# TECHNO ECONOMIC ANALYSIS OF STAND-ALONE HYBRID RENEWABLE ENERGY SYSTEM

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# ABSTRACT

Decentralized electricity generation by renewable energy sources is considered as a solution for remote area's electrification. However, intermittent nature of these sources leads to develop sizing rules and use hybrid systems to exploit them. This study proposes an integrated PV/wind hybrid system, with battery storage and diesel generator as a backup. Optimization method utilizes the iterative optimization technique following the loss of power probability and the cost of electricity for power reliability and system costs.

The optimal size of hybrid energy conversion system founded in this study can be performed technically and economically according to the system reliability requirements. In addition, a sensitivity analysis was carried out on the PV contribution as the most important parameters influencing the economic performances of the hybrid system.

This investigation is executed as a techno-economic analysis to design an optimum autonomous hybrid PV-wind-diesel-battery system to meet the load in remote areas of Malaysia

The hybrid system with 56-61% of photovoltaic energy penetration combined with wind turbines, diesel generator with a rated power, and storage batteries was found to be an optimal system and economically feasible one.

# ABSTRAK

Kuasa penjanaan elektrik oleh sumber tenaga boleh baharu dianggap sebagai penyelesaian kepada elektrifikasi kawasan pedalaman. Walau bagaimanapun, sifat berkala sumber-sumber ini mewujudkan peraturan ukuran dan menggunakan sistem hibrid untuk mengeksploitasi mereka. Kajian ini mencadangkan sistem hibrid bersepadu PV / angin, dengan penyimpanan bateri dan penjana diesel sebagai sokongan. Kaedah optimum menggunakan teknik lelaran optimum adalah berikutan kebarangkalian kehilangan kuasa dan kos elektrik terhadap kebolehpercayaan kuasa dan kos sistem.

Sistem penukaran tenaga hibrid yang diasaskan dalam kajian ini dipercayai baik secara teknikal dan ekonomi. Di samping itu, analisis kepekaan telah dijalankan dan sumbangan PV sebagai parameter penting dalam mempengaruhi prestasi ekonomi sistem hibrid.

Kajian mengkaji teknologi dan eknomi analisis terhadap system hybrid. Ini kerana kami ingin mengoptimkan sebaik mungkin sistem hibrid yang mampu memenuhi keperluan dan harga yang rendah dengan tenaga yang boleh dipercayai

Sistem hibrid dengan 66% penembusan tenaga fotovoltaik yang digabungkan dengan turbin angin, penjana diesel dengan kuasa tertinggi, dan bateri penyimpanan telah ditemui sebagai sistem yang optimum dan ekonomi tersaur

# ACKNOWLEDGEMENT

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# CHAPTER 1

# INTRODUCTION

## 1.1    Introduction

Nowadays renewable energy resources are one of the promising ways to address many problems encountered since 1970 when the world major industries faced the shortage of Petroleum and worst energy crises . Climate change, desertification, greenhouse effect, etc., lead the world towards sustainable energy era. Using natural and renewable resources such as wind, solar, geothermal, tidal, wave and hydroelectric offer clean alternatives for fossil fuel; in which they are omnipresent, abundant, free, clean and easily accessible even in isolated and undeveloped places.

Design a renewable energy system with the low adverse socio-economic and environmental impacts, are one of the challenges for its developments. Renewable energy systems need to be adequately informed and assessed at initial stages. Unpredictable nature of these resources is one of the drawbacks for their development, especially when having a reliable source of energy to match the time distribution of load demand is essential.  This drawback together with high initial cost, and dependency on weather conditions lead to combine different renewable resources to form a Hybrid system which can be flexible, cost effective, reliable and efficient. However, careful planning and assessment is required to ensure the successful implementation of a hybrid power system. Training of operators, involving local community on electrification programs, overseeing installation and commissioning, maintenance procedures , system monitoring and reporting are all part of the successful hybrid power system implementation process.

Since wind and solar energies are complementary in electric power generation from the complementarity of time and region; in stand-alone systems, energy provided by wind turbine and PV are the major renewable energy resources (Y. j. Li, Yue et al. 2009). Moreover, storage resources such as diesel generator (DG), battery, super capacitor bank, super conducting magnetic energy storage (SMES), and fuel cell-electrolyzer are used to overcome the intermittent nature of wind and solar energies (Agbossou, Kolhe et al. 2004; Caisheng and Nehrir 2008; Strunz and Kristina Brock 2006) .

Since the combination of PV and wind are the most common sources of renewable energies in stand-alone systems, in this project, optimization of hybrid systems which include PV and wind as the sources of energy generations combined with battery and diesel will be investigated.

Component models of renewable resources are summarized in the following section and later the arrangement of sources and connections of hybrid systems will be discussed to predict the hybrid renewable energy systems (HRES's) performance.

## 1.2 Problem Statement

Renewable sources such as wind, solar, and hydro power, which offer clean alternatives for fossil fuel, are omnipresent, abundant, free, clean and easily accessible even in isolated and undeveloped places in the form of stand-alone hybrid systems. These systems are mainly used in remote area communities to generate electricity. However unpredictable nature of these resources is one of the drawbacks for their development, especially when having a reliable source of energy to match the time distribution of load demand is essential.

This drawback together with high initial cost, and dependency on weather conditions result in combining different renewable resources to form a Hybrid system

which can be flexible, cost effective, reliable and efficient. However hybrid systems need to be adequately informed and assessed at initial stages. Design a renewable energy system with the low adverse socio-economic and environmental impacts, are one of the challenges for hybrid renewable energy developments. Thereby, knowledge of all factors which influence the performance of the system and accurate modeling for each component are prerequisites for designing an accurate model of the HRES. In recent years, there are a number of studies conducted on different aspects of stand-alone hybrid systems in terms of component or configuration to optimize the stand alone systems. Therefore, finding the best suited model for a particular region would be the basic need of any study.

## 1.3 Motivation

Mainly, hybrid systems are divided into two categories as stand-alone and grid-connected systems. Stand-alone systems are the most promising technologies for supplying load in remote and rural areas. They provide greater reliability, higher efficiency and lower cost in comparison with using single resources technologies.

Since the combination of PV and wind are the most common sources of renewable energies in stand-alone systems, in this study of optimization of hybrid systems which include photovoltaic (PV) and wind as the sources of energy generations combined with battery and diesel will be investigated.

## 1.4    Project Objective

The expected outcomes of the proposed work are as follows:

- To study hybrid stand-alone energy systems.

- To design a reliable and cost-effective hybrid renewable energy system

- To perform technical and economic analysis for the designed system.

## 1.5    Thesis Outline

This thesis consists of six chapters. Chapter 1 presents the introduction of the project, and the objective and scope of project. Chapter 2 surveys previous literature and studies relevant to the project. It also reviews mathematical equations, simulation programs, and computational methods which are commonly used in literatures.

In Chapter 3, the methodology of the project is described. Here, design parameters, optimization algorithm, and techno-economic flowchart are explained.

In Chapter 4, the simulation results are presented. Power extracted from different resources, sensitivity analysis on some of major parameters in design of hybrid systems, techno-economic analysis of hybrid renewable energy system for rural area in Malaysia, optimization of hybrid system, considering low cost and high reliability, are presented in this chapter.

Design consideration of hybrid system is investigated in Chapter 5. Stand-alone hybrid system for individual house and micro-grid configuration for number of houses is designed in this section.

Chapter 6 concludes the overall aspect of the project. In addition, recommendation and possible future work are also proposed.

# CHAPTER 2

# LITERATURE REVIEW

While hybrid renewable energies have obvious advantages over other energy sources, these systems should be able to meet the need of complex conditions due to stochastic nature of renewable energy resources. Performance improvement, predicting the output accurately, and reliability are some of the essential needs for designing a stand-alone hybrid renewable energy system (HRES). In addition economic assessment of the designed system can have a crucial role in wider acceptance of renewable energy technologies.

Therefore, to meet all the aforementioned and make more comprehensive decisions, a complex design is needed. The simulation programs and computational methods are commonly used in this regard.

## 2.1 Introduction

Nowadays renewable energy resources are one of the promising ways to address many problems encountered since the end of fossil fuel era. Climate change, desertification, greenhouse effect, etc. lead the world towards sustainable energy era by using natural and renewable sources such as wind, solar, and hydro power, which offer clean alternatives for fossil fuel. They are omnipresent, abundant, free, clean and easily accessible even in isolated and undeveloped places. These systems are mainly used in remote area communities to generate electricity. However unpredictable nature of these resources is one of the drawbacks for their development, especially when having a reliable source of energy to match the generation with time distribution of load demand is essential (A. Gupta, Saini et al. 2008).

This drawback together with high initial cost, and dependency on weather conditions result in combining different renewable resources to form a Hybrid system which can be flexible, cost effective, reliable and efficient. However hybrid systems need to be adequately informed and assessed at initial stages. Design a renewable energy system with the low adverse socio-economic and environmental impacts, are one of the challenges for hybrid renewable energy developments. Thereby, knowledge of all factors which influence the performance of the system and accurate modeling for each component are prerequisites for designing an accurate model of the system (Thapar, Agnihotri et al. 2011). In recent years, there are numbers of studies conducted on different aspects of stand-alone hybrid systems in terms of component or configuration to optimize the stand alone systems. Therefore, finding the best suited model for a particular region would be the basic need of any study. Accordingly, this study tries to review on different models of each component and examine various combinations of stand-alone hybrid systems based on solar and wind energies. Finally different approaches for technical and economic optimization of systems are reviewed. To the best of our knowledge, no such review exists at present, although reviews of optimization methods of hybrid renewable energy systems can be found.

## 2.2 Modeling

Mainly, hybrid systems are divided into two categories as stand-alone and grid-connected systems. Since wind and solar energies are complementary in electric power generation from the complementarity of time and region; in stand-alone systems, energy provides by wind turbine and PV are the major renewable energy resources (Y. j. Li, Yue, et al. 2009; Sreeraj, Chatterjee et al. 2010). Moreover, storage resources such as diesel generator (DG), battery, super capacitor bank, super conducting magnetic energy storage (SMES), and fuel cell-electrolyzer are used to overcome the intermittent nature

of wind and solar energies(Agbossou, Kolhe, et al. 2004; Caisheng and Nehrir 2008; Strunz and Kristina Brock 2006) .

Stand-alone systems are the most promising technologies for supplying load in remote and rural areas. They provide greater reliability, higher efficiency and lower cost in comparison with using single resources technologies.

Since the combination of PV and wind are the most common sources of renewable energies in stand-alone systems, in this study of optimization of hybrid systems which include PV and wind as the sources of energy generations combined with battery and diesel will be investigated. Component models of renewable resources are summarized in the following section and later the arrangement of sources and connections of hybrid systems will be discussed to predict the hybrid renewable energy systems (HRES's) performance.

### 2.2.1 Photo Voltaic (PV) Technology and Modeling

Photovoltaic systems are classified into two categories of grid-connected and stand −alone systems which are known as Remote area power supply (RAPS) systems (Hancock, Outhred et al. 1994). Figure 2-1 illustrates the classification of PV stand-alone systems.
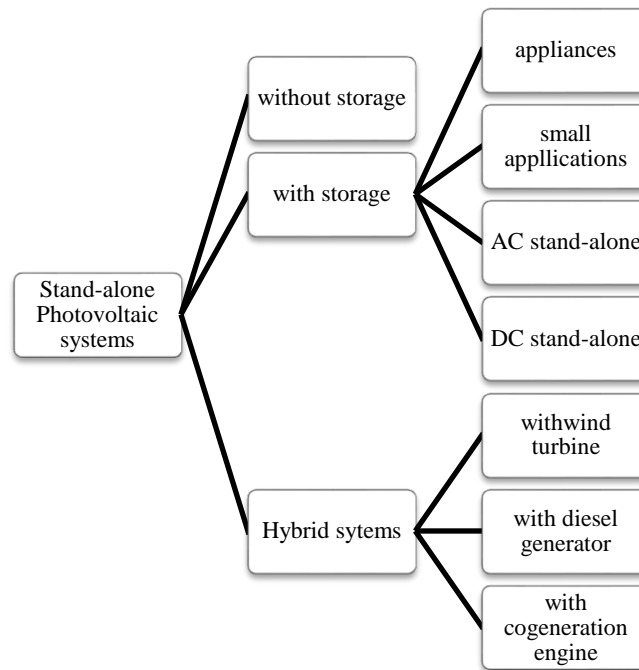
Figure 2-1:Classification of PV systems (Messenger and Ventre 2004)

All technologies related to capturing sunlight or artificial light and convert it into the electricity are known as photovoltaic (PV), which are classified into crystalline, thin film, compound semiconductor and nanotechnology. Technological development in PV technology would lead to the more promising and demanding projects in rural electrification(Bala and Siddique 2009).

Crystalline silicon solar cell was developed in 1950's (Luque and Marti 2010). Considering its head start, reliability and material availability, it has always been the most widely used solar cell which has lead the global PV market (L.Oikkonen ; Willeke 2008).

### 2.2.1.1 PV Models and Equations

The performance of a PV is affected by availability of solar irradiance at the specific location and the PV-module temperature (Zhou, Yang et al. 2007). The crystalline silicon solar cell can be expressed by a single-diode. In this model, a current source which is representing the irradiance stimulated current, is in parallel with an

ideal diode under positive bias and a resistance $R_{sh.}$ The current flows to the load through a series resistance $R_S$ (Kajihara and Harakawa 2005; Nguyen and Lehman 2006). The key parameters of this model are short circuit current ($I_{sc}$) and open circuit voltage ($V_{oc}$), which are affected by solar irradiance at the required location, material and temperature of PV Cells. Another two most important electrical characteristics of a PV module are: Maximum power output ($P_{max}$) and fill factor (FF). $P_{max}$ is calculated by $V_{mp} \times I_{mp}$, when $V_{mp}$ and $I_{mp}$ are the voltage and Current at the maximum point respectively. $P_{max}$ can also be calculated graphically by the largest rectangle fitted under the I-V curve as shown in Figure 2-2 (S.R. Wenham 2007). FF measures the quality of the solar cells as compared to different solar cells under the same reference conditions (Chenni, Makhlouf et al. 2007). FF is dimensionless; the closer it to the unity, the higher the quality of the PV module would be. It is ranged from 0.5 to 0.82 and calculated by the following equation (El Chaar, lamont et al. 2011):

$$FF = \frac{P_{max}}{V_{OC}I_{SC}} = \frac{I_{max}V_{max}}{V_{OC}I_{SC}} \tag{2.1}$$

FF is also interpreted graphically from I-V curve of PV modules as shown in Figure 2-2:

$$FF = \frac{P_{MAX}}{P_T} = \frac{I_{MP}.V_{MP}}{I_{SC}.V_{OC}} \tag{2.2}$$
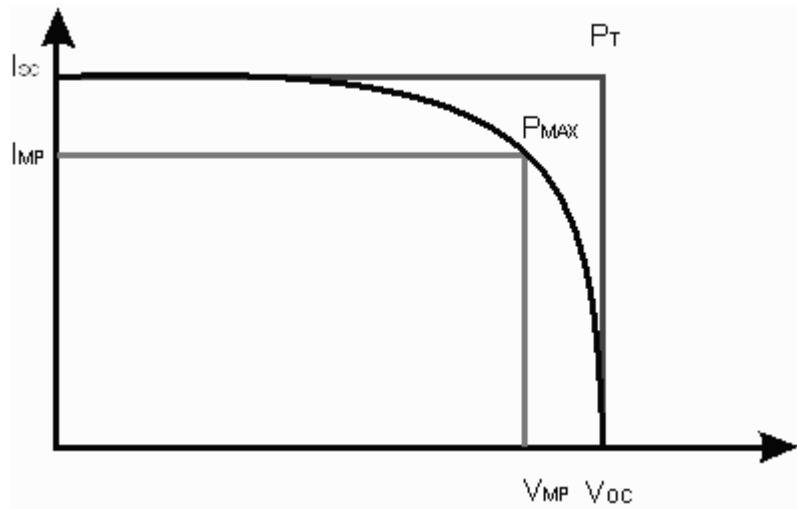
Figure 2-2: Calculating the fill factor (FF) from the I-V curve

Finally the most important figure of merit is efficiency, which is derived by: (Luque and Hegedus 2003)

$$\eta = \frac{FF \times V_{OC} \times I_{SC}}{P_{in}} \qquad (2.3)$$

Where $\eta$ and $P_{in}$ represent the power conversion efficiency and the input power, respectively.

In most applications several cells can be usually connected into a series string to form a module in order to get the desired output voltage (Figure 2-3).
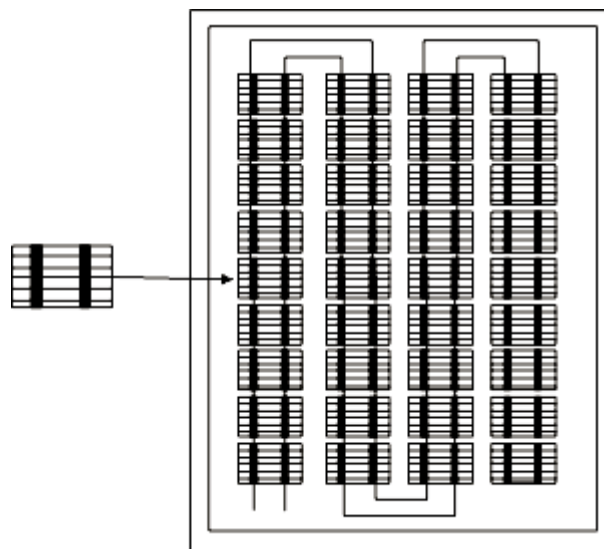


Figure 2-3: PV module

Array is a structure that consists of a number of PV modules connected in parallel to increase the current, or in series to enhance the voltage.

Power of PV array with $N_S$ modules and $N_P$ modules in parallel is calculated as below:(Kalantar and Mousavi G 2010)

$$P_A = N_P . N_S . P_M . \eta_{MPPT} . \eta_{Other}$$

(2.4)

Where $\eta_{MPPT}$ is efficiency of the maximum power point tracking (e.g.93-97%), and $\eta_{Other}$ is the factor that indicates other losses i.e. loss caused by cable resistance, accumulative dust, etc.

The power of photovoltaic is extremely affected by weather conditions such as temperature and solar radiation. Taking into account all these factors the maximum power output of PV module can be calculated by the following equation (Yang, Zhou et al. 2008; Zhou, Yang, et al. 2007) :

$$P_M = FF . I_{sc} . V_{oc} =$$

$$\frac{\frac{V_{OC}}{n_{MPP}\frac{KT}{q}} - Ln\left(\frac{V_{OC}}{n_{MPP}\frac{KT}{q}} + 0.72\right)}{1 + \frac{V_{OC}}{n_{MPP}\frac{KT}{q}}} . \left(1 - \frac{RS}{\frac{V_{OC}}{I_{SC}}}\right) . I_{SCO}\left(\frac{G}{G0}\right)^{\alpha} . \frac{V_{OC0}}{1 + \beta Ln\left(\frac{G_0}{G}\right)} . \left(\frac{T_0}{T}\right)^{\gamma}$$

(2.5)

Where, T is temperature of PV module, K is the Boltzmann constant ($1.38 \times 10^{-23}$J/K), q is the magnitude of the electron charge ($1.6 \times 10^{-9}$ C), G0 and G are standard and normal incident solar irradiance respectively. And $n_{MPP}$ represents the ideality factor of PV module at maximum-power point ($1 < n_{MPP} < 2$) which can be computed (Zhou, Yang, et al. 2007) as given below:

$$n_{MPP} = (V_{MPP} + I_{MPP}R_S)/[V_{OC} + V_t Ln\left(\frac{I_{SC} - I_{MPP}}{I_{SC}}\right)] \qquad (2.6)$$

The α and γ are the exponents responsible for nonlinear effects of photocurrent and temperature-voltage, and β is the coefficient for solar cell technology specific (e.g.0.085) (van Dyk, Meyer et al. 2002). They can be determined by the equations 7 to 9, respectively:

$$\alpha = \frac{Ln\left(\frac{I_{sc}}{I_{sc1}}\right)}{Ln\left(\frac{G_0}{G_1}\right)} \qquad (2.7) \qquad \beta = \frac{\frac{V_{oc0}}{V_{oc1}} - 1}{Ln\left(\frac{G_0}{G_1}\right)} \qquad (2.8) \qquad \text{y} = \frac{Ln\left(\frac{V_{oc0}}{V_{0c1}}\right)}{Ln\left(\frac{T_1}{T_0}\right)} \qquad (2.9)$$

### 2.2.2  Wind turbine technology and Modeling

Wind turbines harness the power of the wind and convert it into electricity energy. Being low-cost, easily available and environmental friendly, it continues to be the fastest growing electricity generator technology in the world (Jafarian and Ranjbar 2010; Kiranoudis, Voros et al. 2001; M. Li and Li 2005). Wind turbines can be classified based on the orientation of the axis of the rotor with respect to the Ground: those whose rotor rotates around a horizontal axis, and those whose rotor shaft rotates around a vertical axis. Horizontal axes wind turbines are more common (Ofualagba and Ubeku 2008) and generally are used for large scale electrical grid-connected power plants (Robert Foster 2009).The vertical axis wind turbine is an eggbeater-shape and often known as Darrieus rotor after its inventor (Ofualagba and Ubeku 2008). Despite a few problems with the vertical-axis, its advantages outweigh disadvantages in several aspects: Unlike horizontal-axis wind turbines (HAWT), they can accept wind from any direction. The speed increaser and generator can be installed at ground level that makes it accessible and it doesn't need over-speed protection. They are applicable in low-wind speed and since they don't require tower, the capital cost for vertical-axis wind turbines (VAWT) is lower (Kanellos and Hatziargyriou 2008; Ross and Altman 2011).

However the problem is that the rotor is closer to the ground and cycling variation of power will happen on each rotor revolution(Eriksson, Bernhoff et al. 2008).

Small wind turbines can provide enough electricity and be cost effective if the following rules are considered: the average of low wind speed month become 3-4m/s, wind tower located away from buildings and trees (Harry L. Wegley 1980) , it is installed not too far away from the load due to more losses and cost of wiring, considering DC having more losses from wind turbine to the load rather than AC(Harry L. Wegley 1980).

### 2.2.2.1   Wind Models and Equations

There are several factors which influence the output power of wind turbine, among them the noteworthy ones are the wind speed distribution and the height of tower, but the wind speed is the prime factor.

### 2.2.2.2   Wind speed distribution

Wind speed distribution determines the performance of wind turbine for specific location by predicting the energy yield from a wind turbine (Kantar and Usta 2008). There are different methods for the predication of wind distribution, namely Weibull,Burr, Gamma,Erlang and Inverse Gamma (Carta, Ramírez et al. 2009). Among them, Weibull distribution function is the most acceptable method, due to its flexibility and simplicity (Carta and Mentado 2007; Islam, Saidur et al. 2011; Jangamshetti and Ran 2001; Manwell, McGowan et al. 2009; Seguro and Lambert 2000).

### 2.2.2.3   Height of tower

Since the wind speed varies with height, the measured wind speed at anemometer height must be converted to desired hub heights. There are many researches on analyzing the variation of wind speed with height, which are discussed in

ref (Bañuelos-Ruedas, Angeles-Camacho et al. 2010; Manwell, McGowan et al. 2010; S. Rehman and Al-Abbadi 2007); however the most commonly used methods are Hellmann exponential law (power law) and the logarithmic profile which are acceptable and more accurate methods in estimating wind shear (Archer 2003).

The power law equation is calculated by the following correlation (C.G 1978; Elliott, Holladay et al. 1986):

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad (2.10)$$

In which $v_2$ is the speed at the hub height ($h_2$) and $v_0$ is the speed at the reference height ($h_1$), and α is the friction coefficient, Hellmann exponent, Wind Gradient, or power-law exponent. Since α has a direct effect on energy production and plant capacity factor of the site, it should be chosen carefully (S. Rehman and Al-Abbadi 2007). α is a function of parameters such as wind speed, roughness of terrain, the height above ground, temperature, hour of the day and time of the year (Farrugia 2003; Jaramillo and Borja 2004; S. Rehman and Al-Abbadi 2007); however the most common way of defining α is based on different types of terrains which can be found in literature (Bañuelos-Ruedas, Angeles-Camacho, et al. 2010; Bechrakis and Sparis 2000; Patel 1999).

Logarithmic profile equation is another widely used method to calculate the wind shear at the desired height: (Bañuelos-Ruedas, Angeles-Camacho, et al. 2010)

$$\frac{v_2}{v_1} = \frac{\ln\left(h_2/h_0\right)}{\ln\left(h_1/h_0\right)} \qquad (2.11)$$

In which $h_0$ is roughness index of the region in meter and characterizes the roughness of the surrounding terrain. Value of $h_0$ ranging based on land type, spacing

and height of the roughness factor from 0.0002m in water surface to 1.6m for a large city with high sky scrapers (Manwell, McGowan, et al. 2010).

**2.2.2.4 Wind power**

There are many researches on determining power output of the wind turbines. However the accuracy of each one depends on the wind turbine characteristics, wind speed of the region and wind turbine application.

Table 2-1 shows some of the methods for mathematical modeling of wind turbines performance given in literatures, and the merits and demerits of each method.

Table 2-1: methods for mathematical modeling of wind turbine (Thapar, Agnihotri, et al. 2011)

| Wind turbine modelling | | Characteristics | | Modelling concept |
|---|---|---|---|---|
| Base on fundamental correlations of the available power in the wind | | -Depends on many parameters.<br>-not suitable for hourly output power generation. | | Based on eq.(2.12) |
| Based on power curve of wind turbine | Presume power curve | -Simple to use.<br>-Not very accurate.<br>-Appropriate for high annual average wind speeds. | | Based on linear power curve. |
| | | | | Based on cubic law. |
| | | | | Based on Weibuii's parameters. |
| | Manufacturer's actual output power curve | Accurate | For smooth and not so smooth power curve | Based on least squares method. |
| | | | For smooth power curve | Based on Cubic spline interpolation method. |

Performance of wind turbine can be estimated by two different techniques (Thapar, Agnihotri, et al. 2011), first method is wind energy captured by the rotor which is based on fundamental correlations which determine the available power in the wind and calculated by the following equation: (Eriksson, Bernhoff, et al. 2008;

Kanellos and Hatziargyriou 2008; Ofualagba and Ubeku 2008; Robert Foster 2009;

Ross and Altman 2011)

$$P_r = \frac{1}{2} \cdot \rho \cdot A v^3$$

(2.12)

Where, P is the mechanical power(watt), $v$ is the upstream wind speed at the

entrance of the rotor blades (m/s), A is area swept by the rotor blades (m$^2$), and $\rho$ is air

density (kg/m$^3$) which is a function of temperature, altitude, and humidity level with the

least effect (Patel 1999). The mechanical power is then transferred to electrical power

which is given by (Thapar, Agnihotri, et al. 2011):

$$P_e = (C_p \eta_m \eta_g) P_r$$

(2.13)

The term in the bracket represents the overall efficiency of wind turbine (WT);

where $\eta_m$ is mechanical transmission efficiency (like the gearbox, which converts the

slow, high-torque rotation of the turbine to higher rotational speeds on the electrical

generator side), $\eta_g$ is electrical generator efficiency, and $C_P$ is the power coefficient

which represents the aero dynamic efficiency of the wind turbine. The maximum $C_P$ is

governed by Betz limit. It states that the maximum value of $C_P$ which can be achieved

for all types of wind turbine cannot exceed 59%. Nevertheless, in the practical designs,

it achieves the value between 0.4 to 0.5 for two-blade, high-speed wind turbines; and

0.2 for slow-speed wind turbines with more blades (Patel 1999).

Another method for estimation of wind turbine performance is based on the

power curve (Thapar, Agnihotri, et al. 2011). Figure 2-4 indicates power curve for a

typical wind turbine.
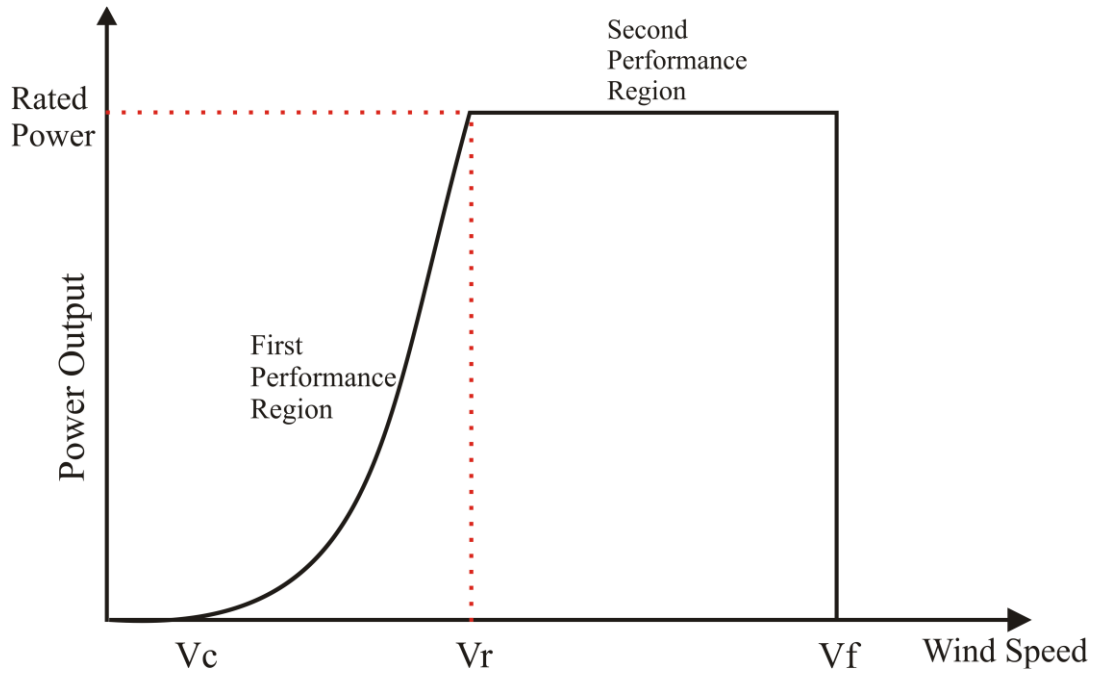
Figure 2-4: Power curve for typical wind turbine

Power output of wind turbine is approximated by different equations as given below (Yang, Wei et al. 2009):

$$
\begin{cases}
0 & V< V_{\text{cut-in}} , V > V_{\text{cut-off}} \\[2mm]
P_{\text{wg-max}} \times ((V\text{-}V_{\text{cut-in}})/(V_{\text{rated}}\text{-}V_{\text{cut-in}}))^3 & V_{\text{cut-in}} \leq V < V_{\text{rated}} \qquad (2.14) \\[2mm]
P_{\text{wg-max}} \times \dfrac{P_{\text{furl}} - P_{\text{rated}}}{V_{\text{cut-off}} - V_{\text{rated}}} (V\text{-}V_{\text{rated}}) & V_{\text{rated}} \leq V \leq V_{\text{cut-off}}
\end{cases}
$$

For small-scale wind turbines, the $V_{\text{cut-in}}$ is rather smaller than for large-scale ones, thus even when wind speed is not very high, the wind turbines can operate efficiently.

Based on the output power, wind turbines can be divided into three categories as follows: large (>1MW), medium (40KW-1MW), small (<40KW) (Spera 1994). Generally, large turbines are connected to the grid, while small turbines are applicable for villages and rural areas (Lanzafame and Messina 2010).

The overall efficiency of the wind turbine is calculated by the following equation (Ibrahim 2009):

$$E = E_r \times E_g \times E_t$$

(2.15)

Where, E is the overall efficiency, $E_r$ is the efficiency of the rotor and $E_t$ is the transmission efficiency.

## 2.3 Battery technology and modeling

The battery storage is usually used as a backup for the hybrid stand-alone systems to increase its availability, and provide load leveling for short-term fluctuations. As given in the literature, there are various methods for storing the renewable energy. A study on using super capacitor is conducted by Samson, G.T., et al. (Samson, Undeland et al. 2009). The results show that battery life time increased by relieving the battery of narrow and repeated transient charging and discharging. Ref. (Díaz-González, Sumper et al. 2012) reviews the different methods for wind energy storage, and Ref. (Rahman, Rehman et al. 2012) is an overview of renewable energy storage in Saudi Arabia. However, to date Lead-acid batteries have been the most commonly used energy storage units in hybrid systems by delivering electricity in range of 5 V to 24 V DC ("Battery modelling for HEV simulation, Thermo Analytics, etc." 1999; Jantharamin and Zhang 2008). They are of low cost, readily available, and highly efficient. Capacity of lead-acid batteries is ranging from 10Ah up to 1000Ah. There are some limitations in using lead-acid batteries as they are subject to frequent maintenance and sensitivity to harsh temperatures (Wang 2011).

Modeling of the batteries is a key issue of hybrid power system, due to the life cycle cost of the batteries as one of the major expenses for the systems (Henrik Bindner). Defining a general model for the battery, which covers all the factors, is quite difficult. Accordingly, depending on the application of the model, different approaches

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have been applied. Modeling of the batteries is classified into three categories i.e. Chemical Model, Electrical Models, charge accumulation and empirical models (Zhou, Lou et al. 2010). Most of modeling focus on three different characteristics: performance or a charge model, voltage model, and the lifetime model (Henrik Bindner).

The battery characteristics which play a significant role in designing a hybrid renewable system are as follows: battery capacity, battery voltage, battery state of charge (Piller, Perrin et al. 2001), depth of discharge, life-time of battery (Wenzl, Baring-Gould et al. 2005), and charging regime as well as the cost analysis of the battery.

Cycle life of the battery is defined as the number of charging and discharging that a battery can undergo before it reaches the end of its lifetime. The battery's float life is affected by the ambient temperature and normally every 10°C rise in average ambient temperature halves the battery's life time (Dall, Lenzen et al. 2010). The energy capacity (Wh) of a battery is defined by the energy that a fully charged battery can deliver under the specified conditions.

Depth of discharge (DOD) is the ampere-hours removed from a fully charged battery. It is defined by the percentage ratio of the battery rated capacity to the applicable discharge rate (A). Battery bank is used as a backup system and it is sized to meet the load demand when the renewable energy resources failed to satisfy the load; the number of days a fully charged battery can feed the load without any contribution of auxiliary power sources is represented by days of autonomy, and is taken to be 2 or 3 days.

The capacity of battery bank is estimated by the following equation (Deshmukh and Deshmukh 2008):

$$C_B = \frac{E_L . S_D}{V_B . DOD_{max} . T_{cf} . \eta_B} \qquad (2.16)$$

Where, $E_L$ represents the load demand in Wh; $S_D$ is days of autonomy; $V_B$ is the operating voltage of the battery; $DOD_{max}$ is the maximum depth of discharge; $T_{cf}$ is the temperature correction factor and $\eta_B$ is the charging/discharging efficiency (Chaurey and Kandpal 2010).

One of the most important points in control and management of hybrid systems is the knowledge of state of charge (SOC) of the battery in each step. Deep discharge or overcharge can lead to irreversible damage in the battery and this involves major expenses of the system (Piller, Perrin, et al. 2001).

There are different methods to estimate the SOC of the battery for different applications which are discussed in ref. (Shuo, Farrell et al. 2001). However, it can be defined as the ratio of the available capacity to the rated capacity in AHr and is defined by the following equation (Deepti and Ramanarayanan 2006):

$$SOC = \frac{Available\ Capacity (AHr)}{Rated\ Capacity (AHr)} \times 100 \qquad (2.17)$$

Hybrid system optimizations are usually done using the iteration techniques which need the SOC in every moment during the specific period or for a specific load profile, consequently it can be calculated using:

$$SOC(t) = SOC(t-1).(1-\sigma) + \left[ E_{Gen}(t) - \frac{E_L(t)}{\eta_{inv}} \right] . \eta_B \qquad (2.18)$$

And

$$SOC(t) = SOC(t-1).(1-\sigma) + \left[ \frac{E_L(t)}{\eta_{inv}} - E_{Gen}(t) \right] \qquad (2.19)$$

Where, $\sigma$ is hourly self-discharge rate, $E_L$ is load demand, and $E_{GEN}$ is the generated energy by hybrid system, considering the energy loss in controller. Eq.(2.18) is used when the battery is charging and Eq.(2.19) is applied for battery discharge

regime. From the equation it can be seen that the SOC in each moment is related to the previous step (Ajai Gupta, Saini et al. 2011). However, in each moment the state of charge should not exceed 1 or become less than $SOC_{min}$ which is determined by following equation:

$$SOC_{min} = 1 - Depth\ of\ discharge \qquad (2.20)$$

The battery's lifetime can be prolonged to the maximum if depth of discharge takes the value of 30-50%. The higher is depth of discharge; the lower is the battery life cycle.

## 2.4 Diesel generator

For remote communities and rural industries the standard power supplies are provided through diesel generators. They are used as a secondary energy source during the peak demand, or in the case of battery depletion. Diesel generators have low capital cost; nevertheless, they are expensive to operate and maintain, and provide electricity only for a few hours a day. Therefore, there are two aspects using renewable energy with diesel generators: adding renewable energies (REs) to existing diesel power plants as a fuel saver, or integrated diesel generator to hybrid systems for village power.

Avoiding unloaded or even lightly loaded operation for the diesel generator is one of the considerations that should be taken into account (Said H 1998). In addition it is recommended that the diesel generator operates until the battery bank reaches roughly about 90% of SOC in order to avoid excessive operation, and improves the service life and fuel consumption (Coleman 1989). It is to be noted that Optimum operation range for a diesel generator is between 70% and 89% of its rated power (Said H 1998).

Efficiency and hourly fuel consumption are the characteristics of a diesel generator which should be considered in designing a hybrid system and can be expressed by (Ashari and Nayar 1999; Skarstein and Uhlen 1989):

$$q(t) = a.P(t) + b.P_r \qquad (2.21)$$

Where, (t) is fuel consumption (lit/h), P (t) is generated power (kw), $P_r$ is rated power, a and b are constant numbers (lit/kw) which represent the coefficients of fuel consumption and they can be approximated to 0.246 and 0.08415, respectively (Azoumah, Yamegueu et al. 2011).

The efficiency of a diesel generator is calculated by: (Deshmukh and Deshmukh 2008)

$$\eta_{overall} = \eta_{brake\ thermal} \times \eta_{generator} \qquad (2.22)$$

Where, $\eta_{overall}$ and $\eta_{brake\ thermal}$ represent the overall efficiency and the brake thermal efficiency of diesel generator, respectively.

## 2.5 DC/AC Converter (Inverter)

Inverters convert electrical energy of DC form into AC with the desired frequency of the load. The efficiency of the inverter can be defined by the following equation:

$$\eta_{inv} = \frac{P}{P + P_0 + kP^2} \qquad (2.23)$$

In which, P, $P_0$ and $k$ can be determined by using the following equations: (Darras, Sailler et al. 2010; Diaf, Diaf et al. 2007; Schimd J 1991; Schmid 1988)

$$P_0 = 1 - 99\left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9\right)^2 \qquad (2.24)$$

$$k = \frac{1}{\eta_{100}} - P_0 - 1 \qquad (2.25)$$

$$P = P_{out}/P_n \qquad (2.26)$$

$\eta_{10}$ and $\eta_{100}$ are provided by the manufacturers and present the efficiency of the inverter at 10% and 100% of its nominal power. The efficiency of inverter is roughly

assumed to be constant over the whole of the working range (e.g. 90%) (Kashefi Kaviani, Riahy et al. 2009).

## 2.6 Criteria for optimization of hybrid renewable energy systems

### 2.6.1 Economic criteria of hybrid renewable energy systems

For a designed hybrid system the economics evaluation is one of the key factors to ensure the optimum configuration and acceptable economic benefits have been resulted. There are some indicators which are commonly used in literatures i.e. net present cost (NPC), cost of energy (COE), and break-even distance (BED). A brief description of these indicators for economic analysis of hybrid system is shown in the forthcoming subsections.

### 2.6.2 Net present cost (NPC)

The net present cost/value analysis of a project reveals economic profitability of that, considering all significant cost over its life cycle; adding capital, replacement, operating and maintenance (O&M), and fuel cost of each component for every year and discounting them back to a common base which is present worth of the project. It can be calculated by subtracting present worth of benefit from present worth of cost according to the following equation (Mohammadi, Hosseinian et al. 2012):

$$
\begin{aligned}
NPC = {}& initial\ investment\ cost(state\ subsidy - 1) \\
& - recurring\ cost(e.g.O\&M\ cost) \\
& - non_{recurring}cost(e.g.replacement\ cost) + residual\ value
\end{aligned}
$$

(2.27)

### 2.6.3 Cost of Electricity (COE)

Cost of electricity (COE) is one of the most well-known and used indicators of economic profitability of HRES (Kaabeche, Belhamel et al. 2011). It is defined as the

constant price per unit of energy (or cost per unit of electricity). It can be calculated by either of two of the following expressions (Dispenzieri, Kumar et al. 2010; Kaabeche, Belhamel, et al. 2011; Luna-Rubio, Trejo-Perea et al. 2012)

$$COE\left(\frac{\$}{kWh}\right) = \frac{Annualized\ cost(\$)}{annual\ electrical\ energy\ delivered\ by\ the\ system(kWh)}$$

$$= \frac{Total\ Net\ Present\ cost(\$)}{P_{load}(Kw)(8760\frac{h}{year})} \times CRF$$

(2.28)

Total net present cost includes all installed capital cost i.e. the present cost, operation and maintenance cost, and replacement cost. $P_{load}$ is the total energy generated by the HRES during the system life period. Capital recovery factor (CRF) is a ratio to calculate the present value of system components for a given time period, taking into consideration the interest rate. It is calculated by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

(2.29)

Where, i is the interest rate and n is the system life period (or Amortization period), which is usually equal to the life of the PV panel, due to its longer life expectancy compared to other components in HRES (Dufo-López and Bernal-Agustín 2008).

### 2.6.3.1 COE for fuel-burning systems

Reference (Ramakumar 1983) suggested a method for calculating conventional fuel-burning systems (like biomass) by using equation (2.30):

$$C(\frac{\$}{kWh}) = [CRF + m]\frac{P(\frac{\$}{kW})}{87.6k} + 36(\frac{C_f(\frac{\$}{million\ Btu})}{\eta_{0(\%)}})$$

(2.30)

In which, C is generation cost, P is capital cost, $\eta_0$ is the overall efficiency in percentage, $C_f$ is conventional fuel cost, and m is defined as a fraction of the capital cost

per year for operation and maintenance. Notice that for 24 kg of biomass, approximately 1kWH energy is produced.

### 2.6.3.2 COE for diesel generator

The operation cost of diesel generator depends on several factors of fuel consumption, maintenance cost, the operation hours and the demand, The eq. (2.31) shows cost per unit of diesel generator (Ashari and Nayar 1999; Ashari, Nayar et al. 2001):

$$CDF(\frac{\$}{kWh}) = \left(0.246 + 0.08415 \times \frac{P_R(kW)}{P_{OPR}(kW)}\right) C_f(\$) \tag{2.31}$$

Where, $P_R$ is rated power at full load, $P_{OPR}$ is operation power, $C_f$ is fuel price, and 0.246 and 0.08415 represent fuel consumption at no load and incremental diesel fuel consumption rate, respectively.

## 2.7 Technical criteria of hybrid renewable energy systems

### 2.7.1 Reliability

Due to intermittent solar radiation and wind speed characteristics influencing the energy production, energy system reliability analysis should be taken into consideration. Reliability is a function to evaluate the technical criteria of the hybrid system. A reliable system has been defined as a system that can feed the load demand without failure during a certain period. According to ref (Kashefi Kaviani, Riahy, et al. 2009), reliability of hybrid system directly depends of on the reliability of components. Moreover, it is found that the inverter's reliability is an upper limit for the entire system.

There are different reliability evaluation methods i.e. loss of energy expected, loss of power supply probability, equivalent loss factor, and loss of load expected (J. Kaldellis, Zafirakis et al.). However the most common is loss of power supply probability (LPSP), or deficiency of power supply probability (DPSP) in which a

reliable system is defined as a system that can feed sufficient power to the load demand during a certain period without load rejection.

LPSP is a statistical parameter which indicates the probability of power supply failure due to either losing power supply in a bad resource year or technical failure to meet demand. There are two methods of calculating LPSP i.e. chronological simulation and probabilistic techniques. The former technique is using time-series data in a given period (equation (2.32)) and the latter is based on energy accumulation effect of the energy storage system (equation (2.33)). They can be described by either of the following equations (Luna-Rubio, Trejo-Perea, et al. 2012; Rajkumar, Ramachandaramurthy et al. 2011):

$$LPSP = \frac{\sum_{t=0}^{T} Time(P_{available}(t) < P_{needed}(t))}{T} \qquad (2.32)$$

$$LPSP = \frac{\sum(P_{load} - P_{pv} - P_{wind} + P_{soc_{min}})}{\sum P_{load}} \qquad (2.33)$$

## 2.8    Design of hybrid systems

Hybrid systems open an opportunity to use the advantages of renewable resources in combination with conventional power resources. Reviewing the studies shows a significant development on design, analysis and implementation of such systems over the last decade. Based on the reviewed papers, a typical stand-alone HRES includes photovoltaic, Wind, Fuel-Cell, battery, Diesel, and systems controllers. According to the potential of renewable resources and the purpose of using hybrid system in the area of study, different configurations are represented (Table 2-2).

Table 2-2: Conbination of hybrid systems

| stand-alone hybrid systems | Reference |
| --- | --- |
| Wind-Battery | (Roy, Kedare et al. 2009) |
| Wind- Fuel Cell | (M.T 2003) |
| Wind -Micro turbine | (Colson, Wang et al. 2007) |
| PV -Diesel-Battery | (Mondal and Denich 2010; Shaahid and Elhadidy 2003) |
| PV-Fuel Cell | (Hwang, Lai et al. 2009) |
| PV-Wind- Diesel | (McGowan and Manwell) |
| PV- Wind- Fuel Cell | (Kashefi Kaviani, Riahy, et al. 2009) |
| PV-Fuel Cell-Electrolyze | (El-Shatter, Eskandar et al. 2002) |
| PV- Fuel Cell -Super Capacitor Bank | (Zandi, Payman et al. 2011) |
| PV- Fuel Cell -Electrolyze-Battery | (Ulleberg and Mørner) |
| PV- Wind- Fuel Cell -Electrolyze-Battery | (Dufo-López and Bernal-Agustín 2008) |
| PV- Wind-Micro Turbine- Battery | (Kalantar and Mousavi G 2010) |
| PV- Wind- Fuel Cell - Electrolyzer- Battery | (Caisheng and Nehrir 2008) |

There are three ways to integrate different alternative energy sources to form a hybrid System which can be named as AC, DC, and AC/DC bus line coupling. Each method has its own advantages and disadvantages. DC coupling can be used for long distance transmission due to less transmission losses and single-wire connection. However, AC coupling is more economic with standard interfacing and modular structure. In AC/DC bus line, both sides can be used to feed the load demand.

Although combination of photovoltaic and battery bank is known as the fundamental of the majority of designed hybrid systems, in some studies wind energy is used as a major source of generating electricity, for instance ref (Roy, Kedare, et al. 2009) represents a combination of wind-battery system by using design-space approach. The system includes DC and AC buses to feed the load. Ref (Colson, Wang, et al. 2007) studied the modeling, control and power managment of hybrid system using wind turbine and micro turbine , which is shown- in Figure 2-5.
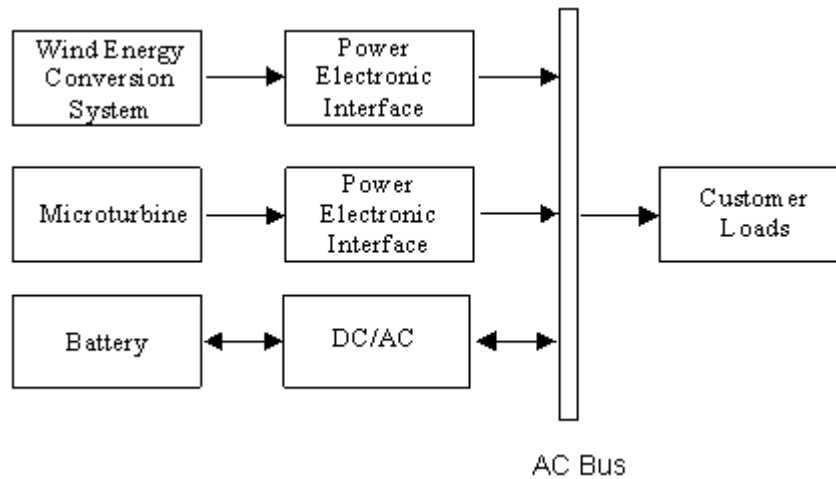
Figure 2-5. Block diagram of hybrid Wind -Micro turbine system (Colson, Wang, et al. 2007)

Another study was conducted by Iqbal (M.T 2003) to determine controllability and expected transients in wind-fuel cell hybrid energy system. Most developers of HRESs prefer to build it in a simple way with a few basic components as possible. Nevertheless, a complex configuration represemted by ref (Kalantar and Mousavi G 2010) to study the dynamic behavior and simulation of wind-pv-micro turbine-battery hybrid system as well as economic evaluation of the proposed system which is Illustrated schematically in Figure 2-6.
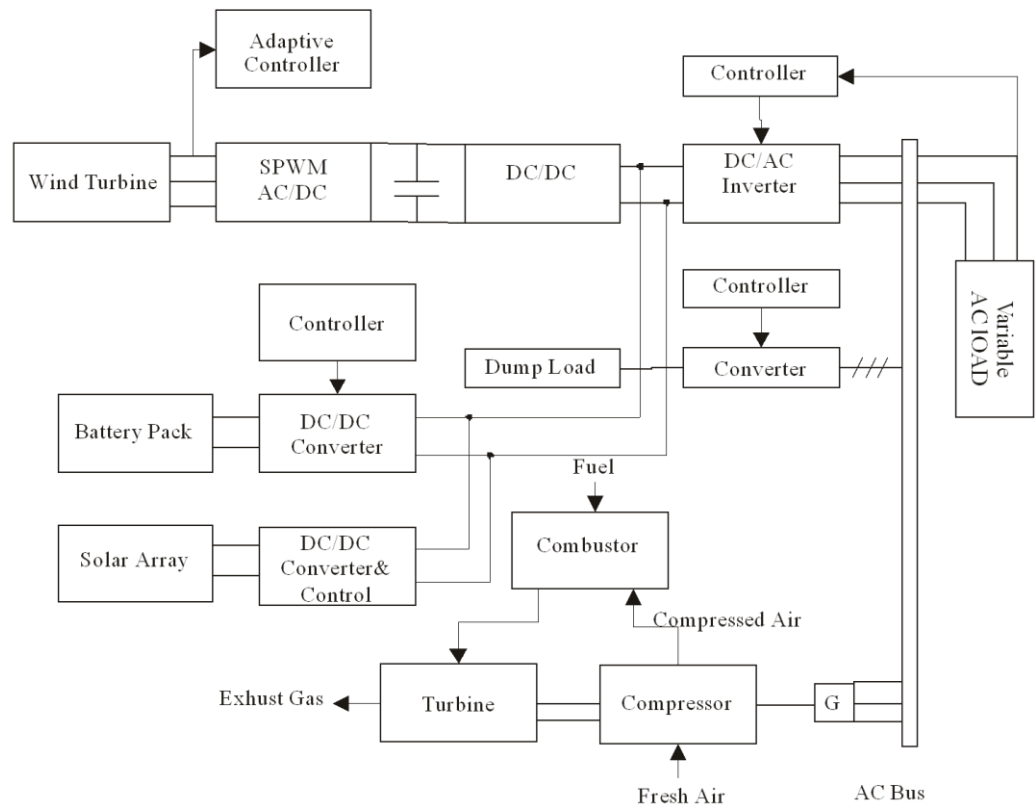
Figure 2-6: Pv-micro turbine-battery hybrid system schematic (Kalantar and

Mousavi G  2010)

Another study conducted by ref (Caisheng and Nehrir  2008) on hybrid wind-photovoltaic- Fuel cell- electrolyzer- battery is illustrated in Figure 2-8. In this study power management and control strategies of system under different scenarios are investigated by using the real time-series data and load profile in Pacific Northwest regions.

Ref (Kashefi Kaviani, Riahy, et al.  2009) proposed a hybrid wind/photovoltaic/fuel cell generation system with hydrogen tank as an energy storage system (Figure 2-7), to minimize the annual cost of the hybrid system by using Particle Swarm Optimization algorithm. It is found that, the cost of the system, directly, depends on its reliability.
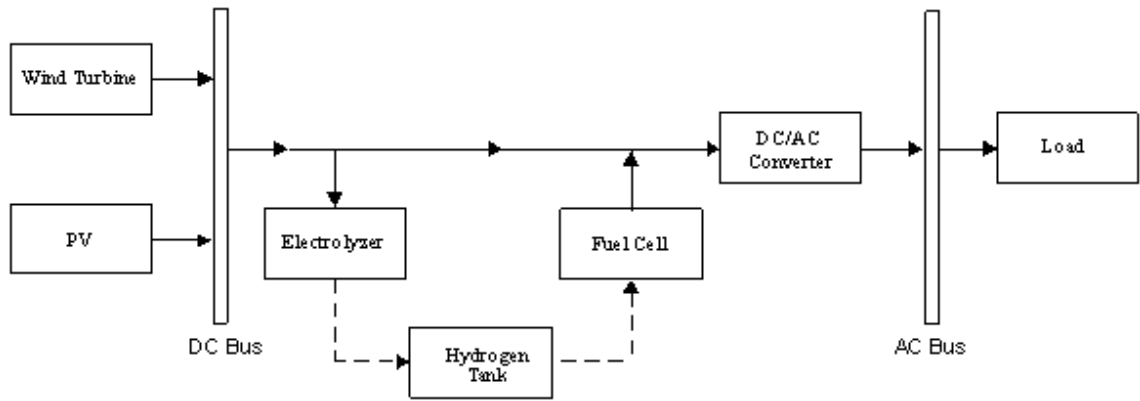
Figure 2-7: Block diagram of a hybrid wind/photovoltaic generation unit.

The aforementioned studies are mostly considered the simulation, power management, economic and efficiency evaluation based on the implemented system. However, the following section investigates the studies on sizing optimization and techno-economic evaluation in order to design an optimum hybrid system.
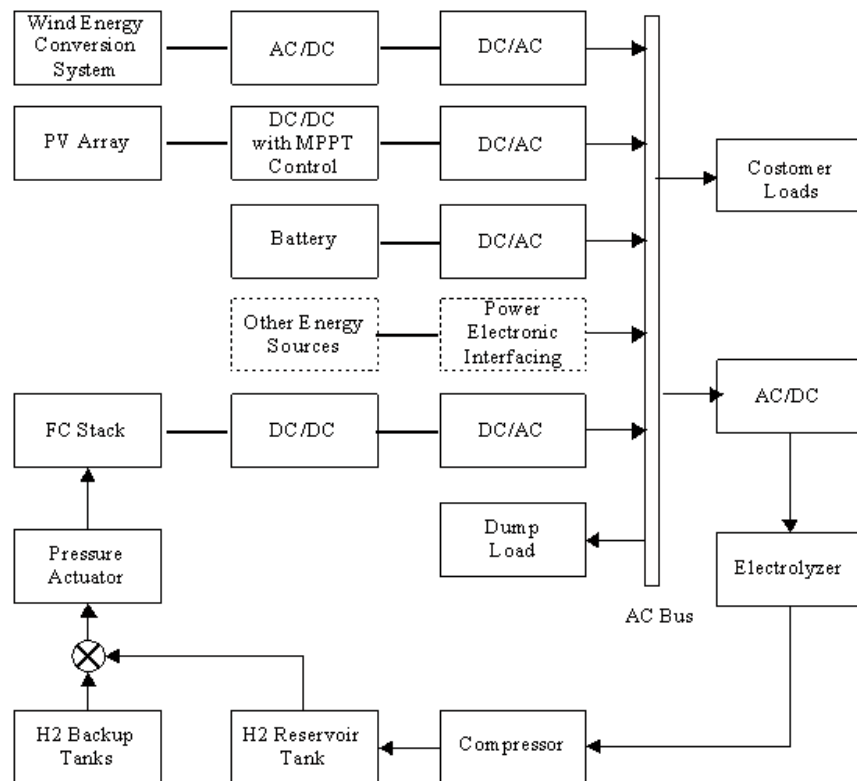


Figure 2-8: System configuration of multisource alternative hybrid energy system (Caisheng and Nehrir 2008).

## 2.9    Sizing and optimization methods

Optimization of hybrid renewable energy systems investigates the process of selecting the best configuration of components and their sizing, considering efficiency, reliability, and cost-effectiveness of the system by applying appropriate evaluating strategy.

Due to the stochastic availability of renewable energies, design and optimizing a reliable system from both technical and economic point of view is always required. The mathematical and computational methods are applied in this regard. However computational methods have been used more in recent years (Baños, Manzano-Agugliaro et al. 2011).

Table 2-3 represents the reviewed studies in sizing optimization of stand-alone systems from 2002 to 2012. It can be seen that software tools are commonly used for techno-economic analysis of stand-alone hybrid systems. HOMER is one of the main simulation programs for economic assessment of the designed hybrid system considering different constraints. Computational analysis is also widely used for optimization of stand-alone HRESs. HOMER is the most commonly used tool, and multi-objective evolutionary algorithms for optimization of stand-alone hybrid wind-solar renewable energy systems is described briefly in the next subsection.

Table 2-3: Classification of sizing optimization of stand-alone systems

| Year Of Publication | Method | Hybrid Resources | Storage and Support system | Case Study | Reference Number |
|---|---|---|---|---|---|
| 2012 | Genetic algorithm | Photovoltaic | Batteries Fuel-Cell | Iran | (Mohammadi, Hosseinian, et al. 2012) |
| 2012 | HOMER | Photovoltaic Wind | Diesel | Saudi Arabia | (Shafiqur Rehman, Mahbub Alam et al. 2012) |
| 2012 | mathematical | Photovoltaic Wind | Fuel-Cell Diesel | Greece | (Panapakidis, Sarafianos et al. 2012) |
| 2012 | MATLAB /Simulink | Photovoltaic Wind | Batteries Fuel-Cell | Turkey | (Dursun and Kilic 2012) |
| 2012 | MATLAB/Fuzzy logic toolkit GenOpt TRNSYS | Photovoltaic Wind | Battery Fuel-Cell | Greece | (Kyriakarakos, Dounis et al. 2012) |
| 2012 | MATLAB/Simscape | Photovoltaic Wind | Battery Fuel-Cell | Turkey | (Dursun, Acarkan et al. 2012) |
| 2012 | RSHAP | Photovoltaic | Battery Fuel-Cell | Australia&USA | (Andrews and Shabani 2012) |
| 2012 | simulation algorithm | Photovoltaic Wind | Battery | Greece | (J. K. Kaldellis, Zafirakis et al. 2012) |
| 2012 | simulation algorithm | Photovoltaic Wind | Battery Diesel | Palestine | (Bernal-Agustín, Dufo-López et al. 2006) |
| 2012 | simulation algorithm | Photovoltaic Wind | Battery Diesel | Sri Lanka | (Perera, Wickremasinghe et al. 2012) |
| 2012 | simulation algorithm | Photovoltaic | Battery | Tunisia | (Wissem, Gueorgui et al. 2012) |
| 2011 | HOMER | Photovoltaic Wind | Battery Diesel | Algeria | (Saheb-Koussa, Koussa et al. 2011) |
| 2011 | HOMER | Photovoltaic | Battery Diesel Fuel-Cell | Greece | (Karakoulidis, Mavridis et al. 2011) |
| 2011 | HOMER | Photovoltaic Wind | Battery Diesel | Malaysia | (W.X 2009) |
| 2011 | HOMER | Wind | Battery Diesel | Australia | (Hessami, Campbell et al. 2011) |
| 2011 | mathematical | Photovoltaic | Battery Diesel | Malaysia | (Khatib, Mohamed et al. 2011) |
| 2011 | Pscad/Emtdc HOGA Homer Anfis | Photovoltaic Wind | Battery | Malaysia | (Rajkumar, Ramachandaramurthy, et al. 2011) |
| 2011 | simulation algorithm | Photovoltaic Wind | Battery | Algeria | (Kaabeche, Belhamel, et al. 2011) |
| 2010 | HOMER | Photovoltaic Wind | Battery Diesel | Bangladesh | (Kumar Nandi and Ranjan Ghosh 2010) |
| 2010 | HOMER | Photovoltaic | Battery | India | (Chaurey and Kandpal 2010) |
| 2010 | ORIENTE | Photovoltaic | Fuel-Cell | France | (Darras, Sailler, et al. 2010) |
| 2009 | HOGA | Photovoltaic | Battery Diesel | Bangladesh | (Bala and Siddique 2009) |
| 2009 | HOMER | Photovoltaic | Battery Diesel | Saudi Arabia | (Shaahid and El-Amin 2009) |
| 2009 | HOMER | Wind | Diesel | Oman | (Al-Badi and Bourdoucen 2009) |
| 2008 | mathematical | Photovoltaic Wind | Battery | Corsica Island | (Diaf, Notton et al. 2008) |
| 2008 | MATLAB /Simulink | Photovoltaic | Battery Fuel-Cell | Morocco | (Lagorse, Simões et al. 2008) |
| 2006 | Genetic algorithm | Photovoltaic Wind | Battery AC generator Fuel-Cell | spain | (Dufo-López, Bernal-Agustín et al. 2007) |
| 2005 | HOGA | Photovoltaic | Battery Diesel | Spain | (Dufo-López and Bernal-Agustín 2005) |
| 2005 | Specially Developed Software | Wind | Fuel-Cell | Greece | (Ntziachristos, Kouridis et al. 2005) |
| 2004 | computer-aided method | Photovoltaic | Battery Diesel | Palestine | (Mahmoud and Ibrik 2006) |
| 2002 | HOMER | Photovoltaic Wind | Batteries | UK | (A.N 2002) |

### 2.9.1 Software for optimization

Since the performance of renewable sources such as wind and solar are varied in different hours of a day as well as different seasons of an year, providing sustainable energy supply for users, requires energy management study. In this respect, software tools are broadly used for simulating, optimizing and sizing HRESs (A. Gupta, Saini, et al. 2008; Zhou, Lou, et al. 2010). The utilized software tools has been named as: HOMER (HOMER), HYBRID2, HYBRIDS (Zhou, Lou, et al. 2010), HOGA (Bala and Siddique 2009), PVSYST, SOMES, RAPSIM (McCruddin 1998), SOLSIM ("SolSim and hybrid designer: self-optimizing software tools for simulation of solar hybrid applications" 1998), INSEL (S. Islam 2002), PV-DESIGN PRO, RSHAP (Andrews and Shabani 2012), ORIENTE (Darras, Sailler, et al. 2010). However HOMER (hybrid optimization model for electric renewables) is so far the most common tools for cost analysis, sensitivity analysis, and validation testes of HRESs. It is produced by the National Renewable Energy Laboratory, US (Zhou, Lou, et al. 2010). Figure 2-9 presents the architecture of HOMER software. The operation of the HOMER software is simple and straightforward. Economic assessment is based on Net Present Cost, and since it is using the annual real interest rate, the impact of inflation has been factored out of the analysis (Zhou, Lou, et al. 2010).
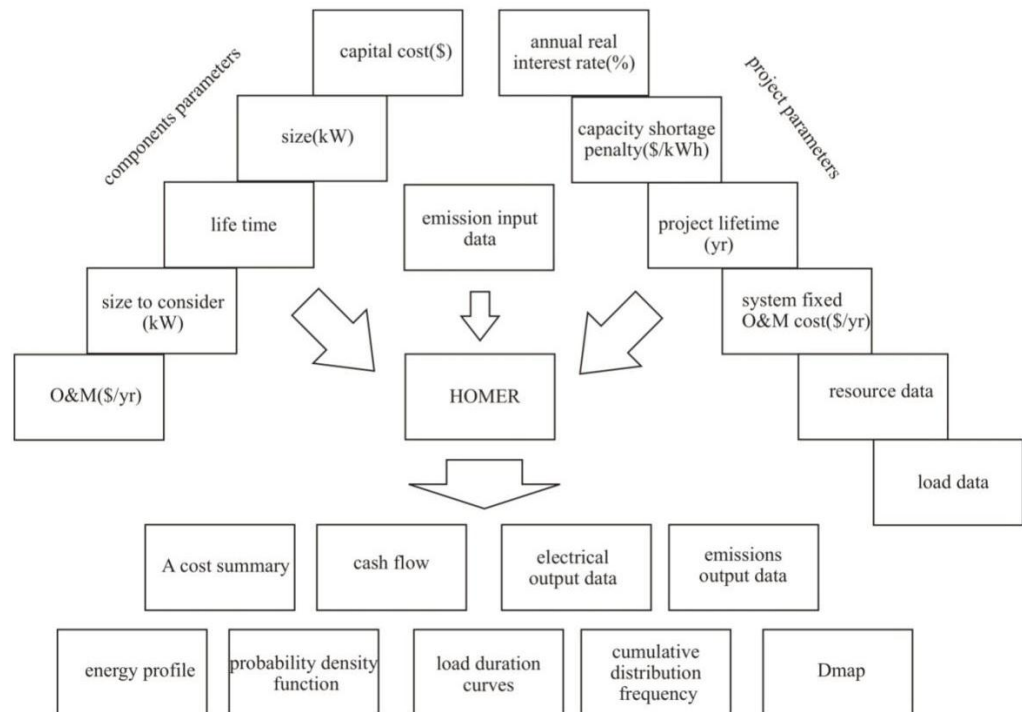
Figure 2-9: Architecture of HOMER software (Mellit and Kalogirou 2008).

### 2.9.2 Computational optimization

The computational optimization methods have been developed significantly in recent years. They can effectively increase the efficiency of hybrid systems by finding the best configuration to optimize the technical and economic criteria as mentioned before. Figure 2-10 illustrates the block diagram of computational optimization methods.
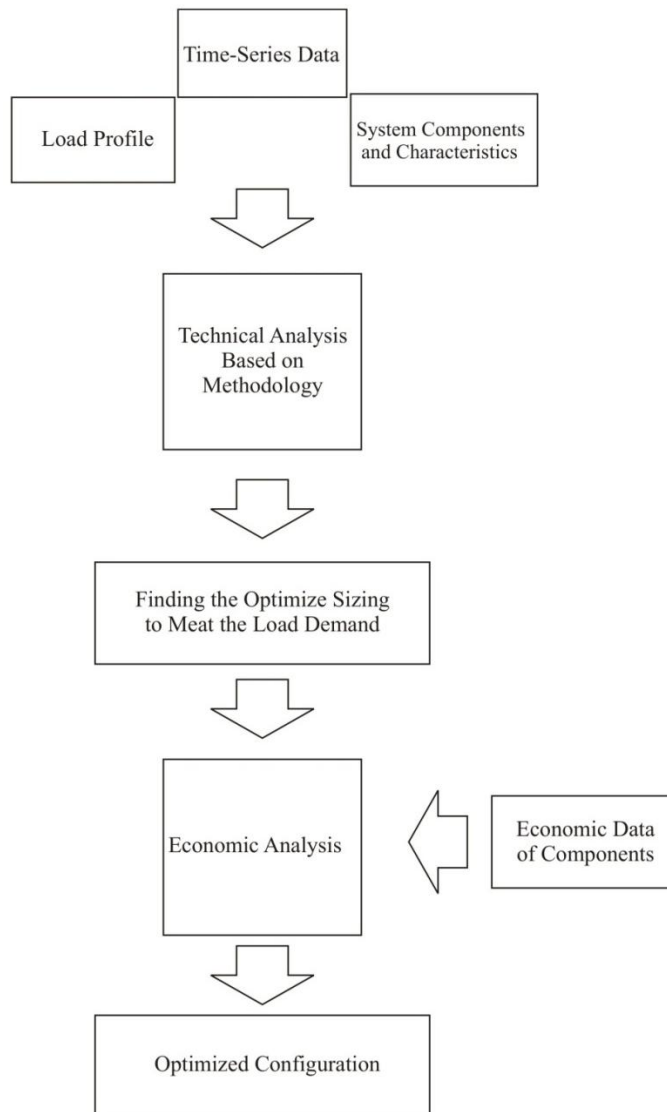
Figure 2-10: Optimization of hybrid systems.

Reference (Erdinc and Uzunoglu 2012) reviewed over two hundred papers on latest computational optimization methods for stand-alone hybrid systems, and categorized them according to the Table 2-4.

Table 2-4: Sizing methodologies

- Genetic algorithm
- Particle swarm optimization
- Neural network
- Simulated annealing
- Linear programming

- Evolutionary algorithm
- Design space based approach
- Probabilistic, iterative, parametric and numerical approaches
- Other approaches (matrix approached.)

In this study computational optimization is defined as "the process of designing, implementing and testing algorithms for solving a large variety of optimization problems. Computational optimization includes the disciplines of mathematics to formulate the model, operations research to model the system, computer science for algorithmic design and analysis, and software engineering to implement the model". It is concluded that the computational optimization methods for wind-solar energy resources increased dramatically over the recent years. In addition it recommended that "the use of heuristic approaches, and parallel processing are promising research areas in this field of renewable and sustainable energy". It is also introducing Ant colony algorithm (ACO) and artificial immune system algorithm (IS) as some examples of potential methodologies for sizing of hybrid systems.

Another study on sizing methodologies was conducted by Luna-Rubio et al. in 2011 (Luna-Rubio, Trejo-Perea, et al. 2012). It classified sizing methodologies into: probabilistic, analytical, iterative, and hybrid techniques. It concluded that one of the most powerful sizing methodologies to optimize the hybrid systems are bio-inspired methodologies which can deal with lack of information and data. Moreover, they are known as powerful methods for multi-objective optimization.

According to the aforementioned information, one of the common methods for optimization of hybrid systems is using bio-inspired technologies, such as genetic algorithm (GA), artificial neural network (ANN), particle swarm optimization (PSO), etc. Ref (Mellit and Kalogirou 2008) reviewed over 335 studies on using artificial intelligence techniques in order to forecasting the incomplete metrological data, sizing and modeling, simulation and control of photovoltaic applications. Another study was done by Jafarin and Ranjbar to estimate annual energy output of wind turbines in 25

different stations in Netherland by applying neural networks and fuzzy logic approaches (Jafarian and Ranjbar 2010).

GA is one of the efficient methods to optimize sizing of the hybrid systems, especially in complex systems, where the number of parameters is high. It provides variety of hybrid systems with different size of components to satisfy the load demand based either load profile of given location or meteorological data of the region, and then it can evaluate them according to defined fitness function.

ANN is another artificial intelligence technique to optimize the hybrid systems. It can be used to predict and modeling of the incomplete meteorological data, and to improve the performance of hybrid system in combination with other methods such as genetic algorithm or fuzzy logic.

PSO like GA is commonly used in literature as an optimization method. It can be pointed out to simple concept, easy coding implementation, robustness to control parameters, and computational efficiency by generating high-quality solutions with shorter calculation time and stable convergence characteristics as the advantages of the PSO.

However, according to the amount of considered input data (including wind speed, solar radiation, load profile, etc.) and multi-objectives nature of hybrid systems' optimization methods, sometimes they fail to offer accurate solutions; in this way hybrid artificial intelligent based optimization methodologies can improve the result. For more detailed information on optimization methods, the readers are addressed to ref (Erdinc and Uzunoglu 2012; Luna-Rubio, Trejo-Perea, et al. 2012).

## 2.10  Conclusion

The unpredictable nature of renewable energy resources, high initial cost, and dependency on weather conditions result in combining different renewable resources to form a Hybrid system which can be flexible, cost effective, reliable and efficient. Techno-economic analysis of hybrid systems ensures that a right combination is chosen. In the present study, the design and techno-economic evaluation of stand-alone hybrid renewable energy systems are reviewed. The existing technologies for photovoltaic solar cells, wind turbines, batteries and diesel generators, as the storage and backup systems, are investigated. To come up with a cost and energy efficient hybrid renewable energy system, the economic and technical criteria to optimize the systems are studied. The possible configurations of the HRES are investigated and their sizing and optimization methods are described. Among the several applied software for optimization, HOMER is one of the common software for cost and sensitivity analysis of the HRES and is explained in detail. It is found that the GA, ANN and PSO are the common computational optimization methods that are applied in the surveys. Despite the significant progress in modeling, sizing and optimization of HRES in the past decade, still there is a gap in implementation and application of HRES in world-wide scale.

# CHAPTER 3

# METHODOLOGY

This chapter is intended to explain the method used for the completion of the project.

## 3.1    Introduction

Goal of this study is optimal design of a diesel-based hybrid Wind/PV renewable energy system. Optimization variables are the number of wind turbines and PV panels, days of autonomy for battery capacity and the number of houses in a village in which renewable hybrid energy system may be shared by them. System costs consist of annualized cost of investment, replacement cost, operation and maintenance cost of components, and fuel cost for diesel generator. The problem is subject to maximum allowable reliability index as well as minimum price of electricity. Particle swarm optimization is used in this regard.

Moreover, optimal combination of number of wind turbines and PV panels, days of autonomy for battery capacity and the number of houses in a village in which renewable hybrid energy system may be shared by them is achieved by applying particle swarm optimization, the optimization problem is subject to maximum allowable reliability index as well as minimum price of electricity.

## 3.2    Simulation Approach

It is assumed 100% reliability for the system which means the system will perform without any interruptions. The developed software optimizes the variables of the hybrid system in order to find the best combination and sizing of the components to meet the load even when the renewable resources are not available.

### 3.2.1 Load profile

For rural and remote tribal areas location, stand-alone hybrid renewable energy system can be used as an alternative solution to provide electricity. However studying the load profile of area is critical to design a reliable and efficient system for a specific area. Sizing and modeling of batteries depend on the load profile. Moreover, peak times in a load profile and behavior of consumers have effect on the reliability of the system, and also, the sizing of the component and the price of electricity will be affected by that.

The hourly load profile of typical rural area is shown in Figure 3-1. The hybrid system is designed to supply this daily load curve.
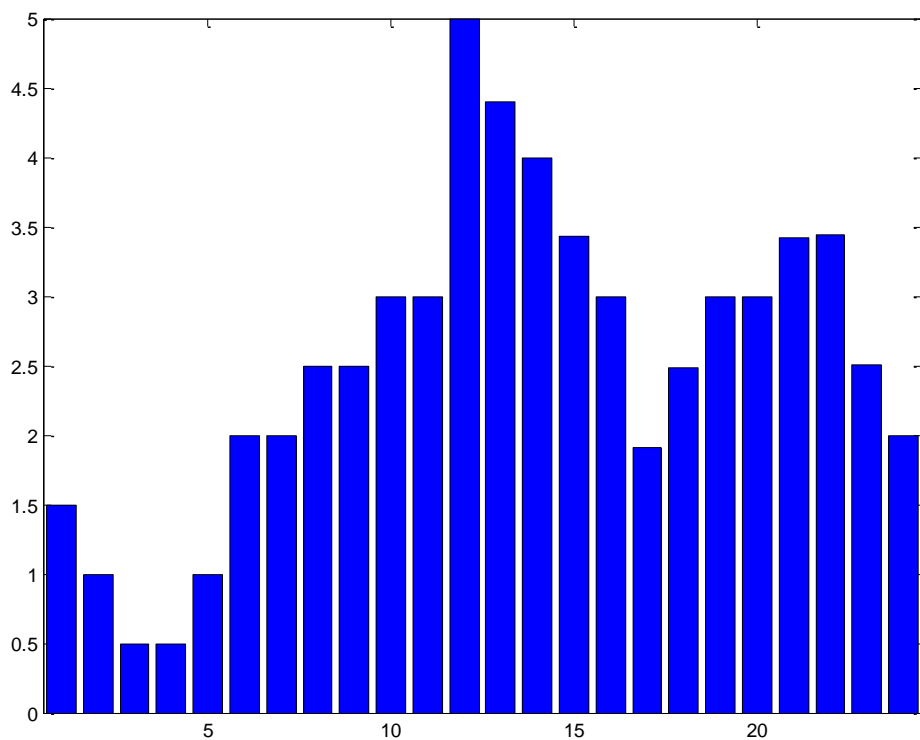


Figure 3-1: Hourly typical rural household load profile (kW)

### 3.2.1.1 Design of battery bank

The battery capacity (kW) of the system is designed according to the load by using the following equation:

$$C_B = \frac{E_L.AD}{DOD.\eta_{inv}.\eta_B} \qquad (3.1)$$

For exapmle, for one house, with the above load profile, we assume, autonomy days=3, depth of discharge(DOD)=80% and $\eta_{inv}$=95%,$\eta_b$=85%; so capacity of battery bank would be :

$$C_B = \frac{(1 * average\ load) \times 3}{0.80 \times 0.95 \times 0.85} = 4.64(average\ load(kW)) \qquad (34)$$

Which means the capacity of battery bank should be designed for 4.5 times of average load (in this case 2.54 kW) to satisfy the load for maximum 3 days of insufficient renewable energy sources; if the voltage of DC bus selected as 48v and the lead acid battery selected as 12v, 100Ah; then 4.64 $_X$ 2.54=11.7856kW, 11785.6/48=245Ah. Therefore, the number of batteries in series would be 4 to obtain the level of DC voltage at the DC bus. The number of batteries in parallel would be 245/100=2.45≈3, so 12 batteries would be needed for one house.

### 3.2.2  Power management strategies

The stand-alone hybrid system is composed from renewable power sources as well as non-renewable resources as a backup. Consequently, the power management strategies for that became very complex. As a basic control rule, the energy extracted from renewable energy sources must be preferentially used to feed the loads. In addition, the battery bank should also be capable of providing the needed power when the renewable resources are not either available or sufficient to meet the load.

Therefore the management strategy would be covering the load demand by adding the power generated from renewable energy sources (wind and PV) and the energy stored in the battery. The diesel generator is switched on as a backup source when  the battery bank is depleted. For each hour step the simulation program compares

the load   demand and the supplied   energy (Wind+PV),   and   according   to   the difference   a   decision   to charge the battery or discharge it or to operate the diesel generator   will   be   taken.   If   the   power   extracted   from   wind   and   PV   is   more   than   is demanded then the surplus power can be used to charge the batteries. If, on the contrary, renewable   resources   fail   to   meet   the   load   demand   then   battery   bank   would   be discharged   to   its   minimum   value.   The   following   cases   will   be   considered   in   the simulation software to apply these strategies:

Case1: Sufficient   generated   energy   is   provided   by   renewable   sources   and   the extra energy is used to charge battery bank.

Case 2: same as case 1 but surplus energy generated by renewable resources is greater than the need to supply the load and the battery bank. Therefore, in this case the surplus energy is consumed by the dump load.

Case 3: renewable resources failed to provide sufficient energy to meet the load. The priority in this case, is to use the stored energy in the batteries rather than operating the diesel generator.

Case 4: The generated energy by the renewable sources is not sufficient to meet the demanded load and the battery bank is also depleted. In this case the diesel generator is switched on to supply the load and charge the batteries. The hybrid system would be remained in this mode until the batteries are recharged to their full capacity.

The main flow chart, for different modes of operation, is shown in Figure 3-2. The   algorithms   for   strategy2,   strategy3,   and   strategy4   are   given   in   Figure   3-3, Figure 3-4, and Figure 3-5 respectively.
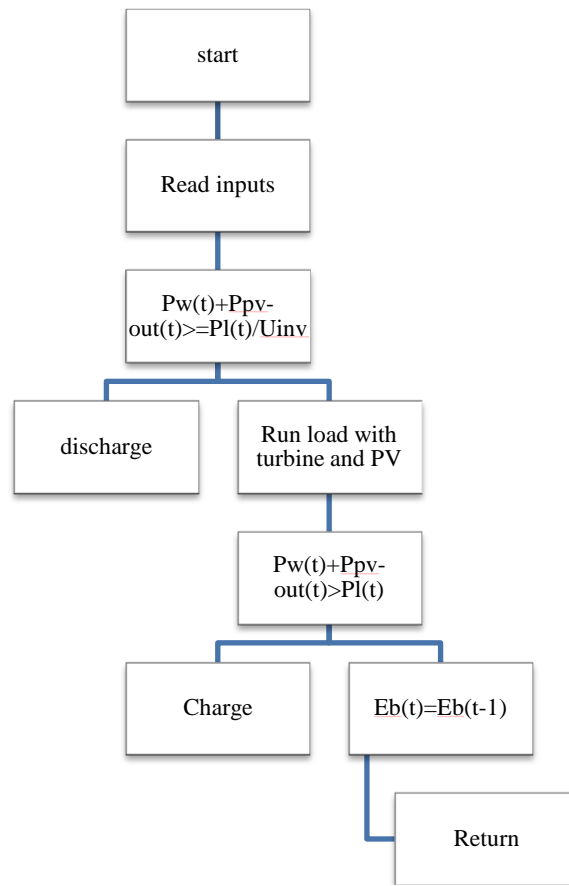
Figure 3-2: Main flowchart of the hybrid system
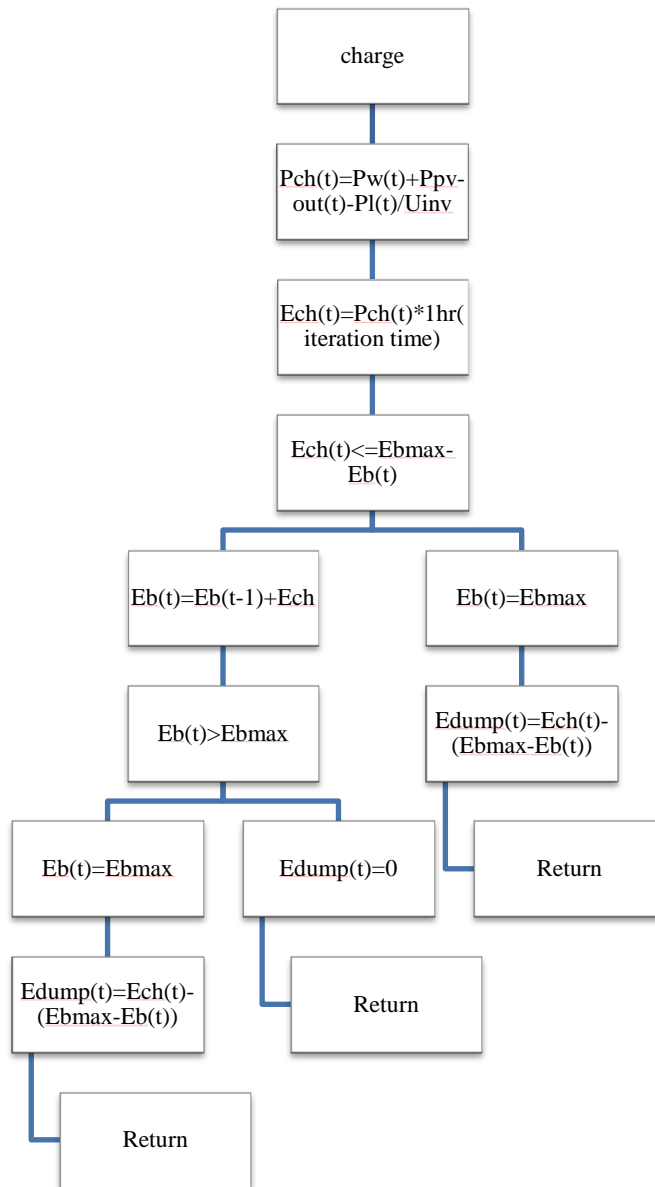
Figure 3-3: Flowchart of charging mode of operation
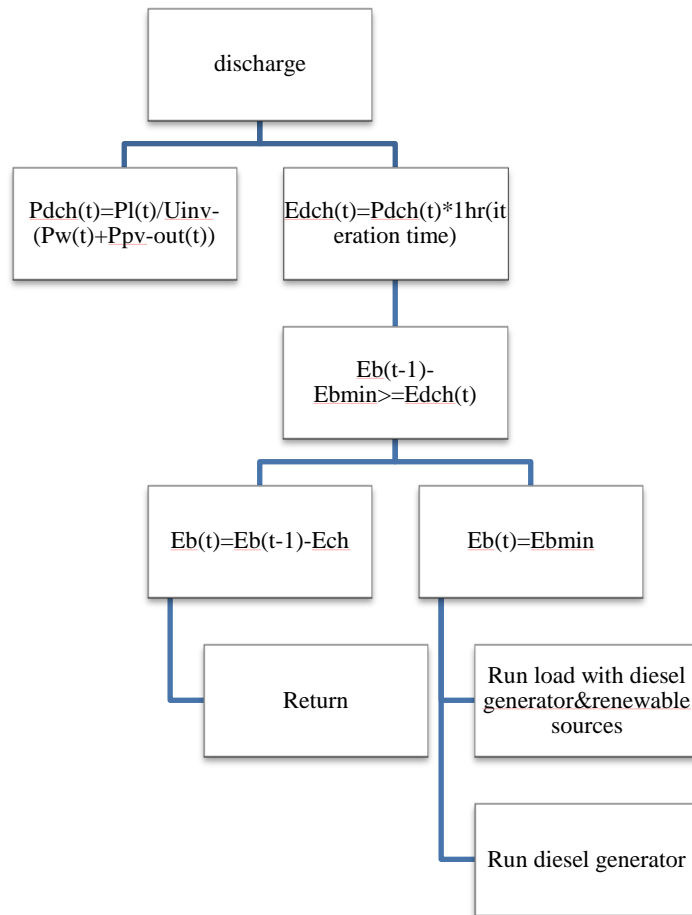
Figure 3-4: Flowchart of the discharging mode of operation
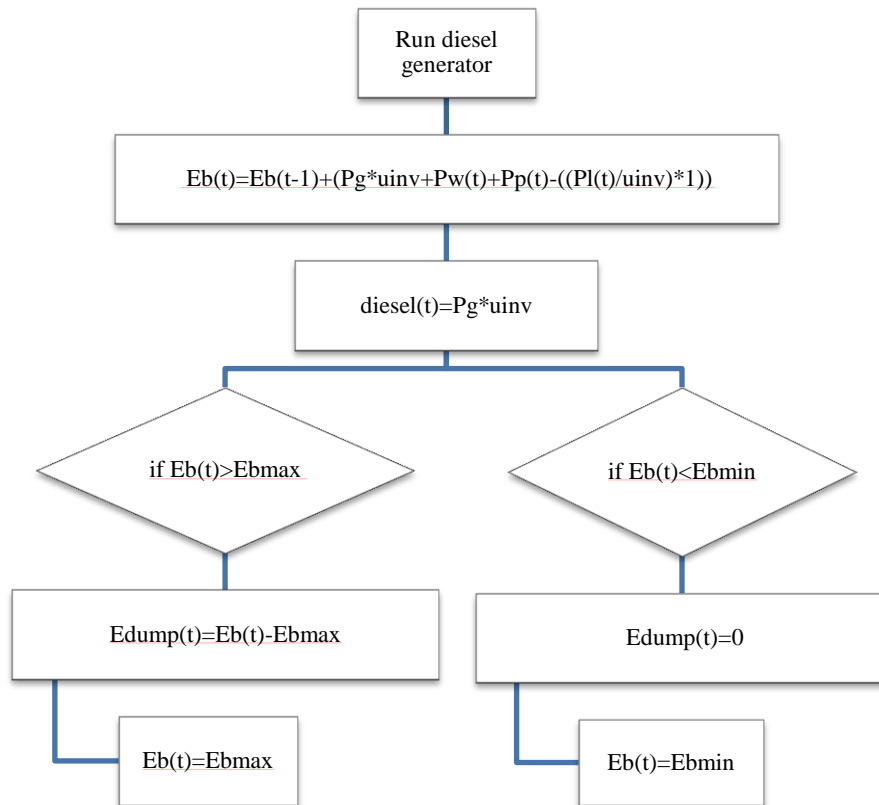
Figure 3-5: Flowchart of the diesel mode of operation

## 3.3 Particle swarm optimization

Generally, artificial algorithms are population-based and demand a number of simulations. Optimal design of such reliable hybrid system is very complex and computationally intensive.

PSO first described by Kenney and Eberhart in 1995, inspired by two separated concepts: the idea of swarm intelligence based on the social interaction exhibited by swarm, and the field of evolutionary computation.

PSO performance is comparable to genetic algorithms or ant colony algorithm since it is faster and less complicated; it has also successfully been applied to a wide variety of problems. It is simple implementation and very efficient global optimizer for continuous variable problems (f.schutte 2005).

The PSO algorithm consists of three main steps as follows:

- Evaluate the fitness of each particle

- Update individual and global best finesses and positions

- Update velocity and position of each particle

Each particle remembers the best fitness value it has achieved during the operation of algorithm. The particle with the best fitness value compared to other particles is also calculated and updated in iterations. The process is repeated until some stopping criteria, such as number of iteration or predefined target fitness value, are met.

The position of each particle in the swarm is updated using the following equation:

$$x_{k+1}^i = x_k^i + v_{k+1}^i \tag{35}$$

Where x is particle position and v is particle velocity in iteration k. The velocity calculated as follows:

$$v_{k+1}^i = k \times [v_k^i + c_1 r_1(p_k^i - x_k^i) + c_2 r_2(p_k^g - x_k^i)] \tag{36}$$

$$k = \frac{2}{|2 - \emptyset - \sqrt{\emptyset^2 - 4\emptyset}} \tag{37}$$

$$\emptyset = c_1 - c_2 \qquad \emptyset > 4 \tag{38}$$

Where, $P^i$ is the best individual particle position and $P^g$ is the best global position, $c_1$ and $c_2$ are cognitive and social parameters, $r_1$ and $r_2$ are random numbers between 0 and 1.

$V_k^i$, called inertia, it makes the particle move in the same direction and with the same velocity.

$c_1.r_1.(p_k^i-x_k^i)$, called the cognitive component, causing the particle return to a previous position in which it has experienced high individual fitness.

$c_2.r_2.(p_k{}^i-x_k{}^i)$, called the social component, causing the particle tend to return to the best region the swarm has found so far and to follow the best neighbor's direction. If $c_1 \gg c_2$ then each particle is much attracted to individual best position, in the contrary, if $c_2 \gg c_1$, then particles are more attracted to global best position.

In this study the value of certain parameters are optimized by using PSO. Figure 3-6 represents the PSO algorithm.
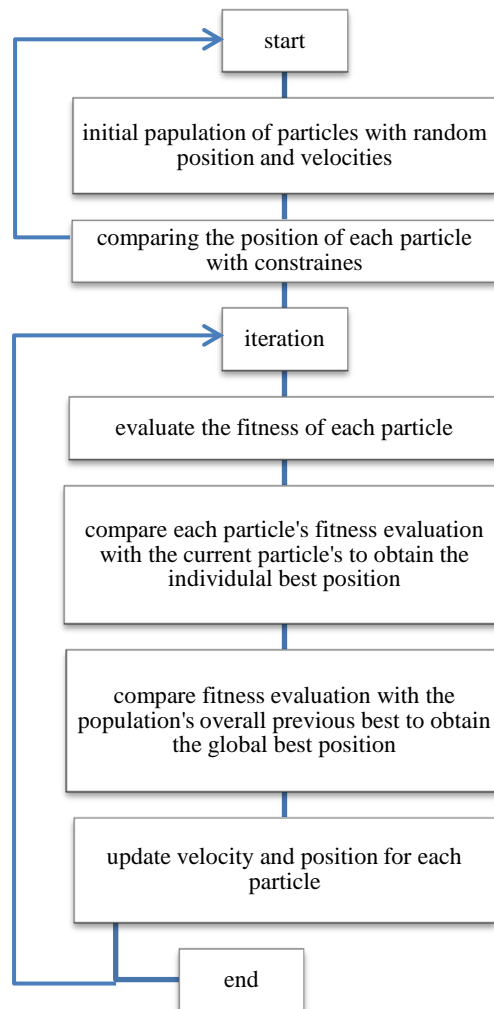


Figure 3-6: PSO flowchart

### 3.4 Reliability and economic analysis

### 3.4.1 Reliability

Several reliability indices are introduced in literatures. Loss of load expected, loss of energy expected, loss of power supply probability, and equivalent loss factor are some of the most common used indices in the reliability evaluation of any system.

Loss of power supply probability (LPSP) is a statistical parameter which indicates the probability of power supply failure due to either losing power supply in a bad resource year or technical failure to meet demand. There are two methods of calculating LPSP i.e. chronological simulation and probabilistic techniques. The former technique is using time-series data in a given period (equation (2.32)) and the latter is based on energy accumulation effect of the energy storage system (equation (2.33)) (Diaf, Belhamel et al. 2008). They can be described by either of the following equations (Deshmukh and Deshmukh 2008; Luna-Rubio, Trejo-Perea, et al. 2012; Rajkumar, Ramachandaramurthy, et al. 2011; Yang, Zhou, et al. 2008):

$$LPSP = \frac{\sum_{t=0}^{T} Time(P_{available}(t) < P_{needed}(t))}{T} \tag{3.7}$$

$$LPSP = \frac{\sum(P_{load} - P_{pv} - P_{wind} + P_{soc_{min}})}{\sum P_{load}} \tag{3.8}$$

In this study the reliability evaluations are carried out for worst conditions. Equation (3.7) is chosen as the main reliability index of this study. In developed countries, electricity suppliers aim at LPSP<0.01%, however, in rural areas and stand-alone applications, LPSP<1% is acceptable (Kashefi Kaviani, Riahy, et al. 2009). Version R2010b for MATLAB is used to calculate the parameters.

### 3.4.2 Economic analysis

Cost of electricity (COE) is one of the most well-known and used indicators of economic profitability of HRES (Kaabeche, Belhamel, et al. 2011). It is defined as the constant price per unit of energy (or cost per unit of electricity). It can be calculated by the following expressions (Kaabeche, Belhamel, et al. 2011; Luna-Rubio, Trejo-Perea, et al. 2012; Rajkumar, Ramachandaramurthy, et al. 2011):

$$COE\left(\frac{\$}{kWh}\right) = \frac{Annualized\ cost(\$)}{annual\ electrical\ energy\ delivered\ by\ the\ system(kWh)}$$

$$= \frac{Total\ Net\ Present\ cost(\$)}{P_{load}(Kw)(8760\frac{h}{year})} \times CRF$$

(3.9)

Total net present cost includes all installed capital cost i.e. the present cost, operation and maintenance cost, and replacement cost. $P_{load}$ is the total energy generated by the HRES during the system life period. CRF or capital recovery factor is a ratio to calculate the present value of system components for a given time period, taking into consideration the interest rate. It is calculated by:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

(3.10)

Where, $i$ is the interest rate and $n$ is the system life period (or Amortization period), which is usually equal to the life of the PV panel, due to its longer life expectancy compared to other components in HRES (Dufo-López and Bernal-Agustín 2008).

### 3.5 Optimization programming

The PSO algorithm is applied, to optimize COE and LOLP. The main program is developed to manage the power and operation of the system. They have been

developed using MATLAB software. The general model that has been applied in this study is described as follows.
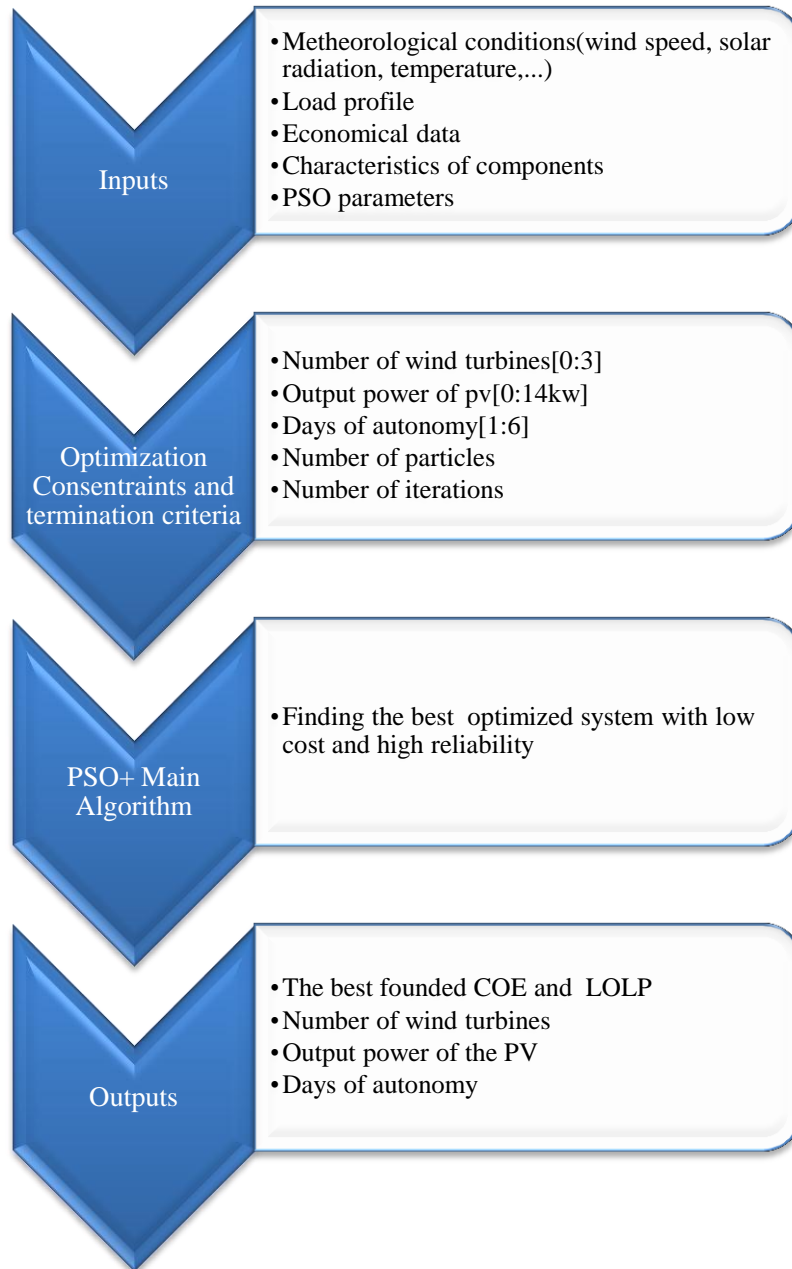


Figure 3-7: General model of hybrid system programming.

In the following paragraphs, the complete flows of the algorithm for techno-economic analysis of HRES are indicated.

Step1) Initialization.

    a) Load meteorological data

    b) Load components characteristics

    c) Load economic parameters

    d) Set the constants:

Personal and Global Learning Coefficient, C1=C2=2,

Maximum of Iteration=40,

Number of Particles=20,

Inertia Weight, W=0.5,

Inertia Weight Damping Ratio, $W_{damp}$=0.99

    e) Set the constraints:

Maximum price of electricity, C=0.5

Maximum loss of load probability, W=0.3

Maximum renewable energy factor (the ratio of diesel output power to renewable energy power in a year), K=0.9

    f) Define the list of tasks as follows. The dimension of PSO algorithm is the number of tasks.

Upper bound and lower bound of nominal power of PV (kW), [0:45]

Upper bound and lower bound of autonomy days, [1:8]

Upper bound and lower bound of number of houses for a hybrid system (Load) [1:10]

Upper bound and lower bound of number of wind turbine, [0:10]

    g) The position and velocity of particles are randomly selected and apply to the objective function to find COE and LOLP.

h) If the positions of randomly chosen particles exceed the limitation of COE or LOLP, return to (d).

i) Evaluate each particle in the swarm and find the best fitness value among the whole swarm. Set the global best value.

Step2) Update iteration variable.

Step3) Update inertia weight.

Step4) Update velocities.

Step5) Update positions.

Step6) Apply to the objective function to find COE and LOLP.

Step7) Update individual best position.

Step8) Update global best position.

Step9) Stopping criterion. If the number of iteration exceeds the maximum number of iterations, then stop; otherwise go to step 2.

## 3.6 Summary

The main goal of designing hybrid renewable energy systems is to provide a reliable supply to the load, under varying weather conditions, and with minimum cost. In this study a hybrid system is designed for 20 years of operation. Moreover, optimal combination of number of wind turbines and PV panels, days of autonomy for battery capacity and the number of houses in a village in which renewable hybrid energy system may be shared by them is achieved by applying particle swarm optimization; the optimization problem is subject to maximum allowable reliability index as well as minimum price of electricity.

# CHAPTER 4

# RESULTS

## 4.1 Introduction

Because of intermittent nature of energy resources and seasonal unbalance, a hybrid PV-Wind system was developed to meet the demanded load in remote areas. Malaysia weather condition is used for this purpose.

In this chapter simulation result using Matlab software, version 7.11 will be discussed. The results present the different configurations of the components for efficient hybrid system to supply typical load in rural areas.

Two methods of optimization are considered in this study, at first the result obtained by running the program in different scenarios is analyzed and then by comparing the results, the best configuration is suggested. The second technique is using PSO to find the best optimum configuration by minimizing the fitness function considering the different constraints.

## 4.2 Renewable energy outputs

The renewable energy sources can be considered the best alternative to reduce energy poverty of the rural areas where the grid extension through a difficult terrain and thick jungle is not possible and economically viable. In this study, the potential of applying renewable sources such as solar and wind for rural electrification, is investigated.

### 4.2.1 Wind output

Wind can be considered as free available energy source that can be utilized for the electrification in Malaysia. In the early 1980s, a study on Malaysia's wind

energy was done at University Kebansaan Malaysia (UKM). Solar Energy Research Group from UKM collected wind data from ten stations in the whole country for a period of 10 years from 1982 to 1991. The data of study include the hourly wind speed in stations, which are mostly located at airports and near coast, where land and sea breezes may influence the wind regime (Sopian, Othman et al. 1995). The study shows that, due to the Malaysia's location, mean wind speed is low and no more than 2m/s. Nonetheless; the wind does not blow uniformly; wind speed varies according to month and region. The strongest wind blows on the East coast of Peninsular Malaysia. The maximum speeds occur in the afternoon and minimum speeds occur just before sunrise (Sopian, Othman, et al. 1995).

Although average flow of wind is light in Malaysia, but it can generate a high amount of energy, especially on remote islands or east coast states of Malaysia, which experiences the wind speed of about 15.4 m/s during strong surges of cold air from the north Sabah and Sarawak. Moreover, it has the high potential of wind energy, which can be reached to 10.2m/s during October to March (Shafie, Mahlia et al. 2011). The greatest wind power potential is for Mersing and Kuala Terengganu which are located in east coast of peninsular Malaysia. In Sabah, wind directions in two stations of Kota Kinabalu and Tawau are consistent wind during the whole of the year. Kota Kinabalu has higher wind power densities at the end of the year; whereas Labuan station shows that the wind power densities are high at the beginning of the year (Sopian, Othman, et al. 1995). The Figure 4-1 illustrates the hourly wind speed data in Mersing, Malaysia.
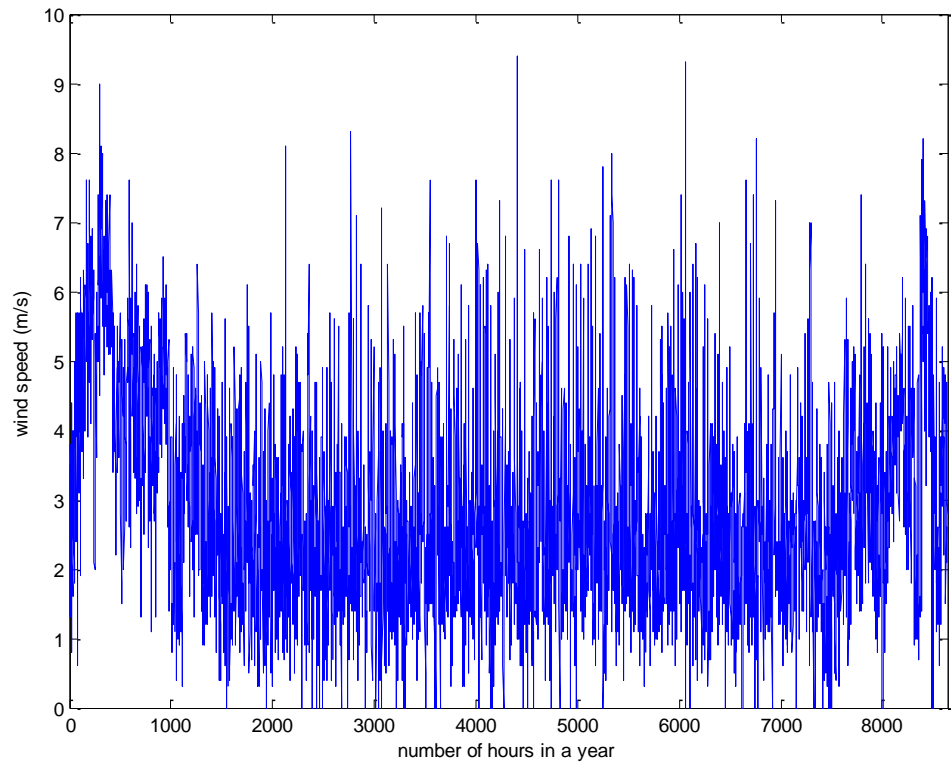
Figure 4-1: Hourly wind speed data in Malaysia

Analyzing the data, it can be seen that, the small wind machines could be used to provide electricity for rural household in Malaysia, that don't have access to national grid (Sopian, Othman, et al. 1995). Therefore, in this study a small wind turbine with 0.3 kW rated power is considered to design the hybrid system. The detailed characteristics of selected wind turbine can be found in Table 4-1. By using equation (2.14), the daily output power of wind turbine is calculated and shown in Figure 4-2.
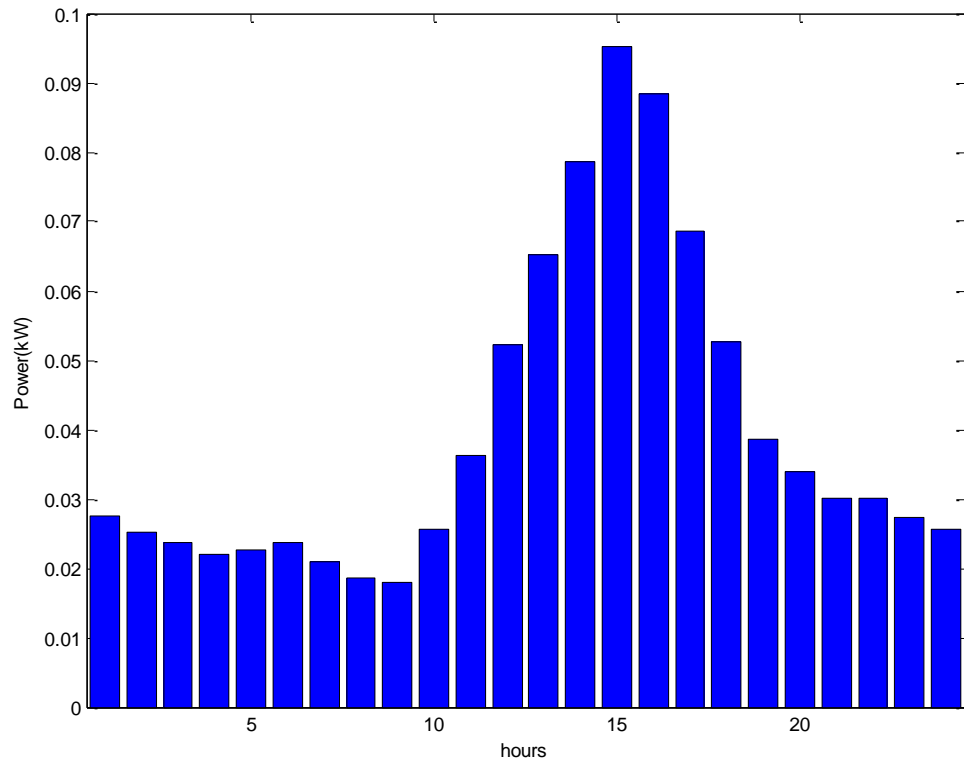
Figure 4-2:Average daily output power from wind turbine in Malaysia

### 4.2.2 PV output

The potential of applying solar energy in Malaysia especially in the rural areas is investigated in this section.

Solar radiation data in Malaysia have been the matter of earlier studies. Malaysia climatic conditions are desirable to extend the PV system utilization, because of the high amount of solar radiation received throughout the year. Solar radiation in Malaysia is relatively high based on the world standards. It is estimated that Malaysia solar power is four times of world fossil fuel resources (Ayu wazira azhari 2008).

Malaysia solar radiation amount is ranging from 0.61kWh/m2 a day in December to 6.8kWh/m$^2$ in August and November. North region and a few places in east of Malaysia receive the highest amount of solar radiation by the average of more than 3kWh/m$^2$ throughout the year. It is estimated that one square meter of

solar panel in Malaysia can cause 40kg of $CO_2$ reduction yearly (Sovacool and Drupady 2011).

The solar radiation has a high effect on performance of PV. The power supplied by the panels is calculated by(Daud and Ismail 2012) :

$$P_{pv-out} = P_{N-pv} \times \frac{G}{G_{ref}} \times [1 + K_t((T_{amb} + (0.0256 \times G)) - T_{ref})] \qquad (3.11)$$

Where, $P_{pv-out}$ is output power of PV, $P_{N-pv}$ is rated power at reference conditions, G is solar radiation (W/m2), $G_{ref}$ is solar radiation in reference condition, $T_{ref}$ is cell temperature at reference condition, $K_t$ is temperature coefficient of maximum power, $T_{amb}$ is the ambient temperature ($G_{ref}$=1000W/m$^2$,$T_{ref}$=25˚c,$K_t$=-3.7*10$^{-3}$(1/˚c)). The average monthly ambient temperature is illustrated in Figure 4-3.
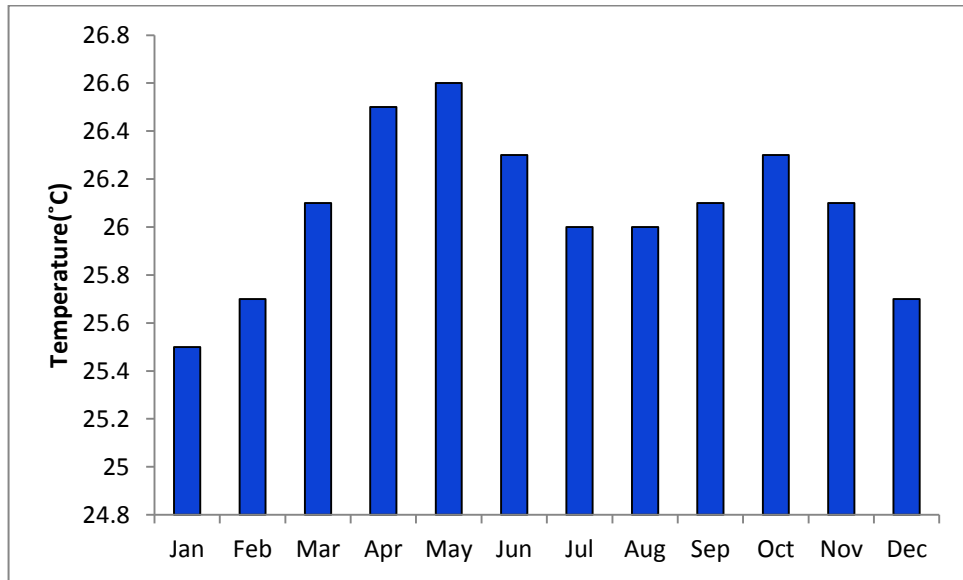


Figure 4-3: Average monthly ambient temperature.

By using data above, average daily PV output power is calculated. Figure 4-4 shows average daily output power from PV in Malaysia. Rated power from PV panel is considered to be 7.3kW. However the mean output power per day would be 2.7kW due to the limited sunshine hours. According to literature, in Malaysia the tilted angle of 15˚ is suitable to install the module upon the roof to generate the maximum power for

domestic usage. The performance of the system with tilted panel in this case would be 98.6% (Elhassan, Zain et al. 2011).
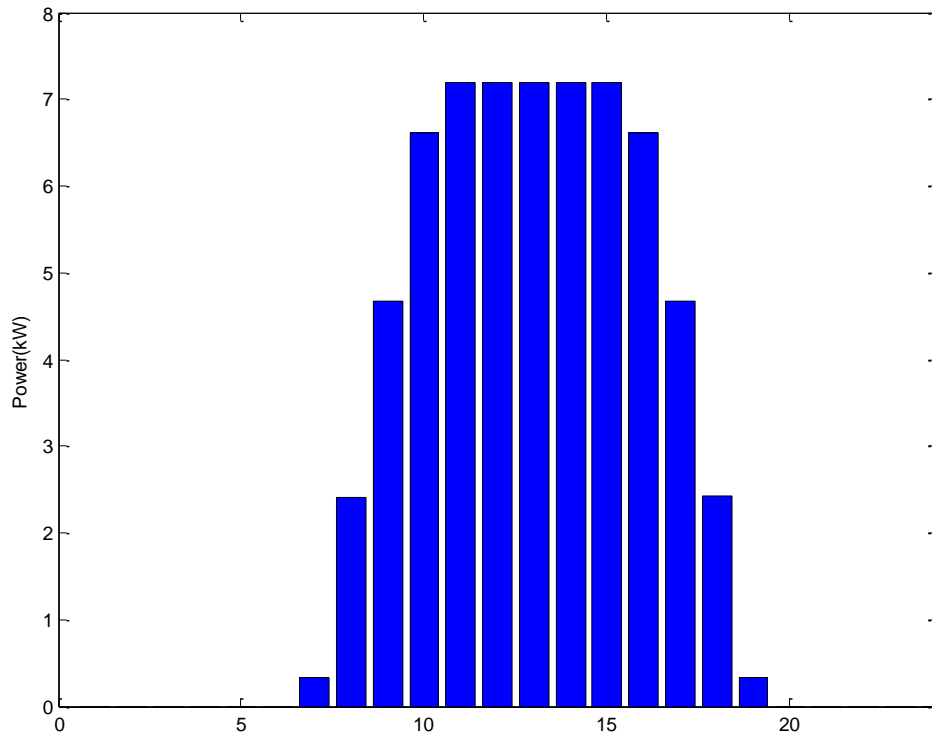


Figure 4-4: Average daily output power from PV in Malaysia

## 4.3 Economic analysis

The initial costs of the different components of hybrid system are shown in Table 4-1. It can be observed that PV panels have the highest cost compared to other components of the system. Also other inputs which are used in programming are tabulated.

Table 4-1: Input parameters

| parameter | unit | value | parameter | unit | value |
|---|---|---|---|---|---|
| **DIESEL GENERATOR** | | | **ECONOMIC PARAMETERS** | | |
| life time | hours | 24000 | discount rate | % | 3 |
| initial cost | $/kW | 1000 | inflation rate | % | 3.2 |
| rated power | kW | 4 | o&m+running cost | % | 20 |
| **INVERTER** | | | fuel inflation rate | % | 5 |
| efficiency | % | 92 | project life time | year | 24 |
| life time | year | 24 | **WIND** | | |
| initial cost | $ | 2500 | Wind regulator cost | $ | 1000 |
| **BATTERY** | | | | | |
| efficiency | % | 85 | blades diameter | m | 6.4 |
| life time | year | 12 | swept area | m$^2$ | 128.6796 |
| initial cost | $/kWh | 280 | efficiency | | 0.95 |
| rated power | kWh | 40 | cut out | m/s | 40 |
| **PV** | | | cut in | m/s | 2.5 |
| PV regulator efficiency | % | 95 | rated speed | m/s | 9.5 |
| life time | year | 24 | rated power | kW | 5 |
| initial cost | $/kW | 3400 | Price | $/kW | 2000 |
| rated power | kWh | 7.3 | | | |
| PV regulator cost | $ | 1500 | life time | year | 24 |

### 4.3.1 Techno-economic analysis of HRES

In this section the effect of days of autonomy, increasing the load, and increasing the power of PV on reliability and cost of electricity is investigated. Notice that because of insufficient output power from wind turbine and complexity of analysis, wind turbine is not included in the analysis.

### 4.3.1.1 Output power of PV versus days of autonomy

Figure 4-5 shows the effect of changing output power of PV and days of autonomy on price of electricity. Figure 4-6 illustrated effects of the same parameters on LPSP. By comparing two graphs, it can be found that, the cheapest price of electricity for one house is achieved when the output power of PV is about 6 kW and days of autonomy is above 4. The LPSP in this range would be zero, which means the system is reliable too.

Figure 4-7 simulate the operating hours of hybrid system for one week. From the figure it can be seen that the diesel generator is run rarely. And the dump load is also runs for a few hours only.

In summary, a system with 6 kW PV panel, autonomy days of 4.5 can be considered as an efficient system to meet a rural household load demand in Malaysia. In this case the price of electricity would be less than 0.16 \$/kW (0.528 RM/kW) and the system would not have any loss of power.
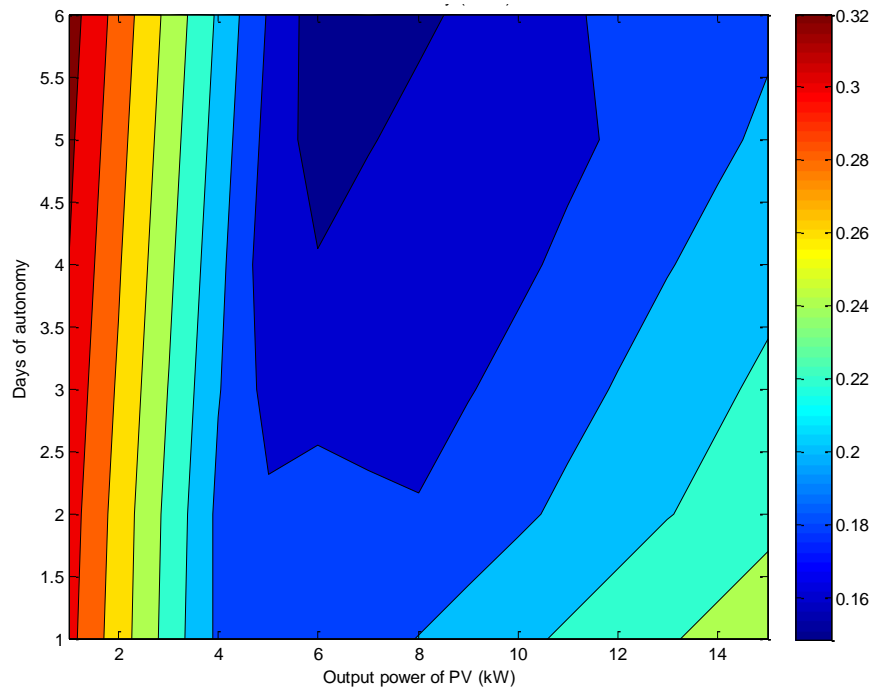
Figure 4-5: Price of electricity for one house ($/kW)
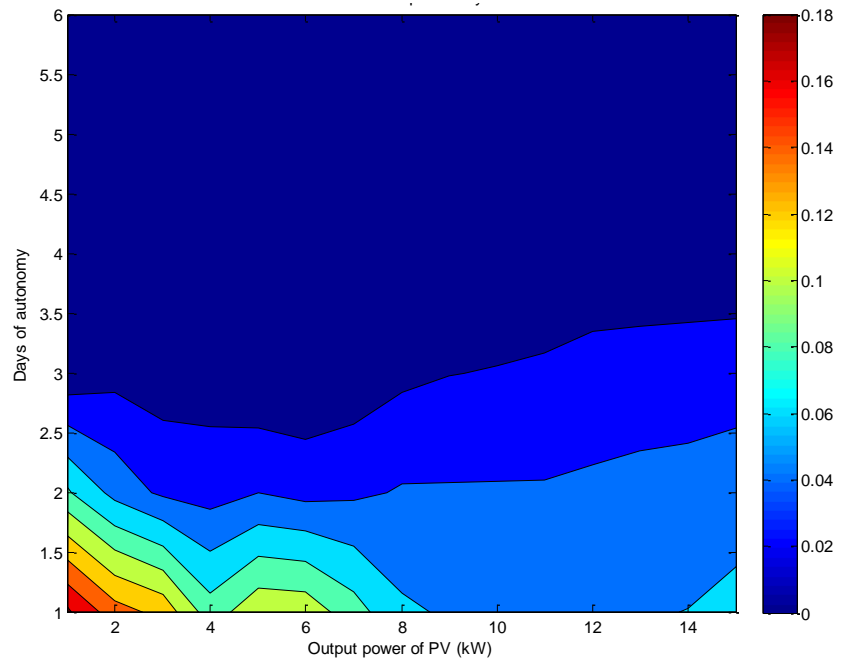


Figure 4-6: LPSP for one house
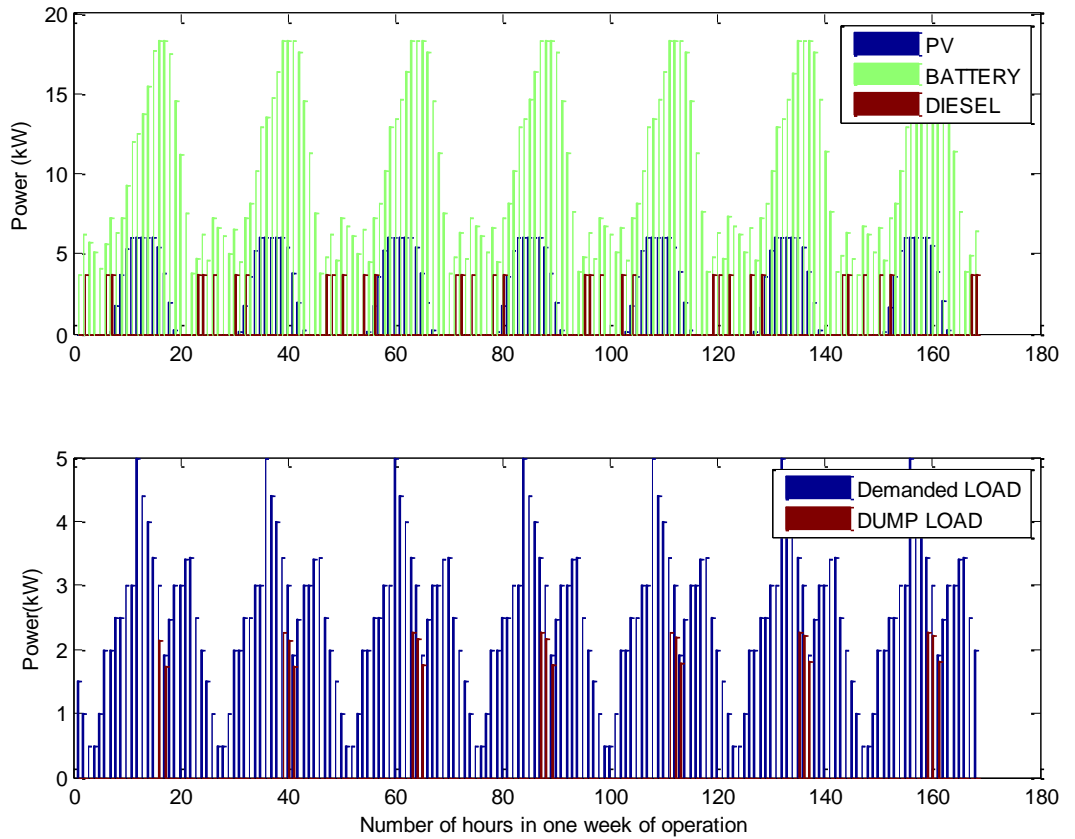
Figure 4-7: Operation of hybrid PV-battery-diesel system in one week

By using these information we design the system and increasing the number of houses to examine whether sharing the hybrid system for number of houses in the form of mini-grid can be effective or not.

### 4.3.2 Output power of PV versus increasing the load demand

In this section we study the feasibility of sharing hybrid system for number of houses in a village. According to the previous results, for each house a 6 kW PV would be sufficient to meet the demand. And 4.5 days of autonomy would be the best option for designing the battery bank.

Figure 4-8 indicates the result of increasing number of houses on the price of electricity. By sharing the system for number of houses in a village, the price of electricity decreased to 0.1$/kW. In the contrary, from Figure 4-9 it can be seen that the reliability of the system decreased dramatically. Therefore, to design a reliable, cost effective system, there is a need to find the optimum configuration. Figure 4-10 is an illustration to show the optimized areas in which both COE and LPSP are on their lowest amount. From the Figure it can concluded that for two houses and PV panel of 16 kW, the hybrid system would be in optimum configuration. In this case price of electricity would be around 0.15$/kW, and LPSP would be less than 10%.

Figure 4-11 simulates operating hours of hybrid system for one week. From the Figure it can be seen that the diesel generator is run rarely. And the dump load also runs for a few hours.

Therefore, to design a system for remote areas the priorities are different. The result shows, if the priority is having the cheapest price, the hybrid system can be shared between two houses. In the contrary, if the priority is having the most reliable system, then for each house the hybrid system can be installed separately.

In the next section the wind turbine is also added to the system and the optimization is performed by PSO algorithm.
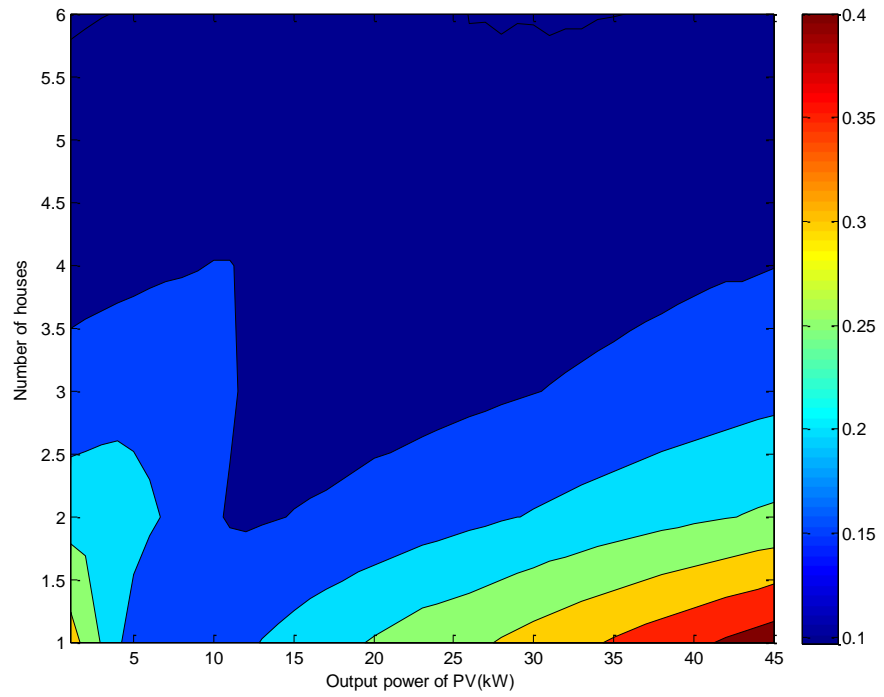
Figure 4-8: Price of electricity for 4 days of autonomy
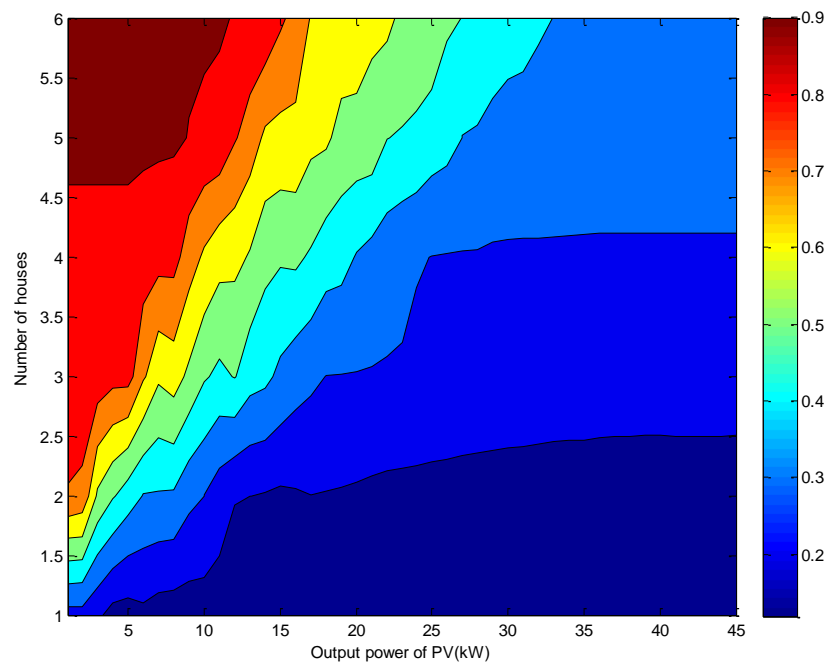


Figure 4-9: LPSP for 4.5 days of autonomy
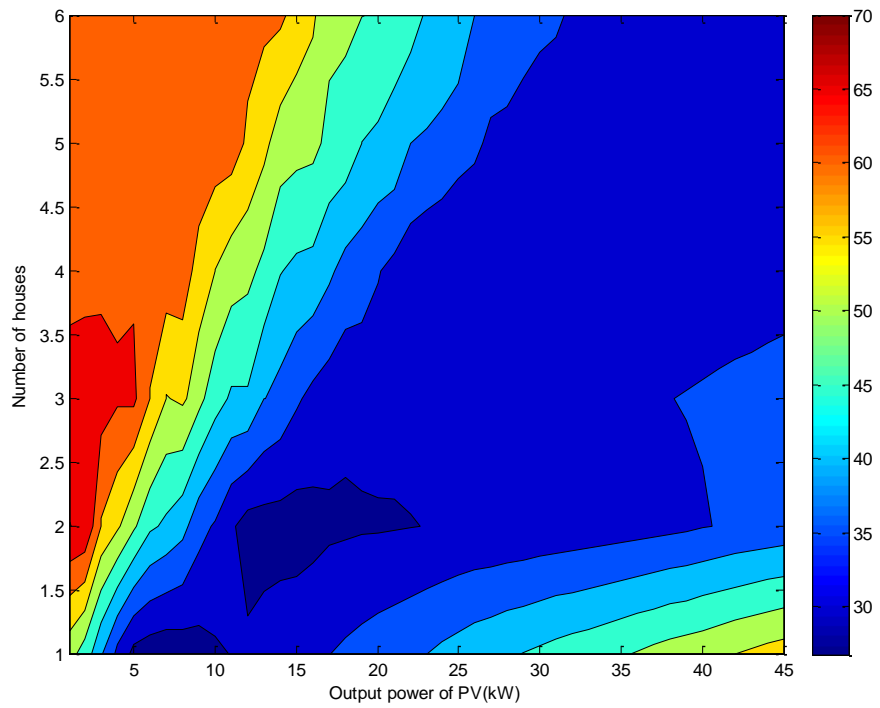
Figure 4-10: Optimum configuration areas (%) considering 4.5 days of autonomy
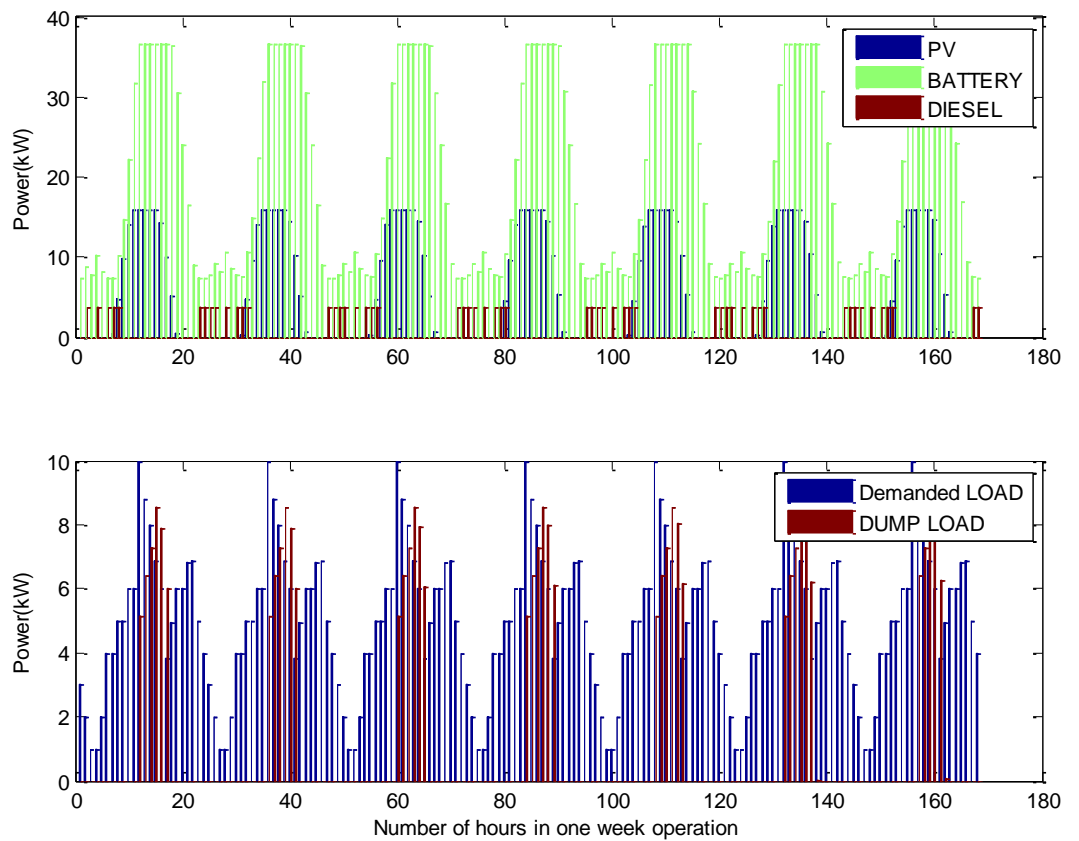


Figure 4-11: Operation of hybrid PV-battery-diesel system in one week for two houses

## 4.4    Particle swarm optimization (PSO)

In this section PSO is applied to optimize certain parameters in the hybrid system. Power of PV panels, days of autonomy, number of houses, and number of wind turbines are optimized by using PSO. The results are shown in Table 4-2. It can be seen that the result in which the hybrid system is shared between the houses have the cheapest price, but the power from PV panels should be high enough to have the better reliability. The lowest cost of electricity founded by PSO is 0.105 $/kW. The battery bank should be designed for 8 days of autonomy and the hybrid system can be used as a mini-grid to share the electricity between 4 houses. The objective function for the PSO programming was the cheapest price with the lowest loss of power probability, as a result, the best founded design to meet these objectives and also cover other limitations such as high contribution of renewable energy in the system, would be a system with 30 kW PV panel, and by considering 8 days of autonomy which is shared between 4 houses. In this case the diesel generator is used rarely (2% of total power); and the PV contribution in the system is about 68% (Figure 4-12). The price of electricity would be 0.1 $/kWh, however this result can be different for other places with different weather conditions.

Since the power extracted from wind energy is negligible, the system is working mainly based on solar energy. Therefore, using wind turbine is not economically feasible. However from PSO result, a small wind turbine can also be used, but the power output from wind turbine wouldn't be noticeable. From the second scenarios of PSO result, we can say that even though Malaysia doesn't have high wind speed we can use small wind turbines in the design of hybrid system with some success.

Table 4-2: Results of optimization from PSO

| PV(kW) | 30 | 29 |
|---|---|---|
| DAYS OF AUTONOMY | 8 | 8 |
| NUMBER OF HOUSES | 4 | 4 |
| NUMBER OF WIND TURBINES | 0 | 1 |
| LOSS OF LOAD PROBABILITY | 0.083 | 0.085 |
| PRICE OF ELECTRICITY ($/kW) | 0.109 | 0.108 |
| RENEWABLE FACTOR | 0.020 | 0.022 |
| Extracted power from different resources in one year | | |
| PV (kW) | 95518.909 | 92334.94 |
| WIND (kW) | 0 | 342.14 |
| BATTERY (kW) | 40320.011 | 40375.39 |
| DIESEL (kW) | 2745.279 | 2966.07 |
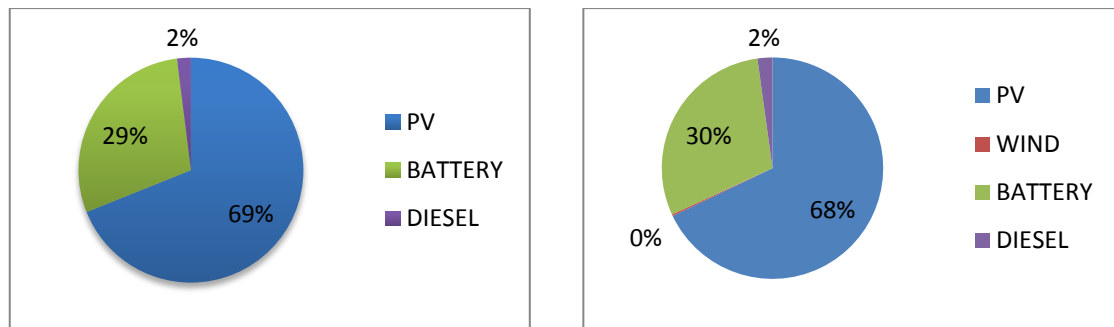


Figure 4-12: Best configurations founded by PSO

Figure 4-13 simulates operating hours of hybrid system for one week. The battery bank is designed for 8 days of autonomy and the hybrid system is designed as a mini-grid to share the electricity between 4 houses. From the Figure it can be seen that the diesel generator is run rarely. And the dump load also runs for a few hours.
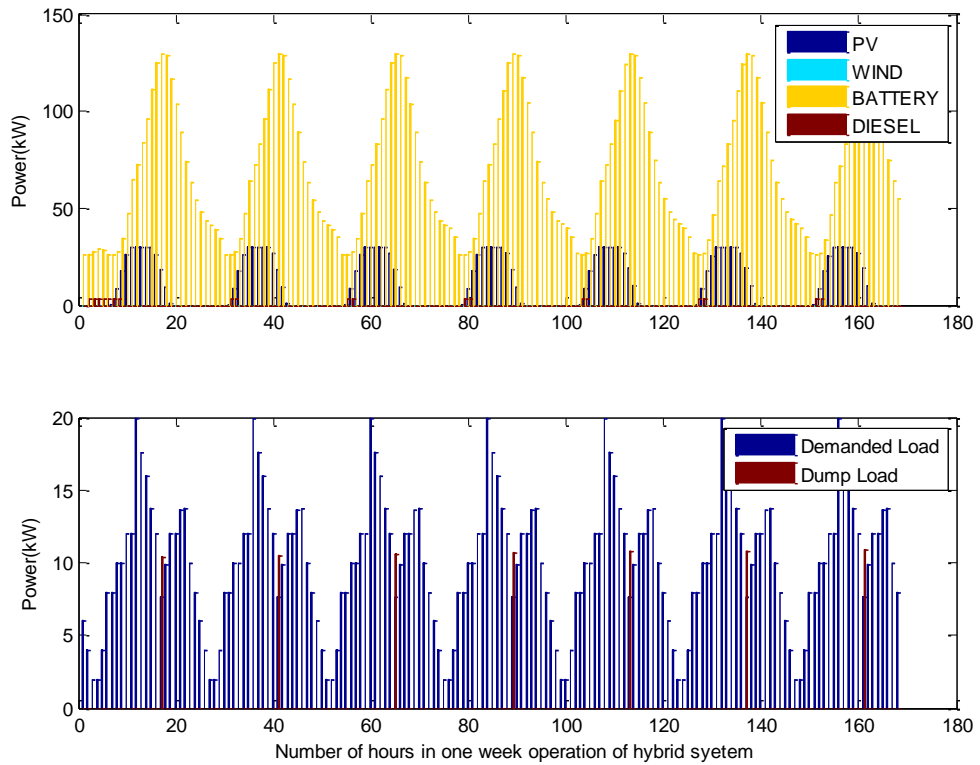
Figure 4-13: Operation of hybrid PV-battery-diesel system in one week for four houses

## 4.5 Conclusion

A hybrid PV-Wind system was developed to meet the demanded load in remote areas in Malaysia. The results presented for different configurations of the components for efficient hybrid system to supply typical load in rural areas. The results also can be used for supplying electricity to emergency requirements such as hospital, school and other purposes according to their energy requirements.

Sensitivity analysis is also carried out by running the program in different scenarios to find the best configuration for one house. A system with 6 kW PV panel, autonomy days of 4.5 reveals as an efficient system to meet a rural household load demand in Malaysia. In this case the COE and LPSP would be minimized. It is also found that the hybrid system can be applied as a mini-grid to share electricity between houses. However with 4.5 days of autonomy, only two houses can be connected to the HRES.

In addition, PSO algorithm is applied to find the best optimum configuration by minimizing the fitness function considering the different constraints. Due to high flexibility of PSO to solve optimization problem for multiple-variable functions, wind turbine is also added to the system. Power of PV panels, days of autonomy, number of houses, and number of wind turbines were optimized by using PSO.

Decreasing COE, LPSP, and increasing the contribution of renewable resources, are considered during optimization of system by PSO algorithm, which poses a very complex problem. This is because when one of the objectives gets improved, the other gets worse. Finally, the best founded design to meet these objectives and also cover other limitations such as high contribution of renewable energy in the system, is founded as a system with 30 kW PV panel, by considering 8 days of autonomy which is shared between 4 houses.

In summary, depending upon priorities to design the hybrid system, there might be villages where micro-grid would be more cost effective as compared to single user hybrid systems. If the priority is having the cheapest price, the hybrid system can be shared between a numbers of houses. On the contrary, if the priority is to have the most reliable system (such as emergency hospital), then, for each user the hybrid system can be installed separately. However geographical terrain and location of houses within the village, available technologies, and weather condition, are some of the additional factors that will influence a choice between these two scenarios.

# CHAPTER 5

# DISCUSSIONS

## 5.1   Introduction

In this section design consideration of hybrid system is investigated. Moreover, according to the literature reviews, and by considering the configuration of optimum systems which are founded in the study, two HRESs are designed for rural areas in Malaysia.

## 5.2   Design considerations of the HRES for one house

### 5.2.1   Design of battery bank

48V DC voltage is selected for DC bus; therefore the batteries shall be connected in series to obtain this level of voltage. 12V, 20/40/75 Ah lead acid batteries usually are used for stand-alone applications.  In this study, capacity of battery bank for each house is selected according to Equation (3.1). By considering 4.5 days of autonomy, 80% DOD, 85% battery efficiency, and 92% inverter efficiency for earlier mentioned load profile, the capacity of battery bank would be 18.27 kWh. Since the voltage of DC bus is 48V, four batteries shall be connected in series to obtain this level of voltage. So, the Ampere-hour capacity of the battery bank to cover the load demand would be 18.27×1000/48=380.625Ah. By choosing lead acid batteries of 75Ah, five parallel strings each has four batteries connected in series are needed to cover the load.

### 5.2.2   Bidirectional inverter

Since, in this study, a diesel generator is used as a backup, a bidirectional inverter in needed to transfer power in both AC and DC buses.  The inverter has to

handle a maximum power of demanded load. It can be chosen 20% higher that of the AC rated load power. Since 48V DC voltage is selected for DC bus; Voltage of Inverter should be rated at 48V.

### 5.2.3 Charge controller

A charge controller acts as interface between PV panel and the DC bus where the battery is connected. Therefore, it should be rated to the DC level of voltage, which is 48V. It controls the energy inflow and outflow into and from the battery to protect battery against either excessive over charge or deep discharge.

### 5.2.4 Design of stand-alone hybrid system

Hybrid systems open an opportunity to use the advantages of renewable resources in combination with conventional power resources. According to the literatures, a typical stand-alone HRES includes photovoltaic, Wind, Fuel-Cell, battery, Diesel, and systems controllers. Different configurations of HRES are tabulated in Table 5-1. The aforementioned studies are mostly considered for the simulation, power management, economy and efficiency evaluations based on the implemented system.

Table 5-1: Combination of hybrid systems

| stand-alone hybrid systems | reference |
|---|---|
| Wind-Battery | (Roy, Kedare, et al. 2009) |
| Wind- Fuel Cell | (M.T 2003) |
| Wind -Micro turbine | (Colson, Wang, et al. 2007) |
| PV -Diesel-Battery | (Mondal and Denich 2010; Shaahid and Elhadidy 2003) |
| PV-Fuel Cell | (Hwang, Lai, et al. 2009) |
| PV-Wind- Diesel | (McGowan and Manwell) |
| PV- Wind- Fuel Cell | (Kashefi Kaviani, Riahy, et al. 2009) |
| PV-Fuel Cell-Electrolyze | (El-Shatter, Eskandar, et al. 2002) |
| PV- Fuel Cell -Super Capacitor Bank | (Zandi, Payman, et al. 2011) |
| PV- Fuel Cell -Electrolyze-Battery | (Ulleberg and Mørner) |
| PV- Wind- Fuel Cell -Electrolyze-Battery | (Dufo-López and Bernal-Agustín 2008) |
| PV- Wind-Micro Turbine- Battery | (Kalantar and Mousavi G 2010) |
| PV- Wind- Fuel Cell - Electrolyzer- Battery | (Caisheng and Nehrir 2008) |

There are three ways to integrate different alternative energy sources to form a hybrid System which can be named as AC, DC, and AC/DC bus line coupling. Each

method has its own advantages and disadvantages. DC coupling can be used for long distance transmission due to less transmission losses and single-wire connection. However, AC coupling is more economic with standard interfacing and modular structure. In AC/DC bus line, both sides can be used to feed the load demand.

In this study, feasibility of hybrid stand-alone renewable energy system for rural area of Malaysia ~~in~~ is investigated. By analyzing the data, combination of PV-Battery-diesel is designed for the electricity generation purpose. Designing this system, three objectives are considered which are usually in conflict. Decreasing COE, LPSP, and increasing the contribution of renewable resources, are considered during optimization of system which poses a very complex problem. This is because of when one of the objectives gets improved, the other gets worse. Figure 5-1 illustrates the designed system for one house in rural areas of Malaysia. Due to insufficient wind speed in Malaysia, the wind turbine would not be a good choice. Therefore, combination of PV-Battery-diesel is distinguished as optimum configuration for the electricity generation purpose.
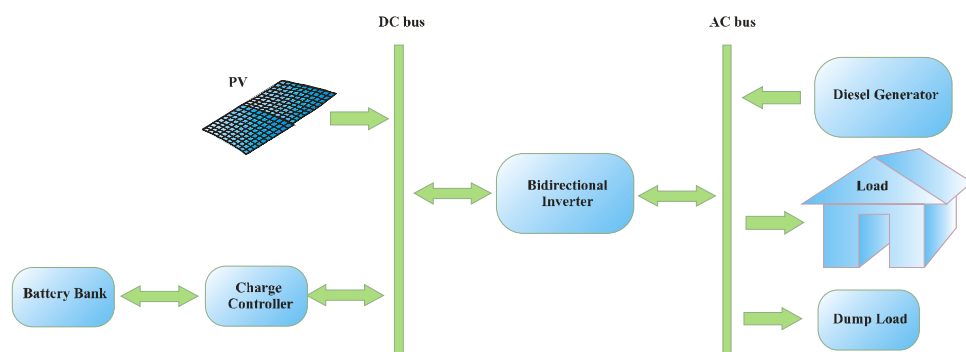


Figure 5-1: PV-Battery-Diesel Hybrid System

## 5.3 Design considerations of the HRESs in micro-grid configuration

In this study two different scenarios are examined, the first scenario as mentioned above, is designing a hybrid system, operating in hybrid solar system configuration for individual household. The second scenario is established a micro-grid

system to generate electricity centrally for a number of households. It can be designed as a single phase, low-tension distribution network to supply 220v, 50Hz, AC electricity. Designing hybrid system in the form of micro-grid has a few advantages; for instance better maintenance, superior load management, increasing security, reduction of storage needs, and superior electrical performance, are reported in literature reviews (Chaurey and Kandpal 2010). The result of optimization in this study also indicates that sharing hybrid system between a numbers of houses would be reliable and cost effective.

### 5.3.1 Design of battery bank

Components of micro-grid typically should be selected to have high efficiency as compared to stand-alone systems which are provided electricity for one house only. The battery bank in a micro-grid usually uses single deep cycle batteries of 100/500/800 Ah. (Chaurey and Kandpal 2010)

48V DC voltage is selected for DC bus; therefore the batteries shall be connected in series to obtain this level of voltage. In this study, capacity of battery bank for each house is selected according to Equation (3.1). By considering 8 days of autonomy (from PSO result), 80% DOD, 85% battery efficiency, and 92% inverter efficiency for four households with earlier mentioned load profile, the capacity of battery bank would be 130 kWh. Since the voltage of DC bus is 48V, four batteries shall be connected in series to obtain this level of voltage. So, the Ampere-hour capacity of the battery block to cover the load demand would be 130×1000/48=2706.73Ah. By choosing lead acid batteries of 800Ah, four parallel strings each has four batteries connected in series are needed to cover the load.

### 5.3.2  Design of micro-grid hybrid system

Figure 5-2 illustrates the PSO-designed system for four houses in rural areas of Malaysia. A micro-grid system is designed to generate electricity centrally for a number of households. It can be designed as a single phase, low-tension distribution network to supply 220v, 50Hz, AC electricity. Dump load can also be used for street lights.
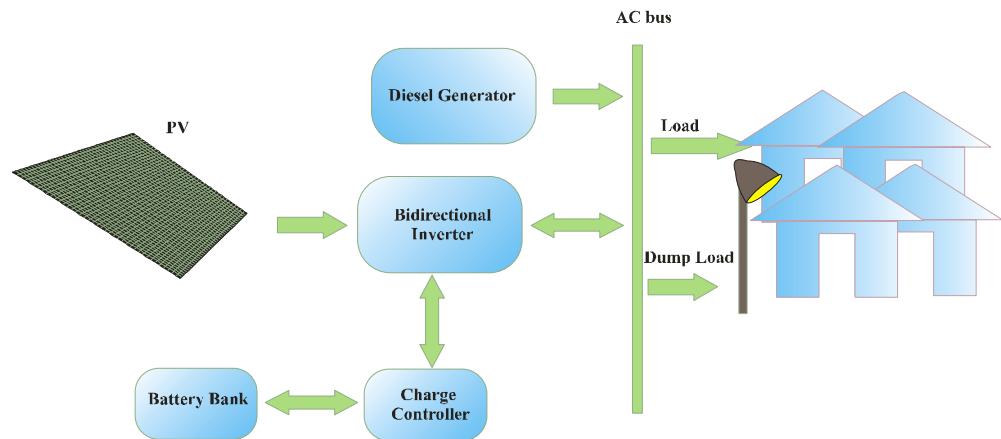


Figure 5-2: Schematic design of micro-grid hybrid system

### 5.4  Optimum configuration in literatures

In this secession the result founded in literatures is compared to the result founded in this study.

Ref (Celik  2003) studied different scenarios on hybrid PV-wind energy system with battery storage. In this paper the least cost of electricity was presented at £3.5 per kW h.

Ref (Rajkumar, Ramachandaramurthy, et al.  2011) present an  ANFIS based optimization approach to model  and optimize  the  sizing  of  a  hybrid PV-wind-battery  standalone  power  system in Malaysia. The results show that the optimized configuration is for LPSP of 0.01 with the price of 4.19 RM/kW considering 5% of initial cost as operation and maintenance cost.

Ref (Karakoulidis, Mavridis, et al.  2011) modeled a hybrid renewable energy system to meet a known electric load in Greece. The best configuration founded by Homer software suggests the combination of PV and diesel generator system, with the cost of 0.65 €/kWh.

Ref (Himri, Boudghene Stambouli et al.  2008) investigated hybrid systems in Algeria; in  this  case,  wind-diesel hybrid system suggested as the most  feasible economically  system with minimum  cost  of  energy  of  0.114$/kWh.

A stand-alone hybrid photovoltaic/wind system with battery storage is presented in Ref (Diaf, Belhamel, et al.  2008). The study applied a set of configurations to meet the desired LPSP, and got the result with the lowest cost of 0.882$/kWh as the optimal one.

A techno-economic analysis was executed to design an optimal autonomous hybrid photovoltaic-diesel-battery system in Ref (Hrayshat  2009) to meet the load of an off-grid house in Jordan. The most economically feasible system presented in this study is a combination of PV and battery with a minimum COE of 0.297 $/kWh.

## 5.5    Conclusion

In this section, design consideration of hybrid system is investigated. By analyzing the data, combination of PV-Battery-diesel is selected for the electricity generation purpose. Moreover, according to the literature reviews, and by considering the configuration of optimum systems which are founded in the study, two HRESs are designed for rural areas in Malaysia. In the first scenario a stand-alone system is designed for individual house. The second scenario, considering the result from PSO algorithm, a micro-grid HRES is suggested for four houses.

# CHAPTER 6

# CONCLUSION

## 6.1  Conclusion

Decentralized electricity generation by renewable energy sources is considered as a solution for remote area electrification. However, intermittent nature of these sources leads to develop sizing rules and use hybrid systems to exploit them. This study proposes an integrated PV/wind hybrid system, with battery storage and diesel generator as a backup. Optimization method utilizes the iterative optimization technique following the loss of power probability and the cost of electricity for power reliability and system costs.

The optimal size of hybrid energy conversion system founded in this study can be performed technically and economically according to the system reliability requirements. In addition, sensitivity analysis was carried out on the PV contribution as the most important parameters influencing the economic performances of the hybrid system. Moreover, the effects of days of autonomy and increasing load demand also investigated.

A system with 6 kW PV panel, autonomy days of, 4.5 are revealed as an efficient system to meet a rural household load demand in Malaysia. In this case the COE and LPSP would be minimized. It is also found that the hybrid system can be applied as a mini-grid to share electricity between houses. However with 4 days of autonomy, only two houses can be connected to the HRES.

In addition, PSO algorithm is applied to find the best optimum configuration by minimizing the fitness function by considering the different constraints. Due to high flexibility of PSO to solve optimization problem for multiple-variable functions, wind

turbine also added to the system. Power of PV panels, days of autonomy, number of houses, and number of wind turbines were optimized by using PSO.

Decreasing COE, LPSP, and increasing the contribution of renewable resources, are considered during optimization of systems by PSO algorithm, which poses a very complex problem. This is because ~~of~~ when one of the objectives gets improved, the other gets worse. Finally, the best founded design to meet these objectives and also cover other limitations such as high contribution of renewable energy in the system, was founded as a system with 30 kW PV panel, by considering 8 days of autonomy which is shared between 4 houses.

In summary, depending upon priorities to design the hybrid system, there might be villages where micro-grid would be more cost effective as compared to single user hybrid system. If the priority is to have the cheapest price, the hybrid system can be shared between a numbers of houses. On the contrary, if the priority is to have the most reliable system (such as hospitals etc.), then, for each user the hybrid system can be installed separately. However geographical terrain and location of houses within the village, available technologies, and weather conditions, are some of the additional factors that will influence a choice between these two scenarios.

## 6.2   Recommendation for Future Work

Based on the presented work, it is found that though there are efforts to develop the hybrid renewable energy systems, it still suffers from techno-economic information on combination of geothermal, biomass, micro-hydro, river-run hydro, in the form of stand-alone hybrid systems, to provide a reliable and economic system. In addition, the potential of super capacitor as a power storage device needs to be studied more. Since

Malaysia has a high potential of using mini hydro power, investigation of mini hydro power combined with other renewable resources is also recommended.

In term of techno-economic analysis, the input data in most of the studies are not very accurate. Since the meteorological information is not available for remote areas, investigating the potential of selected site to design a hybrid system is very critical. In this case using AI-based simulation or in some locations using available software can be helpful to find more accurate data.

Sensitivity analysis and reliability of system also need to be studied more effectively, especially in case of failure in one or two renewable components. It is recommended to conduct an economic comparison between simulation results and actual cost after implementation to prove the accuracy of simulation and for further decision making in rural electrification.

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