# Stand-Alone Hybrid Energy Systems

by

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Bachelor of Technology, Punjab Technical University, 2012

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Electrical and Computer Engineering

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## ABSTRACT

Portugal is highly dependent on imported fuels when it comes to the energy sector. The government continuously aims at creating a sustainable and competitive renewable energy system. The need for balancing the supply and load demand in the electrical sector is a priority. To promote economic development in Portugal, the government always intend to initiate new projects like the construction of the solar plant. The United Kingdom (UK) solar company WELink Energy will develop a 220MW solar plant in south Portugal and have signed an Engineering, Procurement and Construction (EPC) agreement with China Triumph International Engineering Cooperation (CTIEC). There are 4 ongoing solar projects in Algarve that will produce enough electricity to fulfill the load demand. The problem that the government is facing is the expansion of hybrid power system using other renewable resources in order to overcome climatic changes. In order to design a hybrid system, it is very important for the government to consider the minimum net present cost configuration for fulfilling the load demand. The standalone hybrid system consists of a photovoltaic array (PV), a wind turbine (WT), a diesel generator (DG) and a battery. Different scenarios have been considered using HOMER software to obtain the lowest net present cost of the hybrid system. The results will establish the configuration to eradicate the problems the villagers are undergoing due to unavailability of electricity. This will lead to enhanced job opportunities and better living conditions in Algarve.

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# ACKNOWLEDGEMENTS

I would like to express my appreciation to my supervisor Dr. Fayez Gebali for his support, encouragement and continuous motivation during my research. I would like to thank him for sharing his immense knowledge and guiding me to make my report better at every step. I would also like to express my gratitude to my university, for giving me an insight of my project and offering me an opportunity to study with them in a highly knowledgeable university helped me in exhibiting my leadership qualities in a diversify environment. My sincere thanks to the library of University of Victoria for providing me productive information that was beneficial for my research. Lastly I would like to thank my family members for their constant support and being my strength throughout my life.

# DEDICATION

I would like to dedicate my work to Professor Dr. Fayez Gebali, the late Dr. Subhasis Nandi, my parents Mr N.K Sharma, Mrs Vanita Sharma, my husband Mr Ishatpreet Singh Grewal and my mother in law Mrs Jasbir Kaur Grewal.

# Chapter 1

# Introduction

## 1.1 Problem definition and motivation

Many remote communities cannot be economically or physically connected to an electric grid around the world. The electricity demand is supplied by an isolated diesel generator. The operating cost associated with the generators may be too high due to discontinued fossil fuels along with the maintenance of the system. In such cases , renewable energy resources play an alternative solution to supplement the generators in off-grid regions. It is seen from the literature review that the hybrid system can reduce the total life cycle cost (LCC) for a standalone hybrid system used in remote areas. Standalone system can provide economically feasible and reliable solution for local needs. Portugal is highly dependent on imported fuels when it comes to the energy sector. The government continuously aim at creating a sustainable and competitive renewable energy system. The need for balancing the supply and load demand in the electrical sector is a priority. The Algarve is a highly popular tourist destination and developed region in Portugal. To promote economic development in Portugal , the government always intend to initiate new projects like the construction of the solar plant. The United Kingdom (UK) solar company WELink Energy will develop a 220MW solar plant in south Portugal and have signed an Engineering , Procurement and Construction (EPC) agreement with China Triumph International Engineering Cooperation (CTIEC). There are 4 ongoing solar projects in Algarve that will produce enough electricity to fulfill the load demand. The problem that the government is facing is the expansion of hybrid power system using other renewable resources in order to overcome climatic obligations. In order to design a hybrid system , it is very important for the government to consider the minimum net present cost configuration for fulfilling the load demand. The hybrid system consists of a photovoltaic array (PV) , a wind turbine (WT) , a diesel generator (DG) and a battery. Different scenarios have been considered using HOMER software to obtain the lowest net present cost of the hybrid system. The results will establish the configuration to eradicate the problems the villagers are undergoing due to unavailability of electricity. This will lead to enhanced job opportunities and better living conditions in Algarve.

Electricity prices in Portugal have increased on an average by 7.8% and 6.2% annually for domestic and industrial customers , respectively. The Portuguese government boosts the promotion of hydroelectric resources and supports the development of renewable sources like wind , hydro , photovoltaic and biomass. The country is strongly dependent on imported energy resources especially oil. In Portugal , approximately 45% of electricity comes from renewable resources. To achieve the full potential of renewable resources , it is important to design and optimize a renewable hybrid system which has minimum life cycle cost. Life Cycle Cost (LCC) analysis is required to optimize different configurations. LCC is used for calculating the system from inception to disposal. It is important to have a backup source of power generation like diesel generator in this work.

## 1.2 Objective of the Thesis

The aim of the thesis is to minimize the life cycle cost for a hybrid standalone power system. The software tool HOMER was used to estimate the cost of a hybrid system consisting of solar and wind energy sources. Battery bank and diesel generator were used to provide excess energy storage and production when the primary sources like solar and wind are not available. The standalone hybrid system can be modelled near the consume requirement which can reduce the transmission cost , transportation cost and the losses.

## 1.3 Contribution

The contributions of this work are:

1. A hybrid stand-alone energy system was studied using HOMER software. The hybrid system consisted of a photovoltaic array and a wind turbine. A backup diesel generator was used together with a lithium battery storage.

2. The life cycle cost of the system is estimated using several simulation scenarios with constraints on the size of the PV array and wind turbine size.

## 1.4 Outline of the Thesis

The thesis is divided into five chapters. Chapter 1 describes the overall structure of the thesis with the aim of the research. Chapter 2 covers the literature review of the methods that have been implemented for this hybrid system. Chapter 3 deals with the system components review about the photovoltaic cell and wind turbine and their mathematical modelling. Chapter 4 describes the system configuration and simulation results. This is followed by Chapter 5 which deals with the conclusion.

## 1.5 List of Abbreviations

| **Item** | **Comment** |
|---|---|
| CRF | Capital recovery factor for the system |
| DG | Diesel generator |
| DOD | Depth of discharge |
| HOMER | Hybrid optimization model for electric renewables |
| LCC | Life cycle cost |
| NPC | Net present cost |
| O&M | Operation and maintenance |
| PV | Photovoltaic module |
| PI | Proportional integral controller |
| RES | Renewable energy system |
| SOC | State of charge |
| WT | Wind turbine |
| PMSG | Permanent magnet synchronous generator |
| AC | Alternating current |
| DC | Direct current |
| P&O | Perturb and observe |
| HAWT | Horizontal axis wind turbine |
| VAWT | Vertical axis wind turbine |
| MOSFET | Metal oxide semiconductor field effect transistor |
| IGBT | Insulated gate bipolar transistor |
| PWM | Pulse width module |
| DFIG | Doubly fed induction generator |

# Chapter 2

# Literature Review

## 2.1 Wind , PV and Battery Hybrid System

Liu et al. [7] was successful in investigating the performance of photovoltaic array under various circumstances and climatic conditions. The aim was to optimize the size and slope of PV array in the system. Under four climatic zones , tropical , sub-tropical , hot arid and warm temperature , the performance of the PV system is studied and an optimized condition was reached using HOMER software. Finally , it was concluded that PV system can effectively bring down the electric bills and to alleviate carbon dioxide emission. HOMER software was used by Elhassan et al. [8] in Khartoum to develop an efficient power system of sustainable and reliable renewable energy to meet domestic power needs and the total life-cycle cost. For this purpose , the basic data of solar radiation , wind speed and other input information were collected and after that hybrid optimization simulation model was developed. The simulation was used to identify the most technically reliable renewable system meeting household demands. Bekele et al. [9] did some research to check the possibility of electricity supply to a remotely located area in Ethiopia , which is detached from the main electricity grid. Here for power generation , a hybrid system is used consisting of solar panels and wind generator. HOMER software has been used for analysis. Ultimately they came out with a few feasible and reliable power supply systems , sorted according to their net present cost.

HOMER software has been effectively used to study the optimal sizing and operational strategy of hybrid renewable energy system by Razak et al. [10]. This hybrid energy includes wind energy and solar energy. Furthermore , emission to the atmosphere is nil considering this design and also the use of diesel generator can be minimized by maximizing the use of the renewable energy. Different combinations of generating system are tried out in this study to obtain the optimal configuration.

Daud et al. [11] effectively developed a hybrid system especially based on photovoltaic and wind energy , using a computer program for designing and sizing purpose , to meet the load demand of a family house in Palestine according to their requirements. Wind and solar measurements are used as the inputs. The hybrid system minimizes the cost of generation of electricity throughout the lifetime of the project. It is seen that using hybrid energy as the major energy resource for any place proves beneficial both in economic sector and conservation of natural resources HOMER software is used for optimization purpose , in this study.

Another use of HOMER software was made by Kusakana et al. [12] to investigate the possibility and feasibility of using a stand-alone solar/micro hydro-power system for cost-effective power generation which can meet the power requirements of a typical remote and isolated rural area. Here optimization was used effectively to improve the technical configuration and economical performances of the hybrid system.

Lim et al. [13] developed a combination of PV output power and battery power as the backup source to meet the load demands with variable speed generator i.e. both traditional constant speed generator and novel variable-speed generators. To improve the reliability of this system a fossil fuel based constant speed generator is used since renewable power generation technology is largely affected by climatic conditions. Demiroren et al. [14] carried out a study based on HOMER software to develop a system so as to meet the daily load demands of Gokceada , the biggest island of Turkey , using renewable power generation technology. Here , the hybrid system is made up of solar panels , wind turbines and batteries for backup power. Values of components are determined using simulations. The cost of energy is also taken care of so that it can be minimized.

Iqbal [15] used HOMER software to study the feasibility and reliability of a zero energy home in Newfoundland. The input data was year-round recorded wind speed information , solar data and information of power consumption in a typical R-2000 house in Newfoundland. Here optimization was done using HOMER. The performance of the system is analyzed as a whole and detailed elaboration is presented in this study. In another study , developed by Dalton et al. [16] renewable energy technology is used to meet the load demand of a large hotel located in a subtropical coastal area of Queensland in Australia. HOMER software was used for optimization purpose. After successive experiments and analysis , it was concluded that wind energy is more feasible and reliable than PV panels and also more economic as renewable technology in large-scale operations.

## 2.2 PV and Diesel Generator and Battery Hybrid System

HOMER software has been effectively used by P. Lilienthal [17] to design an optimization model which can analyze all small power technologies individually and hybrid systems too to identify the most cost-effective solution to energy requirements. Here with the inputs of renewable resource and daily and monthly load profile , the minimum total discounted cost will be formulated. Baharudin et al. [18] effectively used HOMER software to optimize and design a PV power system for desalination of seawater located at Kuala Perlis. The design consists of site selection , load selection , system sizing and cost-effectiveness. The feasibility and reliability of this design are also verified along with the experimental setup for desalination system. Another study [19] presents the use of HOMER software for the designing and modelling a power system for domestic use for a particular family for household usage in Boulder , Colorado. Here a PV grid is used for power generation with a battery bank for back up power. Cost-effectiveness is considered in this study , Lim et al. [20] forecasted solar irradiance and load demands in supervisory control to develop an off-grid hybrid energy system. Here models are developed for foreseeing and predicting the solar resource and load demand. These models are used to control an off-grid PV variable speed diesel generators hybrid energy system.

## 2.3 Wind , PV , Hydro and Battery Hybrid System

Bekele et al. [21] carried out another study in Ethiopia to identify the reliability and feasibility of a hybrid system consisting of hydro-power , solar energy and wind generator. An experiment is carried out to meet the load demands for lighting , radio , television , electric baker , water pumps and flour mills. Primary schools and health posts are also taken care of. They came out with a system generating power at a cost of less than $0.16 per kWh.

## 2.4 Wind , Diesel Generator and Battery Hybrid System

Since wind energy sometimes fails to produce the required power output given to the meteorological variations of the area under consideration , Rehman [22] incorporated diesel generator as the backup , in a study of a diesel plant of a village in the Northeastern part of Saudi Arabia. HOMER is used for modelling and designing of the system. For simulation purposes , various wind speed data was collected. Fuel prices are kept inside a certain range during the simulation program , and the effectiveness of the system is discussed. Khadem [23] studied the utility of wind home system in a coastal region of Bangladesh using HOMER software. Here there is a possibility of using wind power as a renewable energy technology since wind potential is more or less to that extent in this region. With a variation of wind speed between 4 m/s , it was concluded that considering environmental influence , power consumption and remote accessibility wind home system is applicable in most of the coastal regions.

## 2.5 PV , Hydro , Diesel Generator and Battery Hybrid System

Beluco et al. [24] designed a hybrid system using solar energy , hydro-power and diesel generator. The aim was to evaluate the power generation during peak sunlight hours. The optimization models consist of two variations , one having PV module , diesel generators and micro hydro-power plants and another with PV modules and hydro-power plants. grid-based

## 2.6 Wind , PV and Fuel Cell Hybrid System

Alam et al. [25] used HOMER software to propose a hybrid power generation system for application in remote areas. This hybrid system is a combination of PV panels , wind turbine and fuel cell. For maintaining uniformity in hydrogen supply for fuel cell an electrolyzer and a reformer are also taken into consideration. This particular combination of renewable technology has been found to be successful in meeting the load requirement for standalone applications at remote locations. Turkay et al. [26] researched about the feasibility and reliability of a hybrid system using HOMER. The system consisted of solar and wind energy and hydrogen as the storage unit to fulfill the power demand as a standalone system. Input data used were technological options , cost of components and recourse compliance with final results being feasible system configurations based on net present cost.

## 2.7 Wind , PV , Diesel Generator and Battery Hybrid System

Bajpai [27] designed a hybrid model to improve the electrical supply at the telecom service providers installations. Since problems arose while using only diesel generators , renewable energy resources like solar photovoltaic , wind turbine generators or both are used. It was concluded that using renewable technology prove to be more economical than a single storage system. Rajoriya et al. [28] for power generation in the remote hilly rural area in India with the help of hybrid power generation system successfully used HOMER software. The final design was the one with least emissions of environmental pollutants such as carbon dioxide , carbon monoxide , hydrocarbon , particulate matter , sulphur dioxide and nitrous oxide. This design consisted of five wind turbines (10 kW) , PV panel (9 kW) , 30 batteries (6 V , 6.94 kWh each) and a diesel generator (65 kW). The final net present cost of the setup was \$1,270,921 with a capital cost of \$148,133 with the cost of energy of \$0.296/kWh.

## 2.8 Wind , PV , Diesel Generator , Fuel Cell and Battery Hybrid System

Badawe et al. [29] made effective use of HOMER software to present a study for optimization and comparison between renewable technology and conventional power generation techniques for a telecommunication site in Mulligan , Labrador , in Canada. Renewable technology reduces environmental pollution along with lowering the overall cost of power production. Badawe et al. [29] came up with a solution that was cost-effective , thus reducing the operational time of the diesel generator , as a result , reducing emission level in turn.

## 2.9 PV Biomass and Battery Hybrid System

Barsoum et al. [30] used HOMER for designing , modelling and cost simulation of standalone solar and biomass energy in Sarawak. The main objective of this setup was to develop an optimized , reliable , feasible and autonomous system for meeting the power requirements of the area under consideration and along with that also to ensure cost-effectiveness. HOMER software again comes into play in the Islands of Indian Sundarbans by Mitra et al. [31] to supply electricity to remote villages through renewable energy technology. Around 20 islands with more than 100000 households inhabiting in 131 villages in India need electricity as a very basic need of their daily living. Since the wind potential in this region is very low so the renewable technologies used are biomass and solar panels.

## 2.10 Micro-power System

Lambert et al. [32] used HOMER software for micro-power system to compare power generation technology across a wide range of applications. A system generating electricity and heat to meet a certain load is referred to as a micro-power system. Here the power systems physical behaviour and total life-cycle cost are optimized using HOMER. Hafez et al. [33] successfully used HOMER software for the most favourable and ideal planning , designing and modelling of a renewable energy based supply system for micro-grids. For elaborate analysis four different types of designs are developed viz. a diesel-only , a fully renewable-based , a diesel-renewable mixed and an external grid-connected to a micro-grid configuration. These designs are also analyzed on an economical basis and for all the analysis and designing HOMER software is used. Since India is an area wise very vast country with certain variations in climatic conditions , so to ensure uninterrupted power supply hybrid system consisting of PV panel , wind generator , hydro-power , battery bank and the diesel generator is considered in this study. These components need to be studied to know about their various advantages and disadvantages so as to calculate their outputs which can meet the specific power requirements of the area under consideration.

# Chapter 3

# Modelling System Components

In this chapter , the components of the hybrid system are discussed. A standalone hybrid system consists of a photovoltaic array (PV) , a wind turbine (WT) , a battery backup and a diesel generator (DG) to supply the load. A standalone wind or solar power system will face problems in meeting the load demand with changing weather condition. Optimum designing is essential for the hybrid system , which ensures battery bank usage and prolongs the battery life. Nowadays computer simulation software are available for getting the optimum configuration. This is executed by comparing the performances and energy production costs of different configurations of wind power and PV hybrid generating systems. Apart from these , other requirements like transmission and distribution of power generated from the hybrid system , protection from discharging of battery beyond limits , or over-voltage protection , have to be fulfilled. Hence , a charge controller and an inverter are used in the hybrid system. The Hybrid Optimization Model for Electric Renewable (HOMER) is a computer modelling software to assist in the design of hybrid systems. HOMER models a hybrid system's physical behaviour and its life cycle cost (LCC) , which is defined as the total cost of installing and operating the system over it's life span. HOMER allows the modeller to compare numerous design options based on economic and technological benefits. There are various simulation softwares in the market. Some of them are HOMER , RETScreen , HySim , Hybrid designer and Hybrid 2 but HOMER was selected because it is cost effective and accurate in optimization. Figure 3.1 shows the overall system components [1] as defined by the CAD tool HOMER , which will be discussed below. The hybrid system components are CAT200 as the diesel generator , G10 selected as the wind turbine , ABB1000 as the converter , CS6U-330P as the photovoltaic panel and 1kWh LA as the battery backup source. Every source is connected to the electrical load.

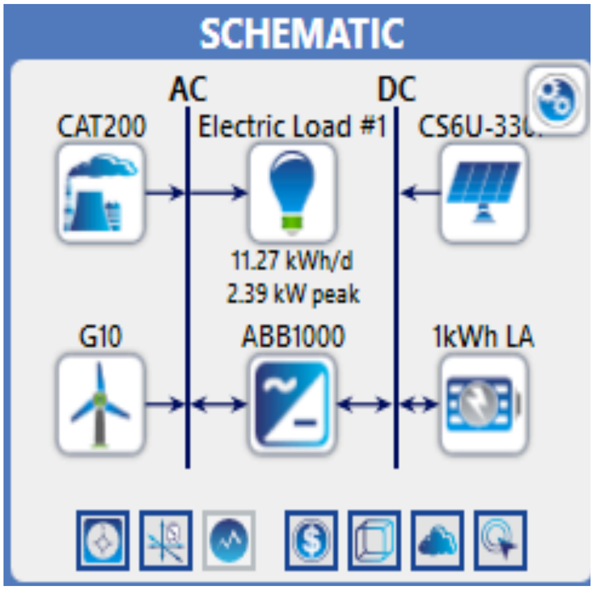

Figure 3.1: Schematic of the overall system [1]

## 3.1 Introduction to HOMER Software

The study in this work is based on the theoretical data available from NASA. The analysis is done using a computer software called as Hybrid Optimization Model for Electric Renewable (HOMER) [34] , [35]. This software is essential for evaluating power system designs having numerous applications. HOMER assists researchers in designing an optimal hybrid power system model based on a comparative economic analysis. The HOMER software determines optimal systems using combinations of photovoltaics , wind turbines , hydro , diesel generation , battery storage and inverter capacity. It takes into account both seasonal and hourly load variations in resource availability such as wind and sunlight. In addition to that , HOMER provides multiple configurations ranked in order of least net present cost (NPC) , which is based on a 25 year lifecycle cost including interest. Designing a micro-power system with various design options and uncertainty issues in demand loads and fuel prices makes it a major challenge. HOMER was designed to overcome these challenges and also the complexity of the renewable energy resource (RES) being discontinuous , seasonal , non-dispatchable and with uncertain availability.

A micro-power system may employ any combination of electrical generation and storage technologies and maybe grid-connected or autonomous , meaning separate from any transmission grid. Some examples of micro-power systems are a solar battery system serving a remote load , a wind-diesel system serving an isolated village , and a grid-connected natural gas micro turbine providing electricity and heat to a factory. HOMER can model grid-connected and off-grid micro-power systems serving electric and thermal loads , and comprising any combination of photovoltaic (PV) modules , wind turbines , small hydro , biomass power , reciprocating engine generators , micro turbines , fuel cells , batteries , and hydrogen storage.

### 3.1.1 Principle of Operation in HOMER

HOMER performs three principal tasks: simulation , optimization and sensitivity analysis. In the simulation process , HOMER figures the performance of a specific system configuration every hour of the yea to determine its technical feasibility and life cycle cost. In optimization software , software simulates many different configurations in search of the one that satisfies the technical constraints at the lowest life cycle cost. In the sensitivity analysis , HOMER performs multiple optimizations under a range of input assumptions to check the effect of uncertainty in the model inputs. A hybrid system containing a battery bank and a generator requires a dispatch strategy. A set of rules indicating how the system charges a battery is called as a dispatch strategy. HOMER has load flowing and cycle charging dispatch strategy. In the load flowing strategy , only the renewable resource charges the battery and not the diesel generator. Whereas in the later , whenever the generator is in use , it produces more power than required to the serve the load and charges the battery as well. In HOMER software , we need to follow the steps for defining the system. Below is a brief introduction to the steps for simulation of the system.

Step 1 Defining the power system: The power system is defined by clicking the Add/Remove Button in the HOMER software. Then we are capable of selecting a number of different components like generators , multiple loads , PV arrays , battery banks and wind turbines and other power system components.

Step 2 Defining the site load: Load is defined as the demand of electricity demand. For a single site HOMER models two different loads which are primary and secondary loads.The average daily consumption the system is averagely determined by HOMER based on the outlines power profiles.

Step 3 Wind and solar resources: Wind resources are determined using NASA surface methodology and solar energy database where wind direction is considered at 50 meters above the earth surface. The monthly average wind speed is provided as the database for the given month over 10 years. The average annual wind speed is a good indicator for running a wind turbine at a given location and generally , values above 5 m/s with few months below 4 m/s are considered adequate for satisfactory results. We see the year-round wind speed in m/s. This can be clearly fed as input in HOMER software so as to help in critical optimization of renewable energy technology.

HOMER runs based on directly imported solar resources from the NASA surfaces methodology and solar energy database by entering the GPS coordinates.

Step 4 Calculating Results: HOMER calculates the different combinations of possible feasible design based on the inputs provided and simulates the power system while we click on the calculate button. We are capable of comparing the standard diesel generator configuration with renewable energy like wind and solar models according to the design requirements. We can evaluate the financial and renewable indicators of different models by sensitivity analysis on diesel price and primary loads. HOMER models a specific system configuration by performing an hourly time series simulation of its operation over one year. It steps through the year one hour at a time calculating the available renewable power. It compares it with the load and decides what needs to be done with surplus power. When the calculation for a year is completed , HOMER makes sure that system satisfies the constraints imposed by the user.

Step 5 Simulation Results: Comprehensive set of data can be accessed by clicking on each of the displayed solutions , providing the detail on each component. The electrical tab provides an overview of the overall and monthly electricity production of the various sources of the system. The size of the solar panels can be increased in order to counterbalance the shortage of electrical provision. Adding more batteries and increasing the size of the photovoltaic cell can improve the system performance. At the same time , capital expenditure of overall system will increase when adequate space is not provided for the site for additional equipment.

## 3.2 Review of Photovoltaic Panels

Solar cells have low efficiency. The major issue using a photovoltaic array (PV) cell connected in series is the internal resistance. It can become worse when the irradiance is not uniform or partial. In areas where there is a lot of plantations , this issue is common. The cells which are under shade produces less current , but these cells are also forced to carry the same current due to the series circuit. There are a lot of schematics (configurations) proposed in the literature according to Volker Quaschning article [36]. The solar radiation denotes the solar radiation received in a particular area and recorded during a specific time frame. This is also called as insolation. If the specific span of time is an hour or a day then the solar irradiation is called as hourly or daily accordingly and the unit of measurement is kWh/m$^2$/time.

The circuit diagram of a PV cell can be obtained after considering the following parameters [37]:

1. Temperature dependence of the diode reverse saturation current.
2. Temperature dependence of the photo current
3. Series resistance (internal losses due to the current flow) , which gives a more accurate shape between the maximum power point and the open circuit voltage.
4. Shunt resistance , in parallel with the diode , this corresponds to the leakage current to the ground.

Figure 3.2 shows a circuit diagram of a solar cell [2] where the series and shunt resistances are ignored. From Fig. 3.2 , we can write the load current as

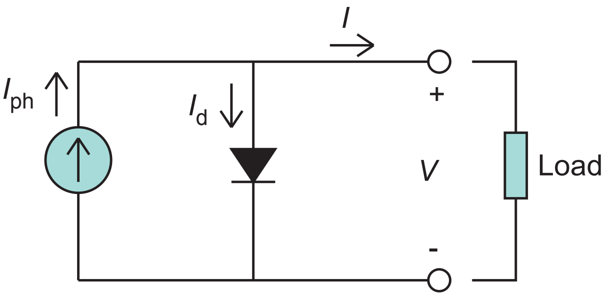

Figure 3.2: Solar cell circuit diagram [2]

$$I = I_{ph} - I_d \tag{3.1}$$

where $I_{ph}$ is the photocurrent due to solar radiation and $I_d$ is the diode current which is given by the usual expression

$$I_d = I_s \times (e^{V/V_T} - 1) \tag{3.2}$$

Where $I_s$ is the reverse saturation current and $V_T \approx .26$ mV is the thermal voltage. Fig 3.3 shows the I-V characteristics of the solar cell [2].

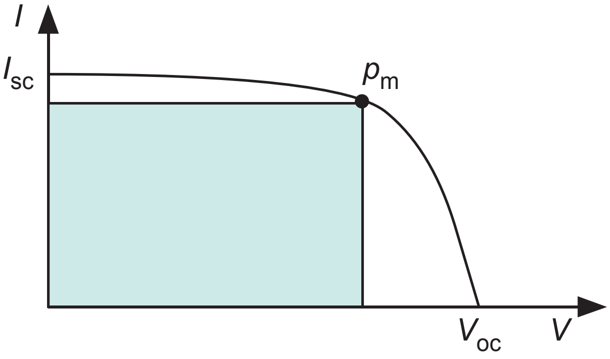

Figure 3.3: I-V characteristics of the solar cell [2]

Figure 3.3 we have the following quantities: $V_{oc}$ is the open-circuit voltage , $I_{sc}$ is the short circuit current and $p_m$ is the maximum power available as indicated as [38].

$$\begin{aligned} I_{sc} &= I_{ph} \qquad (3.3) \\ V_{oc} &= V_T \ln(1 + \frac{I_{ph}}{I_s}) \qquad (3.4) \end{aligned}$$

The maximum power point $p_m$ is obtained by finding maximum value of the product $p = I \times V$.

Using the solar radiation on a tilted surface , the hourly energy output is [39] , [40] , [41]

$$E_{pv} = Gt \times A \times P \times \eta_{pv} \tag{3.5}$$

where $Gt$ is the hourly irradiance in kWh/m$^2$ , $A$ is the surface area in m$^2$ , $P$ is the PV penetration level factor , which is defined as the ratio of total peak PV power to peak apparent power [42] and $\eta_{pv}$ is the efficiency of PV array.

There are different algorithms that are used to estimate the maximum power point such as P&O , constant voltage and incremental conductance [3].

### 3.2.1 Perturb and Observe (P&O)

In this method , the voltage is changed in small portions and this perturbation causes the power of the solar module to change. If the power increases due to the perturbation then the perturbation is continued in the same direction. After the peak power is reached the power at the power change is zero and next instant decreases and hence after that , the perturbation reverses in direction. When the stable condition arrives , the algorithm oscillates around the peak power point. In order to maintain the power variation small then the perturbation size needs to be reduced. The technique is advanced in such a style that it sets a reference voltage of the module corresponding to the peak voltage of the module. A Proportional Integrator (PI) controller then transfers the operating point of the module to that particular voltage level. This algorithm fails to track the maximum power point under fast-changing atmospheric conditions and power loss can also be observed [3].

### 3.2.2 Incremental Conductance

This method takes the incremental conductance ($dI/dV$) of the PV array to compute the sign change in power with respect to the voltage ($dP/dV$). This method computes the maximum power by comparing the incremental conductance ($\Delta i/\Delta v$) to the array conductance (I/V). If the value of the incremental conductance $I$ is equal to the value of array conductance , then that is the value of MPP. The controller will maintain this voltage until the irradiance changes and this iteration is repeated. This relationship is derived from the fact that ($dP/dV$) is negative when the MPPT is to the right side curve of the MPP and positive when it is to the left side curve of the MPP. This algorithm has advantages over P&O in that it can determine when the MPPT has reached the MPP , where P&O oscillates around the MPP. Also , incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher precision than perturb and observe [3].

### 3.2.3 Constant Voltage

The term constant voltage in MPP tracking is used to describe different techniques by different authors , one in which the output voltage is regulated to a constant value under all conditions and one in which the output voltage is regulated based on a constant ratio to the measured open circuit voltage ($V_{OC}$). The latter technique is referred to in contrast as the open voltage method by some authors. If the output voltage is held constant , there is no attempt to track the maximum power point , so it is not a maximum power point tracking technique in a strict sense , though it does have some advantages in cases when the MPP tracking tends to fail , and thus it is sometimes used to supplement an MPPT method in those cases. In the constant voltage MPPT method (also known as the open voltage method) , the power delivered to the load is momentarily interrupted and the open-circuit voltage with zero current is measured. The controller then resumes operation with the voltage controlled at a fixed ratio , such as 0.76 , of the open-circuit voltage $V_{OC}$ [3]. This is usually a value that has been determined to be the maximum power point , either empirically or based on modelling , for expected operating conditions. The operating point of the PV array is thus kept near the MPP by regulating the array voltage and matching it to the fixed reference voltage $V_{ref} = kV_{OC}$. The value of $V_{ref}$ may be also chosen to give optimal performance relative to other factors as well as the MPP , but the central idea in this technique is that $V_{ref}$ is determined by a ratio of $V_{OC}$. One of the inherent approximations to the constant voltage ratio method is that the ratio of the MPP voltage to $V_{OC}$ is only approximately constant , so it leaves room for further possible optimization.

## 3.3 Wind Turbine Conversion System

Wind Turbine (WT) conversion system is used to convert wind energy into mechanical energy that can be useful for generating power. A wind turbine is a rotating machine that takes power from the wind using aerodynamically designed blades. The useful power depends on the wind speed but it is important to control and limit the power at higher speeds to avoid system damage. The WT consists of different components: aerodynamics , mechanical and electrical systems. The various components composed of wind turbine blades , a power electronic converter , a generator and all related control systems [45].

### 3.3.1 Wind Turbine

Nowadays the wind turbines are very common and they transform kinetic to rotating mechanical power. The two basic configurations of the modern wind turbine based on the direction of the rotating shaft or axis are Horizontal axis and Vertical axis turbine. These wind turbines are a very wide range , extending from few tens or hundreds of watts for small machines to as much as 5 megawatts of power for a very large turbine. Horizontal axis wind turbines (HAWT) have blades like airplane propellers. HAWT typically has either 2-3 blades or a large number of blades. The latter is known as high-solidity devices and include multi-blade wind turbines used for water pumping on farms. On the other hand , the wind turbines with 2 or 3 blades are largely vacant , having only a small fraction of this area solid and are referred to as low-solidity devices. The low-solidity turbines are almost universally employed to generate electricity. Vertical axis wind turbines (VAWTs) have blades that go from top to bottom. Savonius is the most common type of these wind turbines and Darrieus is one of the most popular in the global market. Wind can be trapped in any direction by these turbines without any need to reposition the rotor with the change in wind directions.

The hourly energy generated ($E_w$) by wind generator and the rated power output ($P_w$) is [46]

$$P_w = 1/2 \times \rho_w \times A \times v^3 \times C_p(\lambda, \beta) \times \eta_t \times \eta_g \quad (3.6)$$

$$E_w = P_w \times t \quad (3.7)$$

Where:

$\rho_w$ is the density of air in 1.22kg/m$^3$ ,
$A$ is the swept area (m$^2$) ,
$v$ is the wind speed (m/s) ,
$C_p$ is the performance coefficient of the turbine ,
$\lambda$ is the tip speed ratio of the rotor blade tip speed to wind speed ,
$\beta$ is the blade pitch angle (deg) as $0^\circ$ ,
$\eta_t$ is the wind turbine efficiency ,
$\eta_g$ is the generator efficiency.

### 3.3.2 Betz Rule

According to the Betz rule , we can only convert less than 59% of the kinetic energy to mechanical energy using wind turbine. This is because the wind has some kinetic velocity even after passing through the wind turbine. Within the turbine , most of the energy is converted into useful electricity , while other losses can be in the gearbox , bearings , generator , converters and others. Most practical rotors with three blades can have an efficiency of about 50% approximately.

### 3.3.3 Operating Region of the Wind Turbine

The operating region of a variable pitch variable speed wind turbine can be described by their power curve , which gives estimated output power as a function of wind speed [47]. Wind speed power curve is the characteristic , the shape of which depends on the blade area , the choice of airfoil , the number of blades , the shape of the blade , the cut-in wind speed , the shutdown speed , the rated speed and gearing and generator efficiencies , the speed of rotation , the optimum tip-speed ratio. The power output of a wind turbine changes with the wind speed and wind turbine power curve.The description of the three distinct wind speed points that are important for describing the power curve is below

Figure 3.4 shows the operating regions of a wind turbine Some terms are defined for a wind turbine:

1. Cut-in Wind Speed: The lowest wind speed at which the wind turbine starts to generate electricity.

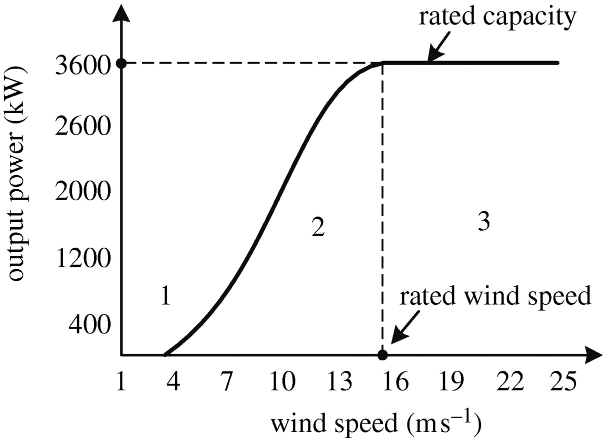

Figure 3.4: Wind turbine operating regions [5]

2. Rated Speed: Rated wind speed is the speed at which the wind turbine generator generated the rated power , which usually is the maximum power wind turbine can produce.
3. Cut-out Wind Speed: Wind speed at which the turbine terminates power generation and is shut down (with automatic brakes or by brake pitching) to protect the turbine from mechanical damage.

### 3.3.4 Electrical Generators

The electrical generator is the unit that converts mechanical energy from the turbine into electrical energy. Generators are composed of a stator , a rotor , a rotating element and a static element. Different types of generators are explained below.

1. Asynchronous Generator

   Asynchronous generators are also called as induction generators. The stator must be connected to an external source of power to start the circulation of current through the stator windings. The grid generally supplies to the source. This rotating current is sent to the rotor through the short circuit for initial excitation. The stator current produces rotating magnetic flux , which will help the rotor to rotate in the same direction. Although the rotor will rotate at a slightly lower speed than the magnetic field , called slip speed. In our work , we have used CAT 200 which is permanent magnet diesel generator.

   Induction generators can only produce electricity when the rotor rotates at a speed above the synchronous speed. The synchronous frequency is generally accepted as the frequency of the supply grid. For each generator , there is a speed , which corresponds to this frequency , called the synchronous speed. However , induction generators have the ability to produce power at varying rotor speeds. There are two types of commonly used rotors , the squirrel-cage rotor , and the wound rotor. The squirrel-cage rotor has current-carrying longitudinal bars around the shaft that are connected by rings , which look similar to a hamster wheel. These bars will spin in concurrence with the rotating magnetic field of the stator. This type of rotor is more commonly used today due to the fact that they require less maintenance and are less expensive to manufacture.

   The wound rotor induction generator is also known as a doubly fed induction generator or a DFIG. This is because both the rotor and the stator have windings that participate in the electrical conversion process. Slip rings and brushes electrically connect the two elements to transfer power between the shaft of the rotor and the electrical system.

These rings and brushes are the reason for the high maintenance required for these generators.

2. Synchronous Generator

   Synchronous generators can produce constant power at a synchronous speed. There is less maintenance required for these types of generators because they do not require slip rings or brushes to transfer electricity from the rotor to the electrical system. In this work , it is a standalone system so the electric load is connected to the source. They also do not require the supply grid to begin excitation in the rotor , so they can be run in island model or as the sole power generation facility. Synchronous generators can supply up to 100% of a facility power requirements , whereas induction generators can only supply up to 1/3 because they depend on the reactive power from the supply grid. Yet another benefit to the synchronous generator is that voltage regulation is possible , which is not the case with induction generators.

   There are also different types of rotors for the synchronous generator family. The brushless wound rotor type is a modified version of the DFIG where the rotor still contains windings , but there is an internal DC source to begin excitation. The internal exciter will begin the spinning of the rotor , which will then lock into the stator rotating magnetic flux and continue to rotate at the synchronous speed [48].

3. Permanent Magnet Synchronous Generator (PMSG)

   PMSG uses a permanent magnet as its excitation field instead of an electromagnetic coil. These types of generators tend to be more expensive due to the material required to make them. However , the cost of the material continues to decline , and they are becoming more and more common in the energy industry due to their high reliability and low maintenance [49].

### 3.3.5 Power Conversion Schemes

Power conversion for wind energy systems generally occurs in two stages. The first stage is rectification , where the alternating current (AC) is transformed into direct current (DC). The second stage is where the direct current is transformed back into the alternating current.

### 3.3.6 Rectification

Rectification is the first stage in the conversion process , also known as AC/DC stage. The most common type of rectification process is a three-phase diode bridge , where the top diode passes the positive cycle of the sine wave and the bottom diode will pass the negative cycle of the sine wave , making both cycles positive. A rectification system can be made by the combination of IGBTs or MOSFETs as switching devices. They can form a complex system because each device will require individual switching signals , such as pulse width modulated (PWM) signal [50] Although they are sufficient than passive diode circuits and control systems can be applied to them , which helps in improving the power quality. A capacitor is used for smoothening the rectified output wave , as it tends to be a bit sinusoidal. It is also called as DC link.

### 3.3.7 Bidirectional Inverter

A bidirectional inverter is an indispensable element in a hybrid system that contains a storage system and a backup diesel generator. It can transfer power simultaneously in both directions. It can function as a rectifier circuit which changes AC diesel generator voltage to DC voltage and charges the battery bank; hence providing an AC bus to the DC bus path. On the other hand , it acts as an inverter which changes DC voltage to AC voltage needed by the load and thus provides a path from DC bus to the AC load. In order to fulfill the demands , an optimal model , simulation and design needs to be developed using HOMER software.

### 3.3.8 Mathematical Model of Converter

The converter contains both rectifier and inverter. The PV panel and the battery are connected to the DC bus. The wind turbine and the diesel generator sub-systems are connected to AC bus. The electric load is connected between these busses.

The rectifier is used to transform the surplus AC power from the wind energy generator and diesel generator to DC power of constant voltage , when the energy generated by the hybrid energy system exceeds the load demand. The rectifier model is [51] , [52] , [38]

$$E_{Rec\_out}t = \eta_{Rec} \times E_{Sur\_AC}t \tag{3.8}$$

$$E_{Sur\_AC}t = E_{DG}t - E_{Load}t \tag{3.9}$$

where $E_{Rec\_out}t$ is the hourly energy output from rectifier (kWh) , $\eta_{Rec}$ is the efficiency of the rectifier , $E_{Sur(AC)}t$ is the amount of surplus energy from AC sources (kWh) and $E_{DG}t$ is the energy generated on hourly basis by diesel generator.

### 3.3.9 Charge Controller

A charge controller is essential in a hybrid system with a storage device. It protects the battery in case of both excessive overcharge and deep discharge. It can switch the battery from the load when a state of discharge is reached. It can also switch the battery from the DC bus when it is fully charged. Charge controller can be adjusted to deal with different charging and discharging conditions. The charge controller plays the role of an interface between each of wind turbine , PV panel and the DC bus where the battery is connected.

Controls can be located at a number of places throughout the WECS [53]. Initially , with an active rectifier , the rotational speed of the generator can be sensed and controlled through a Proportional Integral Derivative (PID) controller. This will optimize the conversion coefficient to maintain maximum power output. Also , an early power factor correction circuit will help maintaining the power quality throughout the system. Secondly , a control system can be implemented through the grid-side inverter PWM signal. It can be used to maintain a constant voltage on the DC link , which will decouple the grid from power fluctuations due to wind variations. Control system can also use output current feedback control to manage output active and reactive power for a full power factor correction approach.

A supplementary control system can also be implemented for the addition of a storage system. The storage cells will connect through the capacitor bank , requiring a DC/DC conversion and controls system. This set of controls will maintain voltage regulation when the turbine is producing excess power. It will also ensure proper power delivery during low or no wind situations.

### 3.3.10 Mathematical Model of Charge Controller

To prevent overcharging of a battery , a charge controller is used to sense when the batteries are fully charged and to stop or decrease the amount of energy flowing from the energy source to the batteries. The model of the charge controller is presented below [51] , [39] , [54]

$$E_{CC\_out}t = E_{CC\_in}t \times \eta_{CC} \tag{3.10}$$

$$E_{CC\_in}t = E_{Rec\_out}t + E_{Sur\_DC}t \tag{3.11}$$

where $E_{CC\_out}t$ is the hourly energy output from the charge controller (kWh) , $E_{CC\_in}t$ is the hourly energy input to the charge controller (kWh) , $\eta_{CC}$ is the efficiency of the charge controller , $E_{Rec\_out}t$ is the hourly energy output from the rectifier (kWh) and $E_{Sur\_DC}t$ is the amount of surplus energy from DC sources (kWh).

## 3.4 Energy Storage

Solar and wind power are renewable resources but these resources are limited to the weather conditions. This is a common issue which the small-scale industries are facing these days. Therefore , to rectify this mismatch between the power required and the ability to generate power , we need a storage system. It is less expensive and common nowadays. Ultracapacitors have a lower internal resistance , so they can provide a surge of power faster than a battery , however , batteries can provide power for a longer period. For hydro electricity , the most common type of storing device is the reservoir. Pumping water up the hill into the reservoir turns the electrical energy generated by the wind and PV array into gravitational potential energy. But the drawback of this kind of storage device is its dependency on how many dams and reservoirs we can have which makes it expensive. Another option for storing energy is called as a compressed air energy storage system. This system works by the electricity that help in compressing the air inside the tank. The compressed air is released to power the wind turbine. Another large-scale energy storage system is the hydrogen fuel cells , which works on the principle of splitting water into hydrogen and oxygen and storing the hydrogen [55] , [40]. The stored hydrogen can be used in the fuel cell , where it will react with the oxygen to generate electricity , with water as the by-product. But this system has a limited scope based on the availability of places required to store hydrogen. A battery is used as a backup system and it also maintains a constant voltage across the load. They are used to store excess energy for later use. The energy is stored in electromechanical form and is used in wide variety of applications.

### 3.4.1 Battery Selection

The output power from the wind turbine and PV panel varies with weather conditions throughout the day. Therefore it is not possible to meet the load demand all the time with individual PV or a wind turbine. This can be compensated using a battery between the DC bus of the hybrid system and the load which acts as a backup power supply during the power crisis. If an excess of energy is generated by the PV and wind turbine after meeting the load demand , that excess energy is stored by charging the battery , for future use. Two main types of batteries used in hybrid systems are nickel-cadmium battery and lead acid battery. Nickel-cadmium batteries are expensive , have lower energy efficiency and limited upper operating temperature. Hence lead-acid batteries are most commonly used in the hybrid systems. The Depth of Discharge (DOD) is a measure of how much energy has been withdrawn from a storage device , expressed as a percentage of full capacity. For example , if the DOD of the battery as mentioned by the manufacturer is 50% then only 50% of the battery capacity will be consumed by the load. The state of charge (SOC) is the reserve of the depth of discharge (DOD). It indicates the present state of the battery in use. The battery cycle is a complete period of discharge and recharge. Generally , it is considered to be discharging from 100% to 20% DOD and then back to 100%. The expected number of cycles a battery can deliver is an indicator of its performance. The average depth of discharge is inversely proportional to the cycle life. When selecting a battery type , usually lead-acid battery is chosen. Generally , lead-acid batteries are more cost-effective than nickel-cadmium batteries , but the latter may be a better choice for greater battery ruggedness. Nickel-cadmium batteries can perform well under rigorous working conditions.

Selection of battery voltage depends on inverter and controller available. They usually come under voltage ratings of 12 , 24 , 48 , 120 and 240 V DC and thus batteries are required to be connected in series to meet the requirement. The number of batteries string that can be connected together is limited to about five without rigorous monitoring and higher maintenance cost. Therefore once the battery bank capacity has been selected the size of the individual battery type must be chosen accordingly. Same battery characteristics must be connected together so as to avoid one battery overcharged and the other undercharged.

### 3.4.2 Mathematical Model of Battery Bank

The battery state of charge $SOC$ is the cumulative sum of the daily charge/discharge transfers. At any hour $t$ the state of the battery is related to the previous state of charge and to the energy production and consumption situation of the system during time from $t-1$ to $t$. During the charging process , when the total output of all generators exceeds the load demand , the available battery bank capacity at the hour $t$ can be described by [56]

$$E_{Bat}t = E_{Bat}t - 1 + E_{CC\_out}t \times \eta_{chg} \tag{3.12}$$

where $E_{Bat}t$ is the energy stored in the battery at the hour $t$ , $E_{CC}t$ is the hourly energy input to charge controller (kWh) and $\eta_{chg}$ is the battery charging efficiency.

On the other hand , when the load demand is greater than the available energy generated , the battery bank is in discharging state. Therefore , the available battery bank capacity at hour $t$ can be expressed as

$$E_{Bat}t = E_{Bat}t - 1 - E_{needed}t \tag{3.13}$$

where $E_{Bat}t$ is the energy stored in the battery at the hour $t$ , $E_{Needed}t$ is the hourly load demand at a particular period of time.

Let $d$ be the ratio of minimum allowable SOC voltage limit to the maximum SOC voltage across the battery terminals when it is fully charged. The Depth of Discharge ($DOD$) is defined as:

$$DOD\% = (1-d) \times 100 \tag{3.14}$$

## 3.5 Diesel Generator Power Systems

A diesel generator is a combination of a diesel engine with an alternator to generate electrical energy. The most common cases where diesel generators are used is as follows

1. If some places are not connected to the power grid

2. An emergency power-supply in case the grid fails
3. To avoid low-load or power crisis.

### 3.5.1 Diesel Generator Selection

A diesel generator should be selected such that it meets the load demands but also runs on an average at high load levels. If a battery storage is installed for a short duration with the diesel generator , it helps to overcome peak load demands and thus reduces the capacity of a diesel generator. The diesel generator charges the battery via charger that converts AC to DC energy. The battery allows the generator to operate close to its rated values resulting in a decrease of fuel consumption [6].

### 3.5.2 Diesel Generator Sizing in Hybrid System

Several generators can run in parallel and are able to fulfill different load levels. The diesel generator integrated with various renewable resources contribute a lot. A diesel generator adds reliability in a hybrid system. Regular repair and maintenance is always recommended to enhance the life span of the generator. Diesel generators are used either when the battery's state of charge has fallen below a specific value or if the battery and renewable energy resource cannot meet the load demands. Diesel generators may shut off if there is sufficient power available from renewable resources and from the battery to supply the load demand.

### 3.5.3 Mathematical Model of Diesel Generator Subsystem

For higher efficiency the diesel generator will always operate within the range of 80 to 100 percent of their kW rating. A diesel generator consumes fuel to produce electricity and also heat as a by-product. The physical properties of the generator are its minimum and maximum electrical output , expected lifetime in operating hours , the type of fuel it uses and its fuel curve , which relates the quantity of fuel consumed to the produced electrical power.

# Chapter 4

# System Configuration and Simulation Results

## 4.1 Selection of Study Area and Load Assessment

In HOMER software for the selected area of Portugal (39 ° 39' N and -8° 22' W) , the solar radiation and wind speed data are downloaded from NASA for the time period between 2005-2012. The data has been analyzed to assess utilization of hybrid PV , wind , battery and diesel generator power systems to meet the load requirements for the standalone system. The wind turbines , solar and other renewables produced an average of 52 percent of Portugal's electricity as of 2015 , which is just 8 percent of the country's target of 60 percent by 2020. As per a report in the Guardian [60] , Portugal ran for four days (approximately 107 hours) straight on renewable energy alone. This shows the importance of renewable energy.

The basic energy requirements for assessing the load in such areas can be classified as domestic and industrial. In the domestic sector electricity is required for appliances. The electrical load from small manufacturing units , cold storage , small milk processing plants and cottage industries in the village sums up the rural industrial load. The primary load for the selected site is downloaded from the HOMER software. The electric load profile is shown in Table 4.1 which shows the scaled average load is 60 kWh/d. Scaled data is created by multiplying baseline data value which is 389.5 kWh/d by the common load factor. Load factor is defined as a dimensionless number equal to the average load divided by the peak load. Common load factor is 0.28 in this work.

### 4.1.1 Input to renewable systems using HOMER

Our study area has three types of loads namely residential load , industrial load , and agricultural load and we are considering only residential load in this work [61]. In this

Table 4.1: Load Profile Month (kW) vs. Hour

| Hour | **Month** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
| 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 1 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 2 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 3 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 4 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| 5 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 6 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| 7 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 |
| 8 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| 9 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 10 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 11 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| 12 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| 13 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| 14 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| 15 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| 16 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| 18 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 |
| 19 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 |
| 20 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| 21 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 |
| 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 |
| 23 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |

thesis , our focus is on the input renewable resources and also to meet the required load demand using a photovoltaic system , a wind turbine , a diesel generator and a battery bank.

### 4.1.2 Photovoltaic Resource Specifications

Table 4.2 shows the solar irradiation. The Clearance Index is defined as the ratio of the global irradiance to the corresponding irradiance available out of the atmosphere [62]. The data was downloaded from the HOMER website after selecting the area of study. Global solar radiation is defined as the beam radiation coming directly from the sun plus the diffuse radiation coming from all other parts of the sky. Solar resource data indicate the amount of global solar radiation that strikes Earth's surface in a year.

Table 4.2: Input Photovoltaic Resource

| Month | Clearance Index | Daily Radiation (kWh/m$^2$/day) |
|---|---|---|
| January | 0.425 | 1.84 |
| February | 0.465 | 2.66 |
| March | 0.494 | 3.80 |
| April | 0.534 | 5.16 |
| May | 0.544 | 6.00 |
| June | 0.551 | 6.38 |
| July | 0.599 | 6.76 |
| August | 0.624 | 6.33 |
| September | 0.576 | 4.81 |
| October | 0.518 | 3.26 |
| November | 0.466 | 2.16 |
| December | 0.419 | 1.64 |

**PV Array Parameters:** The PV array selected for this work is 1 kW rated capacity flat PV , which is a generic PV system. The capital cost is $4,000 with a replacement cost of $3,000. Derating factor is defined as the scaling factor that HOMER applies to the output to present a real-world operating scenario as compared to the rated PV panel [70]. The flat PV has a lifetime of 25 years with a derating factor of 89%. PV sizing is varied for other simulations. In this work , the sizes of PV generator to be considered are 0 kW , 2 kW , 5 kW , 7 kW , 10 kW , 12 kW , and 15 kW [63].

### 4.1.3 Wind Turbine Specifications

Table **??** shows specifications for the wind speed. The average wind speed values are imported from HOMER for the simulation purpose. The average wind speed is 4.22 m/s [63] in this case. The data was downloaded from the HOMER website after selecting the area of study. HOMER can generate hourly data from 12 monthly wind speeds and adds four statistical parameters. The parameters are the Weibull shade factor , the autocorrelation factor , the diurnal pattern strength and the hour of peak wind speed. The Weibull shape factor is a measure of the distribution of wind speeds over the year. The autocorrelation factor is defined as a measure of how strongly the wind speed in an hour tends to depend on the wind speed in the preceding time. The diurnal pattern strength and the hour of peak wind speed indicates the magnitude and the phase respectively of the average wind pattern in the wind speed.

Table 4.3: Average Monthly Wind Velocity

| Month | Average (m/s) |
|---|---|
| January | 4.46 |
| February | 3.92 |
| March | 4.38 |
| April | 5.47 |
| May | 4.29 |
| June | 4.16 |
| July | 3.81 |
| August | 3.52 |
| September | 3.72 |
| October | 3.77 |
| November | 4.52 |
| December | 4.88 |

**Wind Turbine Parameters:** The wind turbine model selected for this work is BWC-Excel-R , having a rated capacity of 8.1 kW. The lifetime is 20 years as per the manufacturer Bergey Windpower [64]. The wind turbine power curve increases gradually with a wind speed starting from 0 m/s to 25 m/s , the power output starts to increase from 0 kW with a wind speed of 4 m/s to 0.247 kW with a speed of 6 m/s. The capital cost for the wind turbine is $29,000 with a replacement cost of $25,000. The operation and maintenance cost is about $400 per year.

### 4.1.4 Battery Bank Specifications

Table 4.4 shows the specifications for battery banks. Lithium-Ion battery is selected with a nominal voltage of 6 V and a nominal capacity of 167 Ah and 1 kWh. The size of the battery is not changed for every simulation. The key physical features of the battery are its nominal voltage , capacity curve , minimum state of charge and the round trip efficiency. The capacity curve shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes. Capacity typically decreases with increasing discharge current. The round-trip efficiency indicates the percentage of the energy going into the battery that can be drawn back out.

Table 4.4: Storage Specifications

| | |
|---|---|
| Nominal Voltage (V) | 6 |
| Nominal Capacity (kWh) | 1 |
| Nominal Capacity (Ah) | 167 |
| Roundtrip Efficiency (%) | 90 |
| Maximum Charge Current (A) | 167 |
| Maximum Discharge Current (A) | 500 |

**Battery Parameters:** As the variations of solar and wind energy do not match the time distribution of the load demand , therefore power generation systems need a storage facility to smooth the mismatch between solar wind generation. Batteries are considered as a major cost factor in small off-grid systems. In this work a Lithium-Ion battery of 6 V , 1 kWh has been chosen. The efficiency of the battery is 90% with the maximum charge current of 167 A and a maximum discharge current of 500 A [1]. Battery stores DC electrical energy in electrochemical form and the amount of energy that can be stored or delivered is managed by the inverter. The capital and the replacement cost of the battery selected is \$500. The operations and management cost is \$10 per year.

### 4.1.5 Diesel Generator Specifications

It is very important to have a backup system in operation at times when the output from the PV and wind fails to fulfill the load demand and the battery is also completely depleted. The price of diesel generator fuel varies from region to region , current market , and transportation cost. The price of diesel fuel used in the paper for the generator [65] is higher than the one selected in this work. A diesel generator is an essential part used in the hybrid model when there are no renewable resources available. The diesel generator selected for this work is abbreviated as DG having a capacity of 10 kW. Site-specific minimum load ratio percentage , which is defined as the average load divided by the peak load in a specific time period , is 30 with a lifetime of 12,000 hours. The capital cost of a diesel generator is \$6000 with a fuel cost of \$0.40/L [1].

### 4.1.6 Converter Specifications

The converter is used which can work in both ways like an inverter-rectifier based on the direction of power flow. In this work , we have selected a converter having an efficiency of 95%. The converter size , which is a decision variable , refers to the inverter capacity which means the maximum amount of power the device can produce by inverting the dc power. The converter size is also varied for simulations from 0 kW , 2 kW , 4 kW , 6 kW , 8 kW and 10 kW. The capital cost of the converter is \$900 with a lifetime of 29 years.

## 4.2 HOMER Simulations

Simulation, optimization and sensitivity analysis are the three major actions run by HOMER. In the simulation process, different micro-power system configurations for every hour of the year are generated with their technical feasibility and LCC. In the optimization process , HOMER simulates many different configurations in search of the one that satisfies the constraints at the lowest LCC. In the sensitivity analysis , multiple optimizations are performed on the selected configurations with a range of uncertain input parameters that are assumed to affect the model inputs with time. Examples of uncertainties are the fuel price and the average wind speed. The effects of these can be analyzed with the help of the sensitivity analysis.

Simulation results help in identifying which configuration is the most optimized and feasible solution. The simulator helps in determining how different sources or hybrid models interact with the load demands for optimized results [66].

## 4.3 System Controls

Two different types of control strategies are modelled by HOMER [67]. With the load flow strategy , whenever the generator is required it only produces enough power to meet the load demand at a given time. In contrast to this , in the cycle charging strategy which is used in this work , the generator is allowed to operate up to maximum power to charge the batteries and serve the load at the same time. HOMER uses dispatch strategy to simulate how the input components will work together in hybrid system. Operating reserve is defined as a safety margin that helps a reliable electricity supply despite of any renewable input resource. Every micro power system must provide with some amount of operating reserve , else the electric load can fluctuate above the operating capacity which will result in an outage. Every hour HOMER determines whether the non-dispatchable renewable resources are capable of supplying the electric load and the required operating reserve. If not , then HOMER determines how to best dispatch the system components to save the loads and operating reserve. The fundamental principle that HOMER follows when dispatching the system in the minimization of the cost [66].

## 4.4 Analysis

HOMER's aim is to minimize the net present cost (NPC) both in finding the optimal system configuration and in operating the system , economics play a crucial role in the simulation. The indicator chosen to compare the different configuration's economics is the life-cycle costs (LCC) , and the total NPC is taken as the economic figure of merit. The advantages of these indicators are described in this section [68]. HOMER performs the simulation for a number of prospectively designed configurations. After examining every design , it selects the one that meets the load with the system constraints at the least LCC. HOMER performs its optimization and sensitivity analysis across all mentioned components and their resources , technical and cost parameters and system constraints and sensitivity data over a range of variables. The main difference between renewable and non-renewable resources regarding costs is that nonrenewable resources usually have low capital and high operating costs. After a considerable investment , in the beginning , the system can be operated at a comparatively low-cost [69]. To be able to compare the economics of numerous different system configurations with a varying share of renewable and non-renewable energy sources , HOMER has to take into account both the operating and capital costs. Since the LCC comprises of all costs incurred during the system's lifespan , it considers these factors and therefore is the appropriate parameter to compare the different configuration economics. This LCC is determined with the help of the NPC , which expresses all costs and proceeds occurring during a system's lifespan in one total sum (in dollars). Future earnings are discounted back to the present using the discount rate , which is just as the system's lifespan set by the system designer. The different items making up the NPC are the costs of construction , maintenance including component replacements , buying power from the grid and miscellaneous other costs. Furthermore , the NPC also considers salvage costs , that is the residual value of system components after the project ends. An alternative to the NPC to compare the economics of various system configurations is the levelized COE , which is defined as the average cost for every kWh of electricity produced by the system. Yet , HOMER has chosen NPC as the primary economic figure of merit.

## 4.5 Simulation Results

HOMER simulates configurations to get feasible results with the renewable resources and the components specified as input. HOMER provides all possible results by simulating every combination for a single model to get the best-optimized results in terms of Net Present Cost (NPC). The strategy in simulations is to ensure the power generator provides enough power to meet the load demand. The renewable energy resources in collaboration with diesel generator were evaluated to get an optimized result based on NPC. In this work , different simulations were done by varying the size of the photovoltaic panel and to check in this hybrid model how much production will be done by a diesel generator to fulfill the load demands.

### 4.5.1 Optimization of Hybrid PV Wind Model

In the stand-alone system , if the demand is greater than the sum of generation and storage , then the power must be supplied by the backup diesel generator. The objective function of this research is to develop a stand-alone hybrid system and minimize the total life-cycle cost. The total net present cost ($\$/year$) includes initial cost , operational and maintenance cost for each renewable resource. The salvage value of each equipment must be supplied. The initial capital cost is defined as the capital cost of every component including the system design cost and installation cost. The initial capital cost for every component is defined as the product of the total capacity (kW) and its respective unit cost ($\$/kW$). Replacement cost is when the system fails before its life expectancy due to any environmental effects , mishandling etc.

The total hybrid power generated at any time is given by

$$P = \sum_{WG=1}^{N_W} P_{WG} + \sum_{PV=1}^{N_P} P_{PV} + \sum_{DG=1}^{N_D} P_{DG} \tag{4.1}$$

where $P$ is the total power generation , $N_W$ is the wind generator unit , $P_{WG}$ is the power generated by the wind energy generator , $N_P$ is the number of PV cells unit , $P_{PV}$ is the power generated by the photovoltaic unit , $N_D$ is the number of diesel generator unit , and $P_{DG}$ is the power generated by the diesel energy generator ,

### 4.5.2 Constraints

The power generated should feed its load. The diesel generator always has the constraint to operate between 80% to 100% of their kW rating. The generator minimum load ratio is the minimum allowable load on the generator as a percentage of its rated capacity. According to the selected site , the diesel generator has a minimum load ratio of 30% to avoid running for a very low load. When this generated power exceeds the load demand then the surplus energy will be stored in the battery bank. This energy will be used when a deficiency of power is seen in order to meet the load demands. In this work , the sizes of PV generator to be considered are 0 kW , 2 kW , 5 kW , 7 kW , 10 kW , 12 kW , and 15 kW. The PV size has a site-specific restriction because of the area. According to the selected site , the derating factor of PV is 80%. Hub height of the wind turbine according to the selected site has to be 10m for optimal size. The battery has a restriction as well. The initial state of charge is 100% and the minimum SOC is 20%. The charged quality of the battery bank has the following limitation

$$SOC_{min} \leq SOCt \ \leq SOC_{max} \tag{4.2}$$

### 4.5.3 Minimization of Cost

The main aim is to reduce the total life cycle cost of the hybrid system. The total capital cost for the hybrid system is given by

$$C_c = \sum_{WT=1}^{N_W} C_{WT} + \sum_{PV=1}^{N_{PV}} C_{PV} + \sum_{DG=1}^{N_D} C_{DG} + \sum_{B=1}^{N_B} C_{Bat} + C_F \tag{4.3}$$

where $C_c$ is the capital cost , $C_{PV}$ , $C_{WT}$ , $C_{DG}$ , $C_{Bat}$ are the cost for a single unit of the photovoltaic , the wind turbine , the diesel generator and the battery respectively , $C_F$ is the fixed cost including the cost of converter and other installation cost. $N_W$ is the wind generator unit , $P_{WG}$ is the power generated by the wind generator and $N_P$ is the number of PV cells unit. These numbers are fed in HOMER software to design the standalone hybrid system for the simulation. The sizes of PV generator to be considered are 0 kW , 2 kW , 5 kW , 7 kW , 10 kW , 12 kW , and 15 kW. The number of units for input components are 1.

Total annualized life-cycle cost of the system comprises both the capital and the operating cost is

$$C_{Annual} = C_c \times CRF + C_O \tag{4.4}$$

where $CRF$ is the capital recovery factor for the system , $C_O$ is the annual operating cost. The unit cost of electricity by hybrid energy system ,

$$COE = \frac{C_{Annual}}{E_T} \tag{4.5}$$

where $E_T$ is the total load served in kWh/year.

### 4.5.4 Scenario 1- PV , Diesel Generator

The first simulation was done by considering a 5 kW PV , a diesel generator of 10 kW , a battery with 16 strings and a 4 kW converter. Table 4.5 shows a comparative net price for all the components.

Table 4.5: Result for Scenario 1

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Converter | 3,600 | 1,147 | 0 | 0 | 4,100 |
| Diesel | 6,000 | 14,312 | 7,583 | 34,707 | 61,537 |
| Li-Ion | 8,000 | 11,271 | 2,068 | 0 | 20,436 |
| PV | 20,000 | 0 | 215 | 0 | 20,215 |
| System | 37,600 | 26,730 | 9,867 | 34,707 | 106,289 |

Table 4.5 indicates the total cost of this particular system is $106,289 which includes all the components capital cost , replacement , fuel , salvage and operations cost. If we add wind turbine as another renewable resource input , then the cost of maintaining the diesel generator might become less which can also reduce the total cost of the system.

Table 4.6: Electrical Production for Scenario 1

| Production | kWh/yr | % |
|---|---|---|
| PV | 6,936 | 28 |
| Diesel | 17,462 | 71 |
| Total | 24,398 | 100 |

Table 4.6 shows that the electrical production per year for PV is 6,936 kWh which contributes 28.4% to the total production of 24,398 kWh/year whereas the electrical production from the diesel generator is 17,462 kWh which is about 71.6%. Table 4.7 shows that the total hours of operation when the diesel generator has to work is 2,933 hours/year with a number of 805 starts per year. The total net present cost is $106,289 with the levelized cost of energy (LCE) of ($0.375 kWh). Thus the operating cost from the simulation is $5,313.47.

### 4.5.5 Scenario 2- PV , Wind Turbine

The second simulation is done by considering a 12 kW PV , a 70 string battery , 1 kW wind turbine and a 8 kW converter. A comparative net pricing for all the components is shown in Table 4.8.

Table 4.7: Diesel Hours of Operation for Scenario 1

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 2,933 | hrs/yr |
| Number of starts | 805 | starts/yr |
| Operational Life | 5 | yr |
| Capacity factor | 20 | % |
| Fixed generation cost | 0.94 | $/hr |

Table 4.8: Result for Scenario 2

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Wind | 58,000 | 15,940 | 10,342 | 0 | 75,298 |
| Converter | 7,200 | 2,295 | 0 | 0 | 8,201 |
| Li-Ion | 35,000 | 14,849 | 9,049 | 0 | 56,104 |
| PV | 48,000 | 0 | 517 | 0 | 48,517 |
| System | 148,200 | 33,085 | 19,908 | 0 | 188,121 |

Table 4.8 shows the total yearly cost of this particular system is $188,121 which includes all the components capital cost , replacement , fuel , salvage and operations cost.

Table 4.9: Electrical Production for Scenario 2

| Production | kWh/yr | % |
|---|---|---|
| PV | 16,647 | 31 |
| BWC-Excel-R | 36,673 | 68 |
| Total | 53,320 | 100 |

Table 4.9 shows that the electrical production per year for PV is 16,647 kWh which contributes 31.2% to the total production of 53,320 kWh/year whereas the electrical production from the wind turbine is 36,673 kWh which is about 68.8%. The average consumption of the AC primary load is 21,900 kWh/year. The total net present cost is $188,121 with the levelized cost of energy (LCE) is ($0.669/$kWh$). Thus the operating cost is around $3,088.

### 4.5.6 Simulation Scenario 3- PV , Wind Turbine , Diesel Generator

The third simulation is done by considering a 2 kW PV , 1 kW wind turbine , a diesel generator of 10 kW , a battery with 8 strings and a 6 kW converter. Table 4.10 shows a comparative net price for all the components.

Table 4.10: Result for Scenario 3

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Wind | 29,000 | 7,970 | 5,171 | 0 | 37,649 |
| Converter | 5,400 | 1,721 | 0 | 0 | 6,151 |
| Diesel | 6,000 | 6,846 | 4,209 | 20,854 | 37,181 |
| Li-Ion | 4,000 | 11,729 | 1,034 | 0 | 16,130 |
| PV | 8,000 | 0 | 86.0 | 0 | 8,086 |
| System | 52,400 | 28,267 | 10,500 | 20,854 | 105,199 |

The table 4.10 shows that the total cost of this particular system is $105,199 which includes all the components capital cost , replacement , fuel , salvage and operations cost.

Table 4.11 shows that the electrical production per year for the diesel generator is 10,922 kWh which is about 34.1% whereas PV and wind turbine together covers 66% of the total production. The average consumption of the AC primary load is 21,900 kWh/year. The total net present cost is $105,199 and the levelized cost of energy (LCE) is ($0.371/$kWh$). Thus the operating cost is around $4,084.

Table 4.11: Electrical Production for Scenario 3

| Production | kWh/yr | % |
|---|---:|---:|
| PV | 2,774 | 8 |
| Diesel | 10,922 | 34 |
| Wind | 18,337 | 57 |
| Total | 32,033 | 100 |

Table 4.12: Diesel Hours of Operation for Scenario 3

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 1,628 | |
| Number of starts | 1,325 | starts/yr |
| Operational Life | 8 | yr |
| Capacity factor | 12 | % |
| Fixed generation cost | 0.94 | \$/hr |

Table 4.12 shows that the total hours of operation when the diesel generator has to work is 1,628 hours/year with 1325 starts per year.

### 4.5.7 Scenario 4- PV , Wind Turbine , Diesel Generator

The fourth simulation is done by considering a 2 kW PV , a diesel generator of 10 kW , 8 string battery , 1 kW wind generator and a 6 kW converter. Comparative net pricing details for all the components is shown in Table 4.13.

Table 4.14 shows that the electrical production per year for PV is 2,774 kWh which contributes 7.55% to the total production of 21,900 kWh/year whereas the electrical production by the diesel generator is 9,047 kWh which is about 24.6% and wind turbine contributes about 67.8%. The total net present cost is \$97,562.with the levelized cost of energy (LCE) is (\$0.344/$kWh$). Thus the operating cost is around \$3,493.

Table 4.15 shows that the total hours of operation the diesel generator has to work is 1,378 per year with a number of 1,132 starts per year.

### 4.5.8 Scenario 5- PV , Wind Turbine , Diesel Generator

The fifth simulation is done by considering a 2 kW PV , a 1 kW wind turbine , a diesel generator of 10 kW , a battery and 4 kW converter. A comparative net price for all the components is shown in Table 4.16.

The total cost of this particular system is \$155,598 which includes all the components capital cost , replacement , fuel , salvage and operations cost.

Table 4.13: Result for Scenario 4

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Wind | 29,000 | 7,970 | 5,171 | 0 | 37,649 |
| Converter | 5,4012.00 | 1,721 | 0 | 0 | 6,151 |
| Diesel | 6,000 | 4,887 | 3,562 | 17,396 | 31,691 |
| Li-Ion | 4,000 | 9,597 | 1,034 | 0 | 13,983 |
| PV | 8,000 | 0 | 86 | 0 | 8,086 |
| System | 52,4012 | 24,176 | 9,854 | 17,396 | 97,562 |

Table 4.14: Electrical Production for Scenario 4

| Production | kWh/yr | % |
|---|---|---|
| PV | 2,774 | 7 |
| Diesel | 9,047 | 24 |
| Wind | 24,944 | 67 |
| Total | 24,598 | 100 |

Table 4.15: Diesel Hours of Operation for Scenario 4

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 1,378 | hrs/yr |
| Number of starts | 1,132 | starts/yr |
| Operational Life | 9 | yr |
| Capacity factor | 10 | % |
| Fixed generation cost | 0.94 | $/hr |

Table 4.16: Result for Scenario 5

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| BWC-Excel-R | 2912,000 | 7,970 | 5,171 | 0 | 37,649 |
| Converter | 3,600 | 1,147 | 0 | 0 | 4,100 |
| Diesel | 6,000 | 32,790 | 16,187 | 51,928.06 | 105,761 |
| PV | 8,000 | 0 | 86 | 0 | 8,086 |
| System | 46,600 | 41,908.00 | 21,445.00 | 51,928 | 155,598 |

Table 4.17: Electrical Production for Scenario 5

| Production | kWh/yr | % |
|---|---:|---:|
| PV | 2,774 | 5 |
| Diesel | 20,133 | 42 |
| Wind | 24,944 | 52 |
| Total | 47,852 | 100 |

Table 4.17 shows that the electrical production per year for PV is 2,774 kWh which contributes 5.8% to the total production of 47,852 kWh/year whereas the electrical production from the diesel generator is 20,133 kWh which is about 42.1% and the wind turbine is 24,944 which is 52.1%. The total net present cost is $155,598 with the levelized cost of energy (LCE) is ($0.549/kWh). Thus the operating cost is around $8,431.

Table 4.18: Diesel Hours of Operation for Scenario 5

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 6,261 | hrs/yr |
| Number of starts | 580 | starts/yr |
| Operational Life | 2 | yr |
| Capacity factor | 23 | % |
| Fixed generation cost | 0.94 | $/hr |

The total number of hours of operation from Table 4.18 , the diesel generator has to work for 6,261 hours/year with a number of 580 starts per year.

### 4.5.9 Scenario 6- PV , Diesel Generator

The sixth simulation is done by considering a 7 kW PV , a diesel generator of 10 kW and a 4 kW converter. A graph with a comparative net price for all the components is shown in Table 4.19.

Table 4.19: Result for Scenario 6

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Wind | 2912,000 | 7,970 | 5,171 | 0 | 37,649 |
| Converter | 5,4012 | 1,721 | 0 | 0 | 6,151 |
| Diesel | 6,000 | 7,637 | 4,943 | 24,958 | 43,519 |
| Li-Ion | 4,500 | 13,902 | 1,163 | 0 | 19,449 |
| PV | 28,000 | 0 | 904 | 0 | 28,904 |
| System | 52,900 | 31,231 | 11,364 | 24,958 | 114,855 |

Table 4.19 shows that the total cost of this particular system will cost $114,855 which includes all the components capital cost , replacement , fuel , salvage and operations cost.

Table 4.20 shows that the electrical production per year from PV is 2,774 kWh which contributes 10% to the total production of 27,717 kWh/year whereas the electrical production from the diesel generator is 24,949 kWh which is about 71.98% and from the wind turbine , the production contributes 42.4%. The total net present cost is $114,856 with the levelized cost of energy (LCE) is ($0.405/kWh). Thus the operating cost is around $4,792.

Table 4.20: Electrical Production for Scenario 6

| Production | kWh/yr | % |
|---|---:|---:|
| PV | 2,774 | 10 |
| Diesel | 24,949 | 71 |
| Wind | 11,755 | 42 |
| Total | 27,717 | 100 |

Table 4.21: Diesel Hours of Operation for Scenario 6

| Quantity | Value | Units |
|---|---:|---|
| Hours of operation | 1,912 | hrs/yr |
| Number of starts | 1,409 | starts/yr |
| Operational Life | 6 | yr |
| Capacity factor | 15 | % |
| Fixed generation cost | 0.94 | $/hr |

Table 4.21 shows that the total hours of operation the diesel generator has to work is 1,912 hours/year with a number of 1,409 starts per year.

### 4.5.10 Scenario 7- PV , Wind Turbine , Diesel Generator

The seventh simulation is done by considering 7 kW PV , 1 kW Wind turbine , 10 kW diesel generator and a 4 kW converter. A comparative net price for all the components is shown in Table 4.22.

Table 4.22: Result for Scenario 7

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Wind | 29,000 | 7,970 | 5,171 | 0 | 37,649 |
| Converter | 9,000 | 2,869 | 0 | 0 | 10,252 |
| Li-Ion | 33,500 | 14,213 | 8,661 | 0 | 53,699 |
| PV | 60,000 | 0 | 646 | 0 | 60,646 |
| System | 131,500 | 25,052 | 14,478 | 0 | 162,247 |

Table 4.22 shows that the total cost of this particular system is $162,247 which includes all the components capital cost , replacement , fuel , salvage and operations cost.

Table 4.23: Electrical Production for Scenario 7

| Production | kWh/yr | % |
|---|---|---|
| PV | 20,808 | 45 |
| Wind | 24,944 | 54 |
| Total | 45,753 | 100 |

Table 4.23 shows that the electrical production per year from PV is 20,808 kWh which is 45.5% and from the wind turbine , it's 54.5%. The total net present cost is $162,247 with the levelized cost of energy (LCE) is ($0.5779/kWh). Thus the operating cost is around $2,378.

### 4.5.11 Scenario 8- PV , Diesel Generator , Wind Turbine

The eighth simulation is done by considering a 7 kW PV , 10 kW diesel generator , 1 kW wind turbine and a 4 kW converter. A comparative net price for all the components is shown in Table 4.24.

Table 4.24 shows that the total cost of this particular system will cost $186,900 which includes all the components capital cost , replacement , fuel , salvage and operations cost. The

Table 4.24: Result for Scenario 8

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Total ($) |
|---|---|---|---|---|---|
| Wind | 29,000 | 7,970 | 5,171 | 0 | 37,649 |
| Converter | 3,600 | 1,147 | 0 | 0 | 4,100 |
| Diesel | 6,000 | 35,867 | 17,775 | 58,016 | 116,848 |
| PV | 28,000 | 0 | 301 | 0 | 28,301 |
| System | 66,600 | 44,985 | 23,247 | 58,016.82 | 186,900 |

total net present cost is $186,900 with the levelized cost of energy (LCE) is ($0.660/kWh). Thus the operating cost is around $9,305.

Table 4.25: Electrical Production for Scenario 8

| Production | kWh/yr | % |
|---|---|---|
| PV | 9,711 | 25 |
| Diesel | 22,879 | 59 |
| Wind | 6,194 | 16 |
| Total | 38,783 | 100 |

Table 4.25 shows that the electrical production per year from diesel generator is 22,879 kWh which contribute 59% to the total production of 38,783 kWh/year whereas the electrical production from the renewable resources is 15,905 kWh which are about 41%.

Table 4.26: Diesel Hours of Operation for Scenario 8

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 6,875 | hrs/yr |
| Number of starts | 452 | starts/yr |
| Operational Life | 1 | yr |
| Capacity factor | 26 | % |
| Fixed generation cost | 0.937 | $/hr |

Table 4.26 shows that the total hours of operation the diesel generator has to work is 6,875 hours/year with a number of 452 starts per year.

### 4.5.12 Discussion

The renewable energy potential of a standalone hybrid system was performed in the study. Different scenarios have been considered namely scenario 1-PV , diesel generator , scenario 2-PV , wind turbine , scenario 3- PV , wind turbine , diesel generator , scenario 4- PV , wind turbine , diesel generator , scenario 5- PV , wind turbine , diesel generator , scenario 6- PV , diesel generator , scenario 7- PV , wind turbine , diesel generator , scenario 8- PV , diesel generator , wind turbine. All the simulations were done in HOMER software. At first , primary load was considered and by using different renewable sources like PV , wind turbine , battery or PV , diesel generator , battery or PV , diesel generator , battery or PV , wind turbine simulations were done. Photovoltaic panel sizes were varied in all the scenarios to obtain the optimal configuration of the hybrid system. The converter size was also changed according to respective PV sizes. The simulation results in scenario 7 shows that after increasing the size of PV panel and keeping rest of the input quantities unchanged , the diesel generator wasn't even required to fulfil the load demands. PV and wind turbine together were able to supply the load. Also by keeping the value of PV to its smallest size and just by changing the size of the converter , diesel usage was reduced as shown in scenario 3. In this thesis , simulations with different scenarios were done in order to obtain the optimal configuration with the least annual cost. It is concluded that the least annual cost was obtained in scenario 5 , which was $15,598 with optimized sized components of 2 kW PV , 1 kW wind turbine , 10 kW diesel generator and 4 kW converter size. The electrical production from renewable resources is approximately 58%. It means that scenario 5 results in the optimized design to fulfil the load demands.

# Chapter 5

# Conclusion

HOMER software was used to design a hybrid system consisting of PV , wind turbine renewable energy sources and a lithium-ion battery for storage with a backup diesel generator. Simulations with different combination of resources were implemented to find the most optimal configuration of the hybrid model. The simulation results show that after increasing the size of PV panel and keeping rest of the input quantities unchanged , diesel generator wasn't even required to fulfil the load demands. PV and wind together were able to supply the load. The renewable energy potential of a standalone hybrid system was performed in the study. Different scenarios have been considered namely scenario 1-PV , diesel generator , scenario 2-PV , wind turbine , scenario 3- PV , wind turbine , diesel generator, scenario 4- PV , wind turbine , diesel generator , scenario 5- PV , wind turbine , diesel generator , scenario 6- PV , diesel generator , scenario 7- PV , wind turbine , diesel generator , scenario 8- PV , diesel generator , wind turbine. In this thesis , simulations with different scenarios were done in order to obtain the optimal configuration with the least annual cost. It is concluded that the least annual cost was obtained in scenario 5 , which was $15,598 with optimized sized components of 2 kW PV , 1 kW wind turbine , 10 kW diesel generator and 4 kW converter size. The electrical production from renewable resources is approximately 58%. It means that scenario 5 results in the optimized design to fulfil the load demands.

## 5.1 Contribution

This thesis contributes to the area of power systems. Portugal and Canada are part of the International Energy Agency (IEA) photovoltaic power systems programme. Specifically in this work , Portugal is selected as the research area as oppose to Canada because of lack of data during winter seasons. The primary contributions from this thesis are the following:

1. The selected area has abundant renewable resources like PV , wind and hydro energy. Therefore to increase the energy utilization , hybrid system is designed accordingly ,

2. The life cycle cost of the system is minimized ,
3. The combination of renewable input resources worked in order to decrease the electrical production from diesel generator.

Key factor is to reduce the life cycle cost of the system for optimized results. We choose solar and wind as input to HOMER software and diesel generator as a back up. Simulations were done by keeping all the same parameters and changing the size of the photovoltaic array for comparative results. From the simulated results , we can conclude that by using a smaller size of photovoltaic array and wind turbine with a moderate size diesel generator , the life cycle cost can be decreased and more electrical production than the diesel generator. This system constitutes the optimized size of the hybrid system for obtaining the minimized life cycle cost.

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