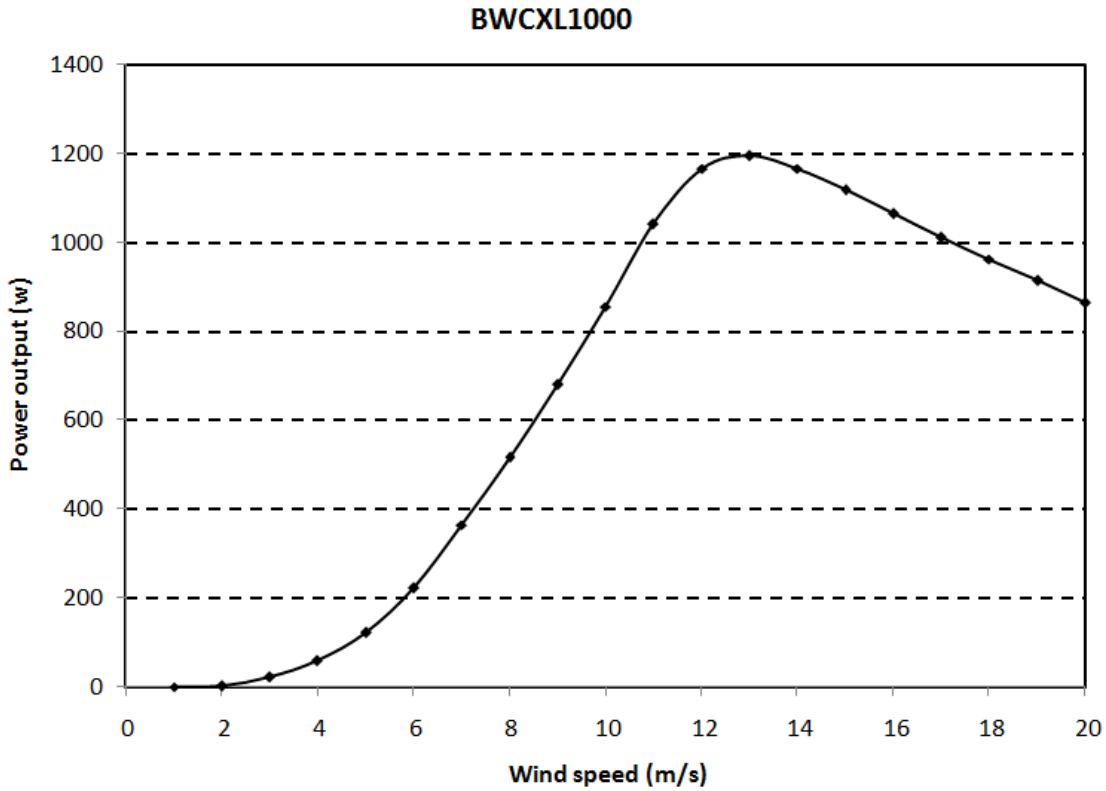
Wind speed(m/s)	3	4	5	6	7	8	9	10	12	14	20
Power(W)	135	180	400	720	1100	1650	2100	2560	2945	3200	2945
Voltage(V)	90	90	90	100	110	137	140	150	155	160	155
Current(A)	1.5	2	4	7	10	12	15	17	19	20	19

$$P(v) = \begin{cases} 0 & for \rightarrow \quad v < 3 \\ -0.566\, v^4 + 8.35\, v^3 + 23.07\, v^2 - 311.84\, v + 680.14 & for \rightarrow \quad 3 \le v < 12 \\ 0.07\, v^4 - 3.90\, v^3 + 57.13\, v^2 & for \rightarrow \quad 12 \le v \le 20 \\ 0 & for \rightarrow \quad v > 20 \end{cases}$$

Specification

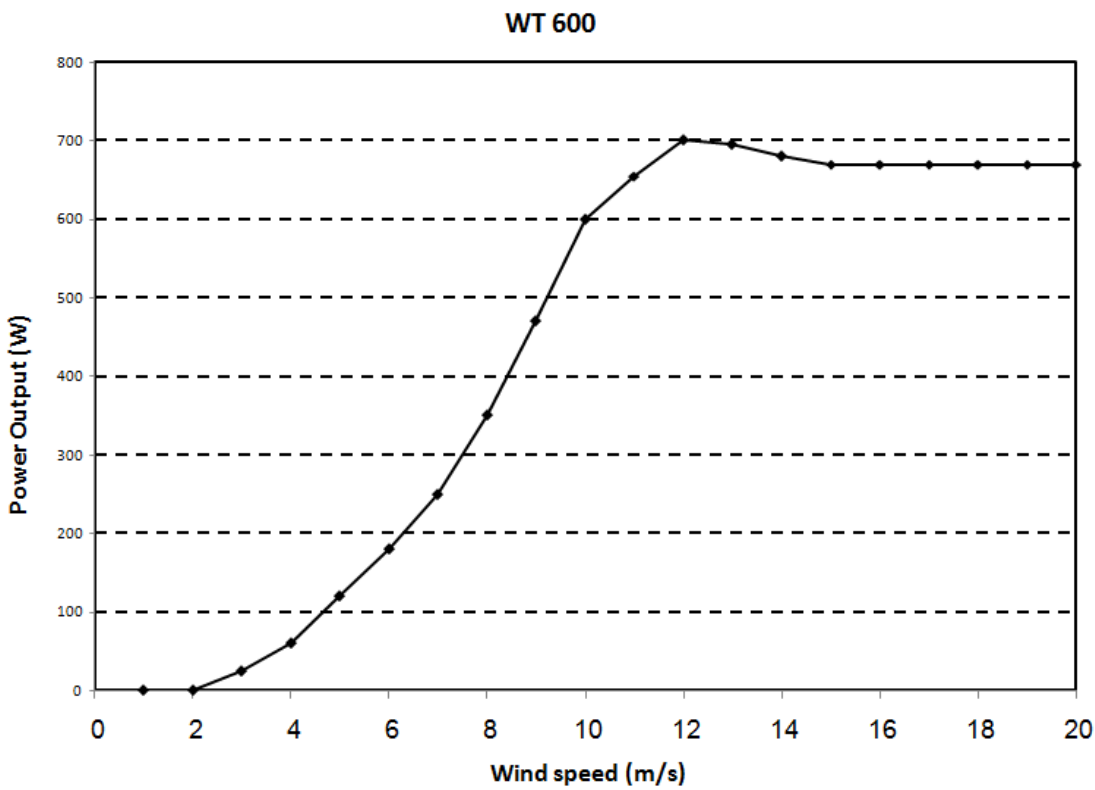
Rated power(W)	2000
Maximum output power（W）	3200
Charging voltage (V)	DC 120
Blade quantity	3
Rotor blade material	GRP
Rotor blade diameter（m）	3.8
Start-up wind speed (m/s)	3.0
Rated wind speed (m/s)	9.0
Rated rotating rate (r/min)	450
Wind energy utilizing ratio (Cp)	0.45
Generator output	Single-phase frequency conversion AC
Rated charging current (A)	15
The maximum charging current (in a short time)(A)	28
Output AC frequency (Hz)	0~370
Generator efficiency	>0.8
Guy tower diameter(mm)	Φ114*2000*5（5pcs）
Tower height(m)	10
The weight of generator(kg)	25
Battery 12V 150Ah/200Ah	10pcs
Noise Index	LAeq=32 dBA 5m bebind turbine@5m/s gusting

4-Wind Turbine (BWCXL1000 W)



$$P(v) = \begin{cases} 0 & for \rightarrow \quad v < 2 \\ -0.22\,v^4 + 4.93\,v^3 - 24.56\,v^2 + 65.95\,v - 69.5 & for \rightarrow \quad 2 \le v < 13 \\ -0.17\,v^4 + 11.7475v^3 - 301.6974\,v^2 + 3368.99\,v - 12557.26 & for \rightarrow \quad 13 \le v \le 20 \\ 0 & for \rightarrow \quad v > 20 \end{cases}$$

5-Wind Turbine (WT600 W)



$$P(v) = \begin{cases} 0 & for \rightarrow \quad v < 3 \\ -0.31\,v^4 + 8.13\,v^3 - 67.06\,v^2 + 269.78\,v - 377.12 & for \rightarrow \quad 3 \le v < 12 \\ -0.0626\,v^4 + 3.91v^3 - 89.53\,v^2 + 884.287\,v - 2478.93 & for \rightarrow \quad 12 \le v \le 20 \\ 0 & for \rightarrow \quad v > 20 \end{cases}$$

NOMENCLATURE

C_B the charge capacity of battery bank

EXC energy excess percentage

F_c is the factor representing connection loss

F_o is the coefficient representing power loss caused by other factors

i_{pv} module optimum operating point current at arbitrary conditions (A)

i_{sc} module short circuit current (A)

i_{mp} module maximum power current (A)

I the irradiance on a horizontal plane, (kW/m^2)

I_o the extraterrestrial total solar irradiance (kW/m^2)

I_T total radiation incident on tilted plane (kW/m^2)

I_{st} standard light intensity (1000 W/m^2)

k_t is the daily clearness index

$LPSP$ is loss of power supply probability

LCE levelized cost of energy

n is the day of the year

P_T is the total energy generated by PV array and wind turbines

P_L is load demand at the time (t)

p_{pv} is the energy generated by the PV module

P_w is the output power of wind turbine at wind speed

R_b is the ratio of beam radiation on the tilted surface to that on a horizontal surface

RC is the renewable contribution

r_d is ratio of diffuse radiation in hour/diffuse radiation in day transmittance absorbance product

T_A is the ambient temperature at arbitrary conditions (°C)

T_{st} is the standard temperature (25 °C)

T_c is the cell temperature (°C)

T_r is the reference temperature for the cell efficiency (°C)

ΔT is the deference between the cell temperature and the standard temperature

V_{pv} module optimum operating point voltage at arbitrary conditions (V)

v_{oc} module open circuit voltage (V)

v_{mp} module maximum power voltage (V)

ΔV is the deference between module optimum operating point voltage at arbitrary conditions and module maximum power voltage eq.(3.6)

v is the wind speed at hub height (z) (m/s)

v_o is wind speed at the reference height (z_o) (m/s)

v_c cut-in wind speed of the wind turbine (m/s)

v_r rated wind speed of the wind turbine (m/s)

v_f cut-off wind speed of the wind turbine (m/s)

WE Wasted energy

α is the ground surface friction coefficient

α_o module current temperature coefficient (A/°C)

φ latitude (deg)

β tilt angle of plane to ground (deg)

β_o module voltage temperature coefficient (V/°C)

δ is the declination of the sun (deg)

η_{r} is the module reference efficiency

η_{m} is the module efficiency

η_{pt} the efficiency of power tracking equipment, which is equal to "1" if a perfect maximum power point tracker

η_{inv} is the efficiency of inverter

η_{batt} is the charge efficiency of battery bank

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