Contents

LIST OF FIGURES

LIST OF TABLES

Nomenclature

I_h	Hourly global irradiation on a horizontal plane
I_d	Hourly diffuse irradiation
I_{bn}	Hourly normal beam irradiation [MJ/m^2]
I_{pv}	Instantaneous or hourly radiation on the array surface
$I_{pv, NOCT}$	Hourly irradiation on the array surface [MJ/m^2]
H_h	Monthly average daily global irradiation on a horizontal plane
rd	Factor for converting monthly average diffuse irradiation to monthly average hourly diffuse irradiation.
Id	Monthly average hourly diffuse irradiation (=r_dH_d) [MJ/m^2]
Ih	factor for converting monthly average daily global irradiation on a horizontal plane to monthly average hourly global irradiation on a horizontal plane
Ipv	Monthly average hourly irradiation on the array surface
ω	Hour angle measured from solar non; +ve for afternoon [radians]
ω_s	sunset hour angle [radians]
ω'_s	sunset angle on an inclined plane [radians]
ϕ	latitude of location; +ve North, -ve South [radians]
δ	the sun's declination angle [radians]
θ_z	angle of incidence of direct irradiance on the horizontal plane [radians].
θ_{array}	angle of incidence of direct irradiance on the array play [radians]
s	Array tilt angle from the horizontal [radians]
C	Concentration ratio: radio of collector aperture to absorber area
η	The efficiency of the array to convert incidence solar radiation into electrical energy..
η_r	Is the PV generator efficiency measured at reference cell temperature, T_r, i.e. under Standard test conditions (25°C).

β	Is a temperature coefficient for cell efficiency (typically 0.004 to 0.005/^{o}C),
T_r	Reference cell temperature for efficiency [^{0}C]
T_c	Cell temperature [^{O}C]
$T_{c, NOCT}$	Cell temperature at nominal operating cell temperature (NOCT) conditions [^{0}C]
Ta	Ambient temperature [^{0}C]
$T_{a, NOCT}$	Ambient temperature at (NOCT) conditions [^{0}C]
A	PV array radiation collection area [m^{2}]
A_0	The array area that would be required to satisfy the daily load if the array delivered a constant power throughout the day at reference efficiency and reference radiation condition [m^{2}].
Q_{pv}	Hourly electrical energy output of the array
Ls	The hourly energy contributed to the load by solar energy
L_{day}	Daily energy demanded by the load
B_{gain}	Hourly energy gain of the storage battery
B_{cap}	Effective battery capacity [kWh]
B_{level}	Battery energy level at beginning of hour in question [kWh
η_{pv}	Is the efficiency of the PV generator
$T_{\min}$	Minimum time the battery is allowed to discharge from full capacity to empty [hours]
$DOD_{\max}$	Maximum allowable depth of discharge
D_A/D_R	The ratio of the average depth of discharge of the battery during the discharge event (D_A), to the manufacturer's rated discharge (D_R)
I_A/I_R	The ratio of the rate of discharge during the discharge event to the manufacturer's rated discharge rate
Q_D	Is the hourly diesel energy output,

L_o	The hourly battery charge or discharge depends on the size of the hourly load
Qpv	PV-generated power

DEDICATION

I wish to express my gratitude and appreciation to the individuals who contributed immensely to the success of this study. These include my supervisor, Mr Hove, husband Wellington and children Ashley and Wellington (Junior). Special dedication to my late mother, Christina Zvinowanda, may her soul rest in peace.

CHAPTER 1

INTRODUCTION

1.0 Introduction

Many rural areas of developing countries lack supply of electricity due to poor distribution of grid electricity and financial resources to aid grid extension (Urmee et al, 2009). These countries usually have under capacity in electricity generation with the scarce electricity being allocated to the more important urban sector. The relatively low energy demand in rural areas does not compensate the cost of long-range transmission lines from the national grid. This justifies the use of more decentralised forms of power supply systems which need to be modular in nature and widespread in distribution so that they can be built anywhere near the locations of use. Such power supply systems should be able to provide uninterrupted power supply. Options for providing these include stand-alone renewables, diesel generator sets or a combination of these forms of energy in a hybrid system.

Wind energy, can be a good power supply option but in Zimbabwe the problem is that wind speeds are not enough for power generation. Wind speed determines the power output from wind generators and the output increases significantly as the wind speed increases. A wind turbine installed in an area with a good wind resource can produce energy cost-effectively, for instance, if wind speed is doubled the system becomes about eight times cheaper (Ackermann, 2005). However, the available wind resource typically varies from season to season, this creates a significant variation in the wind turbine output and some areas do not have sufficient wind speeds for power generation thus limiting resource use.

Another renewable resource is solar energy which is abundant in nature especially in most developing countries and Zimbabwe for example, receives more than 2000 sunshine hours per year. Solar stand-alone systems use photovoltaic modules to supply total electric needs. Photovoltaic systems have a number of merits over conventional power-generating technologies. PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation. PV systems have no moving parts, are modular, easily expandable and even transportable in some cases. This system is completely independent of traditional energy sources and this energy independence and environmental compatibility are two attractive features of PV systems. The fuel (sunlight) is free, and no noise or pollution is created from operating PV systems. In general, PV systems that are well designed and properly installed require minimal maintenance and have long service lifetimes (Nayar et. al, 1993)

The amount of power produced by renewable energy devices such as photovoltaic cells and wind turbines varies significantly on an hourly, daily and seasonal basis due to the variation in the availability of the sun, wind and other renewable resources. This variation means that sometimes power is not available when it is required and on other occasions there is excess power. PV stand-alone systems are also not suitable for high energy-intensive applications. However, to deliver continuous uninterrupted power supply, the PV array and battery of a stand alone solar system have to be excessively over-sized leading to high capital costs. For undersized systems, power shortages will be experienced and the batteries may be damaged by excessive discharge.

Another energy supply option for remote areas is the stand-alone diesel generator sets, which are relatively inexpensive to purchase but expensive to operate and maintain (Karnavas and Papadopoulos, 1999). Some generator sets will produce DC electricity for charging batteries directly and AC electricity for running appliances and electrical equipment. Advantages of this option are the low initial capital costs and generation of power on demand. Gensets can be operated with or without a battery but the problem is that if there is no battery they have to be sized for peak power and are therefore less efficient when the load ratio is low. When a genset is designed this way it will operate at partial load for most of its operating life yet specific fuel consumption characteristics of a typical diesel engine show that a diesel generator must be operated above a certain minimum load level in order to maintain efficiency and to reduce the possibility of premature failures (Beyer et al, 2003).

Generator units perform best when operated near their rated output. As the load on the generator decreases so does the efficiency of the unit. If a generator set runs for long periods at very low loads, significant maintenance problems can occur to include wet stacking. Diesel generators also emit substantial quantities of carbon dioxide per unit of electricity (Beyer et al, 2003). Generally diesel gensets are noisy, have short durability, cause environmental pollution and are expensive to run and maintain. Another disadvantage is that diesel engines use petroleum fuel, which is imported for most countries using premium foreign currency. The rising fuel costs and the impracticality of running generators for long periods at low loads has led to the introduction of renewable energy equipment, batteries and inverter technologies, which reduce fuel costs and maintenance and provide continuous power supply.

An attractive option for power supply that eliminates most of the disadvantages of both diesel and renewable stand-alone is the hybrid concept. Hybrid systems consist of combination of a PV array and a complementary means of electricity generation such as a diesel, gas or wind generator. Figure 1 shows the general layout of a hybrid system.

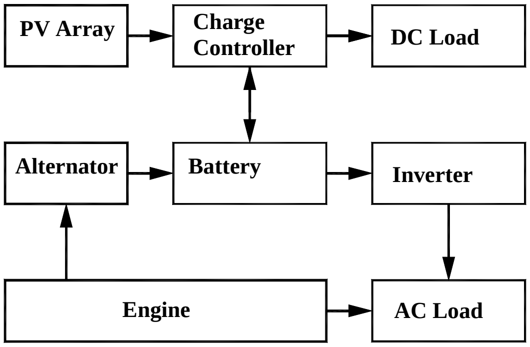

Figure 1 Layout of a typical PV Hybrid Power Supply System

A key feature of hybrid systems is the fact that their constituent system strengths compliment one another thus providing a number of advantages, which are also determined in part by the system type. These include significantly greater reliability in power supply due to the use of two or more energy sources,. more efficient system solutions by virtue of a high degree of flexibility during the design phase and in operation, lower overall maintenance costs due to the shorter operating cycles of the motor generator units and longer service life time of components as a result of reduced use (Kaikhurst, 1998). The main problem of hybrid power supply systems is that they are more complex when compared with stand-alone systems in terms of system sizing and operation strategy of components. Other disadvantages include additional investment cost of renewable energy sources, batteries and power electronics, limited experience of customers and supply utilities with renewable energy and hybrid power system technology and life cycle economic analysis required that is based on detailed system simulation.

Sizing of such systems require simulation of power flows in the system, for example, to decide when the diesel engine is dispatched, what size of array, battery life and many other variables. The sizing requires an economic analysis but this research is concerned with developing a simulation model to analyze the energy performance of a power supply system comprising a PV array, battery, power conditioning equipment etc. The model should be able to come up with information like solar fraction for a given area, battery life, load satisfied and diesel fraction among other things.

The outputs from the model will be used to rationally decide on sizing of the components of the power supply system like the generator, battery, PV array which is done for different dispatch strategies. Dispatch strategy is the criteria used to decide when the genset of a hybrid system is turned on and when it is turned off. The outputs will also be used to show how the dispatch strategy can affect the size of a typical system for a rural clinic. It is therefore hoped that the results from the study will give an insight and link between the variables involved in the design and operation of the PV/Diesel/Battery hybrid power supply system.

The aim of this work is to develop a procedure for sizing the hybrid system components in order to come up with a system that can satisfy the load completely (100%) even when there are poor weather conditions. This will be achieved by identifying the load requirements and using a load matrix to find an hourly load demand. The next step would be to design a model that can simulate the operation of the PV hybrid system. This will be followed by use of the model to size the components and identifying a cost effective energy dispatch strategy. The last step will be to recommend the optimal blending of PV/Diesel/Battery.

While several software tools are available on the market and in research groups, it is sometimes difficult to assess the adequacy of these tools to specific tasks. Also, more details are available from the system when performing optimization than at the planning phase. According to Gabrovska et al (2004) use of such programs require high expertise and financial resource hence the development of simplified computational methods that are less costly.

1.2 Conclusion

In this chapter the researcher looked at the background information, aims and objectives as well as justification of the research. The next chapter is going to focus on review of related literature.

CHAPTER 2

Literature Review

2.1 Introduction

This section makes a review of literature pertaining to remote power supply systems which include renewable stand alones, diesel generator set stand alone and the hybrid system which is the combination the two. The advantages and disadvantages of the power supply options as well as their configurations and dispatch strategies will be considered.

2.2 Power Supply Options for Remote Areas

2.2.1 Wind Stand Alone Systems

Wind energy is one the renewable power supply options for remote areas. Its advantages include low environmental impact and occupy relatively small area of land in proportion to their electrical output. The output from wind generators increases significantly as the wind speed increases, and wind speed increases as height above the ground increases. In evaluating any available wind data the effect of the local topography/geography needs to be considered as it may cause uneven wind patterns that will affect the turbine's output (Ackermann, 2005). A wind turbine installed in an area with a good wind resource can produce energy cost-effectively.

This energy option however has limited use because modern energy converter systems are expensive to set up and if located near homes or workplaces noise of the rotor can be annoying. Another problem is that wind does not blow all the time and in some cases the speeds may not be enough for electricity generation. They are not suitable for mobile needs and maintenance costs are high. If wind- driven generators are linked to diesel generators the efficiency of the diesel plant can be reduced (Wichert, 1997).

2.2.2 Stand-Alone Photovoltaic Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principal classifications are grid-connected or utility-interactive systems and stand-alone systems.

Wichert (1997) argues purports that stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load (Figure 2). Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT), is used between the array and load to help better utilize the available array maximum power output.

Figure 2. Direct-coupled PV system.

In many stand-alone PV systems, batteries are used for energy storage. Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and overdischarge (Wichert, 1997).Figure 2 shows a diagram of a typical stand-alone PV system powering DC and AC loads

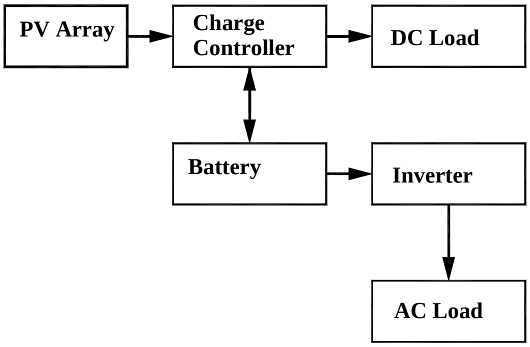

Figure 3 Diagram of stand-alone PV system with battery storage powering DC and AC loads.

PV systems are like any other electrical power generating systems, though the equipment used is different from that used for conventional electromechanical generating systems. However, the principles of operation and interfacing with other electrical systems remain the same, and are guided by a well-established body of electrical codes and standards. Although a PV array produces power when exposed to sunlight, a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances)

The performance of PV modules and arrays are generally rated according to their maximum DC power output (Watts) under Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25^{o} C (77^{o} F), and incident solar irradiance level of 1000 W/m^2 and under Air Mass 1.5 spectral distribution. Since these conditions are not always typical of how PV modules and arrays operate in the field, actual performance is usually 85 to 90 percent of the STC rating. Photovoltaic modules are extremely safe and reliable products, with minimal failure rates and projected service lifetimes of 20 to 30 years. Most major manufacturers offer warranties of 20 or more years for maintaining a high percentage of initial rated power output. When selecting PV modules, one should look for the product listing, qualification testing and warranty information in the module manufacturer's specifications (Wichert, 1997).

2.2.2.1 Merits and demerits of PV Systems

Photovoltaic systems have a number of unique advantages over conventional power-generating technologies. PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation. PV systems have no moving parts, are modular, easily expandable and even transportable in some cases. Energy independence and environmental compatibility are two attractive features of PV systems. The fuel (sunlight) is free, and no noise or pollution is created from operating PV systems. In general, PV systems that are well designed and properly installed require minimal maintenance and have long service lifetimes (Gabrovska et al, 2004).

2.2.3 Diesel Power System

Stand-alone diesel generator sets are relatively inexpensive to purchase but expensive to operate and maintain. Specific fuel consumption characteristics of a typical diesel engine show that a diesel generator must be operated above a certain minimum load level in order to maintain efficiency and to reduce the possibility of premature failures. This is shown in figure 4 which shows a typical curve for specific fuel consumption versus load ratio.

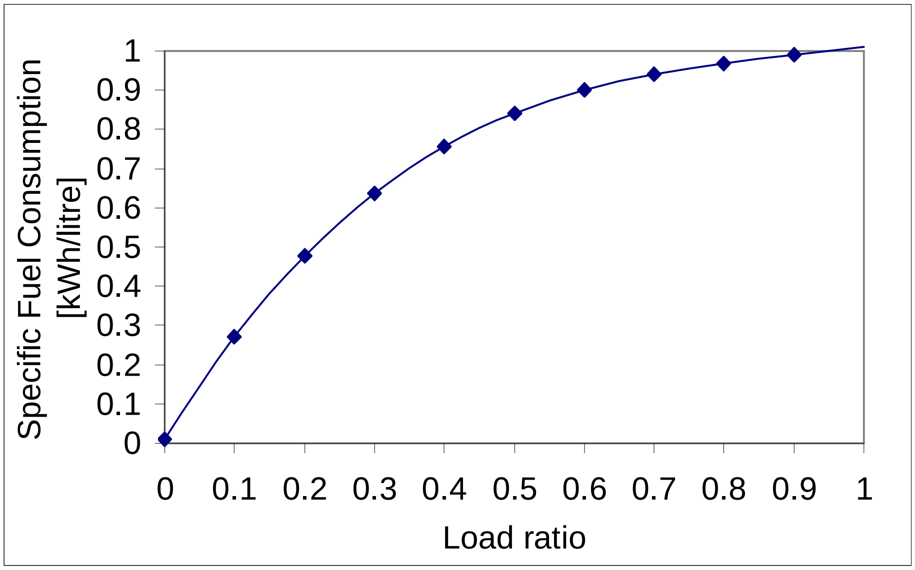

Figure 4 A typical curve for specific fuel consumption versus load ratio.

The typical specific fuel consumption versus load ratio curve generally shows that specific fuel consumption increases as the load ratio increases. The relationship between the two is such that low load ratios result in high fuel consumption.

The problem of selecting a diesel generator size for a newly emerging community, or one which has not had continuous power previously, is difficult while population fluctuations, seasonal demand, increase in number and use of electrical appliances are complex issues for designers to assess. A generator should never be operated at its maximum power output for more than 30 minutes. Rated power, or the power that a generator can produce for long periods of time, is a more reliable measure of generator power (Beyer et al, 2003).

The conventional approach for a stand-alone diesel is to select the diesel generator set according to the peak load. During periods of low loads, the diesel generators will be poorly loaded with the consequences of poor fuel efficiency, wet stacking, low combustion and carbon deposits (glazing) on the cylinder walls, causing premature engine wear. Common practice is to install “dump loads” which deliberately dissipate energy when useful demand is low, to protect the diesel engines.

The same authors argue that several approaches have been considered to maximise the economy of operating diesel generators. One system employs a number of diesel generators that need to operate parallel to achieve peak load supply, but can be shut down systematically as load reduces. This system will require automatic sequencing and synchronisation controls A two-diesel system-one small set and the other larger with manual change over switch- is used to meet the load requirements .The small set is operated during low-demand periods while the larger set is reserved for the high-demand periods. This scheme is a relatively low-cost one, but offers little protection to the larger generator with low demand and is not very convenient.

Although diesel generators have a low initial capital cost and there is support available on how to operate and maintain them, experience has shown that there are significant limitations associated with this method of generation. Getting a maintenance crew on time in such isolated area is a problem. Transportation of fuel is another problem. Diesel gensets have problems with short durability, which is due to the fact that they work very inefficiently when running just at fractions of their rated capacity. Frequent start-up and shut-down procedures also decrease their lifetime (Haupt and Haupt, 1998).

These diesel generators are very expensive to run and maintain and every litre of diesel releases about 3 kg of CO2 gases (Lenzen, 1999). The diesel generator remain in the system to equalize the battery and to act as a backup generator for extended periods of low renewable energy input or high load demand. Such systems are usually installed in locations where fuel supplies are expensive and unreliable, or where strong incentives for the use of renewable energy exist (Drouilet, 1997).

2.2.4 Hybrid Power Systems

Hybrid systems are one means of providing electrical power in remote areas that are not connected to a power grid. A hybrid remote power system integrates two or more power sources. Such systems eliminate problems associated with both PV and diesel stand alone systems.

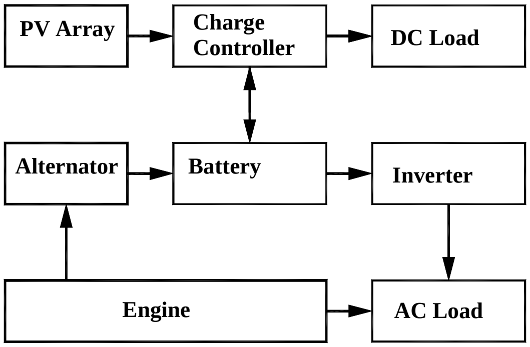

Figure 5 Diagram of photovoltaic hybrid system.

Such systems are inherently reliable due to multiple power sources and generally use diesel generating set-capable of providing full rated power on demand as the second energy source (Behrendorff, 1999). They are independent of a large, centralized electricity grid and incorporate more than one type of power source. Isolated AC systems include at least the following: conventional AC diesel generators, an electrical distribution system, and distributed AC loads. A hybrid system could also include additional power sources such as renewables (wind turbines, photovoltaic panels) and storage.

There may be more than one diesel generator supplying power to the network. These are normally connected to an AC bus in the power house where the diesels are located. This bus provides power to the distribution network. When there is more than one diesel generator, a control system must be employed to properly allocate the power from the diesels. These control systems may take a variety of forms especially as computerized control systems become more widespread and one of the approaches is to use one lead diesel to set the grid frequency and to set the others to run at fixed throttle (Kaikhurst, 1998)

.

2.3 Hybrid Power System Configurations

According to Wichert (1997), hybrid energy systems with or without renewables, are classified according to their configuration as series, switched hybrid, or parallel hybrid.

2.3.1 Series hybrid system

In this system either the renewable energy source or the diesel generator is used to maintain charge in a large battery bank. During periods of low electricity demand the diesel generator is switched off and the load can be supplied from PV together with stored energy. Power from the battery bank is converted to AC at mains voltage and frequency by a converter and is then fed to the load. Battery charging can be controlled by controlling the excitation of the alternator (Wichert, 1997). The charge controller prevents overcharging of the battery bank from PV generator when the PV power exceeds the load demand and the batteries are fully charged. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven generator.

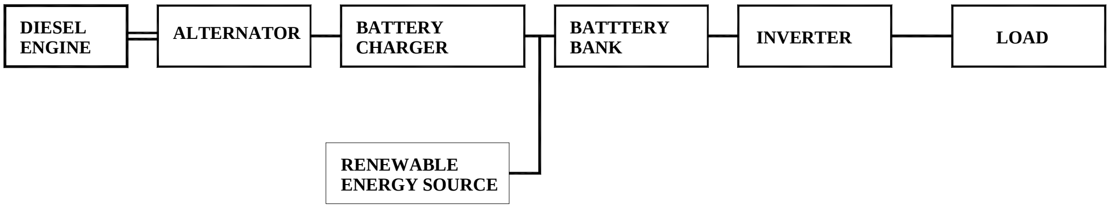

Figure 6 Series hybrid system

Advantages of this configuration include that the engine-driven generator can be sized to be optimally loaded while supplying the load and charging the battery bank, until the state of charge (SOC) of 70-80% is reached. No switching of AC power between the different energy sources is required thus simplifying the electrical output interface. Also the power supplied to the load is not interrupted when the diesel generator is started and the inverter can generate a sine-wave, modified square-waves, or square-wave, depending on the application.

Although the design principles of the series hybrid systems are relatively simple to implement. Islam (1999) highlights its disadvantages to include: low overall efficiency due to the series configuration of system elements; substantially larger battery capacity than the maximum peak load demand resulting in the system being more expensive component to the system; and with renewable inputs, there is limited control of diesel alternator because the system is based on level of charge in the battery rather than the site load.

A series hybrid system is characterized by low overall system efficiency since the diesel cannot supply power directly to the load; large inverter and due to the cycling profile large battery bank is required to limit the depth of discharge; and limited optimisation of diesel alternator and renewable energy sources(SOPAC Miscellaneous Report 406, 2005). The battery bank is cycled frequently, shortening its lifetime. If the inverter fails there is complete loss of power to the load, unless the load can be supplied directly from the diesel generator for emergency purposes.

2.3.2 Switched hybrid system

This system allows with either the engine-driven generator or the inverter as the AC source but no parallel operation of the main generation source is possible (Islam, 1999). Both the diesel generator and the PV array can charge the battery bank. The diesel alternator meets the load during the day and evening peak while the battery bank is charged by the renewables and any excess power from the diesel. Power is supplied to the load by the battery through the inverter during the low load night period. The typical layout of the system is as shown in figure 7.

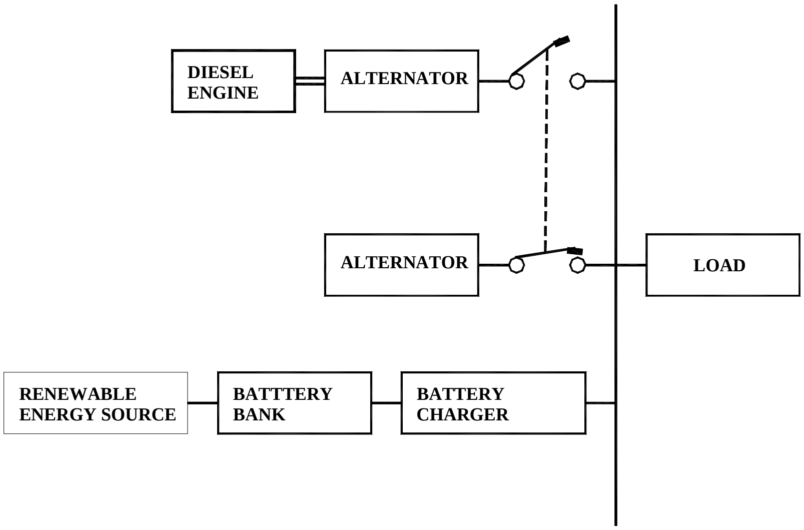

Figure 7 Switched configuration

The main advantages of the system are quiet operation at night and partial improvements in diesel consumption. A switched hybrid system is also characterized by the fact that the diesel generator can supply the load directly, therefore improving the system efficiency and reducing the fuel consumption (SOPAC Miscellaneous Report 406, 2005). As for the series system, the diesel generator is switched off during periods of low electricity demand and the inverter can generate a sine-wave, modified square-wave, or square-wave, depending on the application. Switched hybrid energy systems can be in manual mode, although the increased complexity of the system makes it highly desirable to include an automatic controller, which can be implemented with the addition of appropriate battery voltage sensing start/stop control of the engine-driven.

The diesel system and inverter are typically designed to meet the peak loads, which reduces their efficiency at part load operation and there is no optimisation control on the diesel as the source switching solution is based on a simple time clock. Power to the load is interrupted momentarily when the AC power sources are transferred

2.3.3 Parallel hybrid System (Source/ Charger-

Parallel Inverter/ Storage)

The parallel configuration shown in figure – allows all energy sources to supply the load separately at low or medium demand, as well as supplying quick load from combined sources by synchronizing the inverter with the alternator output wave form the bi-directional inverter can charge the battery bank when access energy is available from the engine driven generator, as well as act as DC-AC converter In this case the renewables and the diesel generator supply part of the load demand directly. The diesel generator and the inverter run in parallel.

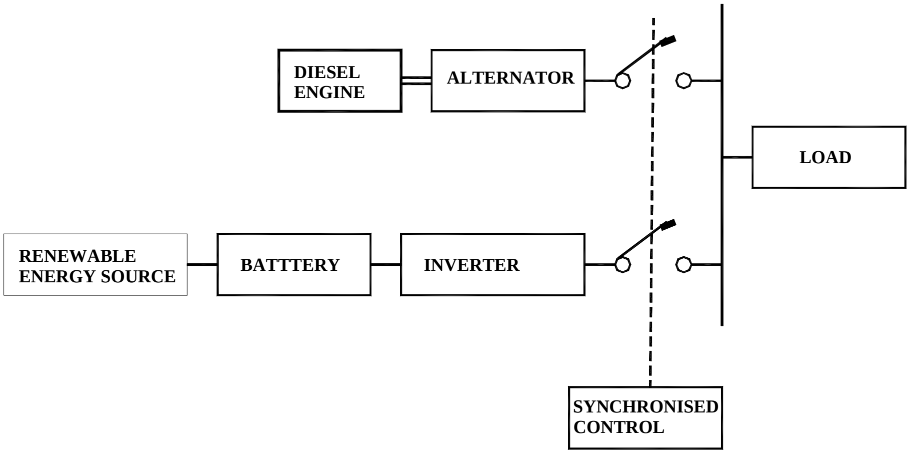

Figure 8 Parallel configuration

Advantages of this configuration over other system configurations are that the system load can be met in the most optimal way, diesel efficiency can be maximized, diesel generator maintenance can be minimized and there is a reduction in the capacities of diesel, battery and renewable sources while load peaks are being met. However, automatic control is essential for the reliable operation of the system and the system operation is less transparent to the untrained user of the system. Also the inverter has to be a true sign wave inverter with the ability to synchronize with a secondary AC source.

2.4 System Benefits

According to Wichert (1997), a key feature of hybrid systems is the fact that their constituent system strengths complement one another. This provides a number of advantages, which are also determined in part by the system type: significantly greater reliability in power supply due to the use of two or more energy sources; more efficient system solutions by virtue of a high degree of flexibility during the design phase and in operation; lower overall maintenance costs due to the shorter operating cycles of the motor generator units; and longer service life time of components as a result of reduced use. Karnavas and Papadopoulos (1999) also highlight the following advantages of solar hybrid systems : reduced operational cost due to less fuel consumption and low PV maintenance; improved reliability through diversifying power sources and continuous power supply; increased operational life due to less genset operating hours; improved energy services and environmentally friendly due to reduced emissions and noise pollution

The fuel savings in hybrid system without storage are affected by two main effects. As the diesel has to be operated in a mode that follows the effective load (load – PV production), it may be forced to operate under part load conditions quite often. This causes an increase of the fuel consumption per kWh produced. Second there is the need to dump PV-power, when the possible PV-production is above the actual load. In view of the lifetime of the diesel gen-set and the system stability it is not recommended to operate the diesel below a certain effective load (e.g. 15% of nominal). This causes another share of PV-energy that needs to be dumped . A hybrid system that relies on photovoltaics for the generation of most of the power during periods when there is sunshine, and use generator power when sunshine is not available offsets capital costs of photovoltaics and operating costs of the diesel generator (Lopez and Agustín, 2004).

Table 1 Summary of merit and demerits of different power supply systems

Power Supply System	**Advantages**	**Disadvantages**
Diesel /battery	• Low initial capital cost	• Noisy

	• Generate power on demand	• Short durability • Very expensive to run and maintain • Environmental pollution
PV Stand -alone	• Safe, clean and quiet to operate; • Highly reliable; • Require virtually no maintenance; • Operate cost-effectively in remote areas and for many applications; • Flexible and can be expanded at any time to meet demand • Increased autonomy – independence from the grid or backup during outages.	• Not well suited for highly energy-intensive uses such as heating
PV/Diesel/Battery Hybrid	• Reduced operational cost due to less fuel consumption and low PV maintenance • Improved reliability through diversifying power sources and continuous power supply • Increased operational life due to less genset operating hours • Improved energy services • Environmentally friendly due to reduced emissions and noise pollution • Smooths out seasonal weather fluctuations • Reduced 'deep-cycling' of batteries • Extended battery life • Avoid noisy generator	• Additional investment cost of renewable energy sources, batteries and power electronics. • Limited experience of customers and supply utilities with renewable energy and hybrid power system technology. • Systems are generally more complex. • Life-cycle economic analysis required – based on detailed system simulation.

2.5 Battery Storage

The battery storage (bank) is used to store electricity. It enables the continuity of power to the load in the event of power failure or for solar sites in the event of cloudy weather and at night. Both nickel cadmium and sealed – lead acid batteries are usually used for remote area power supply systems. The cyclic energy efficiency of a battery (usually 80% for a new lead-acid battery operated in the optimum region) is also paramount, since energy lost requires a larger input source to replace it. Other important factors that determine life-cycle costs (apart from capital cost) are: the number of cycles delivered (at a certain depth of discharge – DOD), lifetime (usually 3 to 7 years in well-designed systems), and how often it must be maintained (Al-Alawi and Islam, 2004).

2.5.1 Storage in hybrid power systems

In order to maximize renewable resource available and/or to minimize use of backup generator, batteries are incorporated in hybrid systems (Lopez and Agustín, 2004). The same author agues that batteries in such systems experience irregular patterns of charge discharge cycles and that estimation of battery life and optimal sizing of batteries is difficult since battery life depends on both depth and rate of discharge as well as on other factors to include temperature and charging strategy.

Important factors in battery life are battery aging which refers to processes that tend to limit the physical integrity of the battery and its ability perform the intended task; and battery wear which refers to processes that tend to limit the amount of electric energy that can be stored or supplied (Behrendorff, 1999). The author further highlights that while aging is mostly accelerated by adverse environmental conditions or improper maintenance, which can be controlled, battery wear is a function of battery's charge-discharge history. The designer or operator has control over some factors that contribute to useful battery life in a given application like cell temperature, charging regime, battery maintenance procedures, dwell time at low and high states of charge and amount and frequency of overcharge but cannot control the depth rate of discharge.

The capacity of the battery is specified by manufacturers in Ah under a certain discharge rate and cell temperature. If energy stored in a battery is C_{25}=100 Ah then it can provide a current of 4 Amps for 25 hours. Energy in Kilowatt Hours (kWh) = Ah x V / 1000, in which V is the battery voltage (Karnavas and Papadopoulos, 1999). Charging rates are specified by battery manufacturers and depend on the battery capacity and state of charge. The depth of discharge refers to the measure of how much of the total battery capacity has been consumed and is usually given in percent while State of Charge refers to a measure of how much of the initial battery capacity is available and is expressed in terms of % of rated capacity.

The maximum recommended depth of discharge is usually around 70% depending on the battery manufacturer’s specifications. Batteries in hybrid power systems are deep cycle batteries that can discharge more of their stored energy while still maintaining long life. Karnavas and Papadopoulos, (1999) also highlight that the operating voltage (12 V / 24 V / 48V) of the battery cell is not constant due to factors such as the internal resistance of the cells and the temperature. The argument is that rate of chemical reaction is reduced when the battery temperature is low, during cold periods and battery capacities are usually given at a reference temperature of 25°C necessitating correction at higher or lower temperatures. Battery bank capacity is usually sized to provide 3-7 days autonomy to a depth of discharge of around 80%.

2.6 Solar Resource Characterization

Photovoltaic systems depend on the availability of the solar resource which is characterized by measured insolation data and parameters related to the site. The site related parameters include geographic information (site latitude and longitude) and temperature information (the nominal ambient temperature or a time series of ambient temperature).

Ambient temperature is used in estimating the solar photovoltaic cell panel temperature. When such data is not available, a representative site mean ambient temperature is used. The value selected should be a daytime temperature, corresponding to the times of highest productivity from the panels. The site latitude is used in solar angle calculations. These calculations are done since solar data is usually taken on a horizontal surface whereas photovoltaic panels are normally installed on a slope. The slope surface generally face south in the northern hemisphere and north in the southern hemisphere.

Sometimes panels are installed on adjustable tracking devices. Solar angle calculations are also needed in those cases. The site longitude is used in solar angle calculations to ensure that the data is converted to solar time. If the solar time is not properly accounted for, errors in the results will appear. Solar resource calculations require knowledge of the day during which the data was taken. Specification of the Julian day of the first data point allows the data to begin on any day of the year. Solar insolation data is assumed to be taken on the horizontal. Data is in Watts per square meter.

2.6.1 Average Hourly Incident Radiation on An Array

Radiation is normally given as daily data, that is as daily global radiation on a horizontal plane, H_h . To solve the global radiation into its beam and diffuse component correlations of the ration $^{Hd}/_{Hh}$ with clearness index, $K = \frac{H_n}{H_o}$

Many correlations have been identified in the literature for different elements and location by different authors e.g. Duffie & Bechaman (1991).

According to Hove and Gottscle (1999), for Zimbabwe and the region.

$$\frac{H_d}{H_h} = 1,0294 - 1,14K \text{ for } K \leq 0,75 \qquad (1)$$

$$= 0,175 \text{ for } K > 0,75$$

To resolve the daily value into hourly value factors r_d and r_h of Liu and Jordan (1996) and Collares Pereira and Rabl (1979) are used.

$$\text{The factor}, \quad r = \frac{\mathrm{I}}{H} \qquad (2)$$

Where I is the hourly radiation and it is the daily radiation.

$$r_d = \frac{\mathrm{I}_d}{H_D} \; and \;\; r_h = \frac{\mathrm{I}_h}{H_H}$$

Since r is a function of hour angle ω and day length ω_s for diffuse radiation.

$$r_d = \frac{\pi}{24} - \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \pi\omega_s}\cos\omega_s \qquad (3)$$

$r_h = (a + b \cos \omega)\, r_d$

where a and b are correlation coefficients given by

$$a = 0{,}409 + 0{,}5016 \sin(\omega_s - 60) \qquad (4)$$

$$b = 0{,}6609 - 0{,}4767 \sin(\omega_s - 60) \qquad (5)$$

By adopting the Collares – Pereira and Rabl Sky Model and making some assumptions the instantaneous radiation incident on the array, L_{array} can be estimated by

$$I_{array} = (I_h - I_d)\mathrm{Cos}\,\theta_{array}/\cos\theta_z + I_d/c \qquad (6)$$

Where I_h is the global, θ_{array} is the angle of incidence of direct irradiance on the array, C is the concentration ratio which is equal to unity for flat-plate array and I_d is the diffuse irradiance.

Geometric factor R_b

This represents the ratio of beam radiation on the tilted surface to that on a horizontal surface at any given time (Duffie & Bechaman, 1991). This factor is important in the solar process design and performance calculations, as it is vital to calculate the hourly radiation on a tilted surface of a collector from estimates of solar radiation on a horizontal surface. The ratio, after some simplifications, is given by

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad (7)$$

where θ_z is found in standard texts and is a function of the declination angle δ

Declination Angle, δ

This refers to the angular position of the sun at solar noon and is found by

$$\delta = 23{,}45 \sin\left[\frac{360}{365}(n + 284)\right] \qquad (8)$$

For the purpose of calculation in the model the monthly average day is used as adopted from Klein (1977).

The angle of incidence as given in various texts [e.g (Duffie & Bechaman, 1991)] is as follows:

$$\cos\theta = \sin\delta\sin\Phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos y + \cos\delta\cos\phi\cos\beta\cos w + \cos\delta\sin\theta\sin\beta\cos y\cos w + \cos\delta\sin\beta\sin y\sin w \tag{9}$$

This is the angle between the beam radiation on a surface and the normal to that surface (Hove and Gottsche, 1999).

Hour Angle (ω) according to Hove and Gottsche (1999) is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^0 per hour, morning negative and afternoon positive.

The slope (β) refers to the angle between the plane at the surface in the practice when installing solar arrays is to place them at an angle β = latitude of location.

2.7 Energy dispatch strategy

Dispatch strategy is the criteria the controller uses to decide when the genset of a hybrid system is turned on, at what loading rate it operates, and when it is turned off (Beyer et al, 2003). In small hybrid systems dispatch strategies are simple, the genset is usually turned on automatically when a low voltage set point is reached and runs until the battery reaches a voltage set point, the battery is fully charged or a preset minimum run time of several hours has elapsed. Many controllers also start the genset when the net load exceed a certain level; sometimes it is left to the user to start the generator manually when this condition exists.

In most hybrid systems the genset runs at full load and any power not required by the load contributes to battery charging. Partial loading of the genset occurs when the battery is approaching full charge and cannot accept the full current of the genset. In some systems, however, the genset turns on only if the load is reasonably large and then runs on the loading which supplies just enough power to keep the battery from discharging. (i.e. it supplies power equivalent to the load power minus and power available from other generators.)

In certain hybrid systems, the battery is used only to buffer transients in demand and therefore there is no real dispatch strategy. The genset runs at all times supplying the average of the difference between the load and the power available from renewable sources. In systems with multiple gensets where the number of genset on line is determined by the loading level associated with the average as oppose to the maximum, when there is brief demand for more power, a small battery makes up the shortfall.

Dispatch strategies are sometimes implemented with operating set points that have been selected by rules of thump (Beyer et al, 2003).While these set points may work they generally will not achieve least-cost operation of the system. Methods exist that can help select optimum strategies and set points but it is important to note that most hybrid system controllers currently available are sufficiently sophisticated that they can implement optimal dispatch strategies, the challenge is the selection of the strategy not its implementation.

An optimal dispatch is the one that minimize the life-cycle cost of the hybrid system and dispatch strategies affect costs associated with genset fuel use, genset maintenance and battery life but the influence is difficult to quantify for the last two (Beyer et al, 2003). It should also be noted that the overall system performance depends on the dispatch strategy.

2.8 System sizing

Major issues that arise when designing a system include that the load placed on the system is not constant, that the amount of energy available from the renewable energy source is variable and that technology that best suits site should be implemented (Hove, 2000). Therefore the design has to be iterative using simulation models that can evaluate instantaneous system performance.

Several software tools are available on the market and in research groups to optimize and simulate hybrid energy systems, but it is sometimes difficult to assess the adequacy of these tools to specific tasks. Also, more details are available from the system when performing optimization than at the planning phase. According to http://www.ecs.umass.edu/mie/labs/rerl/hy2/theory/pdf/users.pdf, use of such programs require high expertise and financial resource hence the development of simplified computational methods that are less costly. Also the user does not get an intuitive understanding of the system since figures are just fed into the system, hence the development of simpler home-made models. In the development of these homemade models the user is able to include specific things that one needs to use. A system can be designed with a smaller or larger solar array or battery, or may make more use of the diesel generator. The problem is to find a system that provides an optimal combination of solar array, battery and usage of the diesel engine.

2.8.1 Estimation of Electrical Load

The electrical loads can be estimated if the power used by each appliance is known. The total energy required will depend on this power draw and the operating time of the appliance. Overall electrical loads can be determined by drawing up a list of all items, their power use and their average operating time per day. The total will be used in determining the size and type of system required.

2.8.2 Load Profiles

The load profile has been defined by Karnavas and Papadopoulos (1999) as the power requirements for the demand-side converters (appliance loads) over time. Once energy conservation (demand side management) techniques are used to reduce the electrical load as far as economically possible whilst still providing the required service, the load profile should be determined to decide the type of hybrid system needed to provide power. The load profile may vary by the hour, day, week, month, season, or year. The peak demand spikes can be met from the batteries and the engine generator started and operated at a steady load when the battery state-of-charge drops below a pre-set level.

The most convenient method of determining the load profile of a system is by measuring electricity demand using an energy (kilowatt / kilowatt-hour) meter, and logging the output hourly, or more often, for at least a week, preferably a month or year (seasonal variations). This can be done either manually if someone can read the meter at regular intervals, or a data logger can be used, in which case much more detailed information is available. This will reveal the daily and weekly profiles. If seasonal variations in load are suspected, longer-term (yearly) load monitoring will be required to reveal the seasonal profile (Karnavas and Papadopoulos , 1999)

2.8.3 Photovoltaic Modules: Technician's method

According to Klein (1977) to determine the actual required PV array output, divide the daily energy requirement by the battery efficiency which is usually between 0.70 and 0.95 and depends on the coulombic efficiency of the batteries in both charging and discharging. Generally 0.95 is used for very efficient batteries installed in good conditions and 0.7 for the least efficient batteries.

The author highlights that to work out the output from the array, it is important to know under what conditions the output will be determined, and need to know what the inclination of the array will be. This is measured in peak sun hours, which is dependent on latitude, season and inclination of the array. The scenario generally chosen for solar / generator hybrid systems is the yearly average peak sun hours. If tables of peak sun hours are not available they can be determined from the average of daily total global radiation. To convert daily global radiation (MJ/m_2) to peak sun hours divide by 3.6. The output of the modules will be average annual peak sun hours times the module rating.

To determine the number of modules in the array first work out the number of modules in series so that the operating voltage is sufficient for battery charging. Divide the system voltage by the nominal operating voltage of each module. To determine the number of modules in parallel the array output required (Ah) is divided by the output of each module (Ah). However this method does not apply in this research as it does not take into account many things and in a hybrid system energy flows need to be known from hour to hour.

2.8.4 Sizing The Charge Controller/ Battery Charger

Generators in renewable systems are used to power the battery charger, particularly during poor weather, or to supply heavy loads. They can be automatically or manually controlled. In most systems, either diesel, petrol or gas driven generators are used (Hove, 2000).

A battery charger converts the AC output to DC for the purpose of battery charging. The battery charger should be selected such that it converts the 240 volt, 50 Hz AC to DC at the required bus voltage of the battery storage bank. It should be able to provide a direct current up to the maximum allowable charge rate of the batteries. The two critical factors to consider when selecting a battery charger are the system voltage and the maximum rate of charge of the batteries. There may not be a battery charger with exactly the maximum current specified so a charger with lower current would be chosen. The most likely available charger would be 24 Volt 60 Amps. The size of the battery charger is determined by the size of the battery bank (Hove, 2000).

A charge controller should be sized to pass the expected continuous current from the array (or sub-array) into the battery, and should be able to withstand temporary peak currents due to sunnier than normal conditions. It is critical that the controller be adequately sized since the costs associated with the controller are much greater than the cost of initially installing a slightly larger controller. A module will normally have a maximum current output which is its rated short circuit current (when battery voltage is low). It is possible for irradiance levels to reach 3000 watts/m^2; the short circuit current is normally rated for irradiance levels of 1000 watts/ m^2. Charge controllers should be sized therefore, to regulate 130% of a module’s normal short circuit current. The size of a controller can be calculated by multiplying the I_{sc} current of a module by the number of modules in parallel and the 1.3 safety factor. Consult with the manufacturers to determine if they have already build a safety factor into their rating value; oversizing by 130% may not be necessary if the controller is already designed to handle higher than rated currents (Beyer, 2003).

2.8.5 Inverter Power

The inverter converts DC power from the battery bank and/or PV array to AC whenever power from diesel generator sets is not available. It changes DC energy stored within the batteries to AC energy, suitable for the standard appliance operating voltage of 240V. An inverter can generally only supply loads up to its kilowatt rating, although all inverters have a surge rating for electrical peaks. This allows for motor starting, or other brief overloads (http://www.energymatters.com.au/renewable-energy/solar-power/stand-alone-power-systems/).

The output power (wattage) of an inverter indicates how much power the inverter can supply during standard operation. It is important to choose an inverter, which will satisfy a system’s peak load requirements. Most inverters are able to exceed their rated wattage for limited periods of time. This is necessary since appliances may require many times their rated wattage during start up and the minimum surge requirement may be calculated by multiplying the required wattage by three. Some Inverters have the added advantage that they have a built-in battery charger so that when the batteries need charging from an AC source (generator), the current can be fed into the inverter, changed to DC, and then used to charge the batteries (Behrendorff, 1999)

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This section looks at the energy demand analysis, demand matrix, demand profile and the methods used to determine the sizes of the diesel generator and minimum battery capacity for an autonomous system to operate under the worst case when the weather conditions are not favorable. With solar, the actual battery size for instance is determined by simulation from a table, hence the design of the model is described.

3.2 Energy Demand Analysis

The first step was to carry out an energy demand analysis which was done as shown in Table 2 load data gives detailed information about the appliances or equipment to be powered: their number, nominal power, and the number of hours of operation on a typical day. The first column shows the code number of the appliance followed by the appliance and the number of appliances. The power rating in watts is shown in the next column the last column shows the total power obtained by multiplying the appliance number by the power rating of each appliance and can be treated as an N_A *1 matrix where N_A is the number of appliances.

Table 2 Load Data

Code Number	Appliance	Number	Power Rating (W)	Total Power (W)
1	Drug refrigerator	1	300	300
2	Clinic lights	15	20	300
3	Computer	1	150	150
4	Water pump	1	800	800
5	House lights	18	20	360
6	Washing machine	1	1100	1100
7	Fridge	3	300	900
8	Pressing Iron	3	500	1500
9	TV	3	150	450

3.3 Appliance Usage Matrix

Table 3 shows an appliance usage matrix, which is a new method convenient for the computation of the above data. It shows the time of the day and the appliance in use for each hour. This represents a 24* $N_{\mathbf{A}}$ matrix which when multiplied by the $N_{\mathbf{A}}$ *1 matrix give a 1*24 matrix that represents the load as shown in table 4.

Table 3 Appliance Usage Matrix

	Appliance in Use								
Time	1	2	3	4	5	6	7	8	9
1:00	1	1	0	0	0	0	1	0	0
2:00	1	1	0	0	0	0	1	0	0
3:00	1	1	0	0	0	0	1	0	0
4:00	1	1	0	0	0	0	1	0	0
5:00	1	1	0	0	0	0	1	0	1
6:00	1	1	0	0	0	0	1	0	1
7:00	1	0	0	0	0	0	1	0	1
8:00	1	0	1	0	0	0	1	0	0
9:00	1	0	1	1	0	1	1	0	0
10:00	1	0	1	1	0	1	1	0	0
11:00	1	0	1	1	0	0	1	0	0
12:00	1	0	1	1	0	0	1	0	0
13:00	1	0	1	1	0	0	1	0	0
14:00	1	0	1	1	0	0	1	0	0
15:00	1	0	1	1	0	0	1	0	0
16:00	1	0	1	1	0	0	1	0	0
17:00	1	0	1	0	0	0	1	0	1
18:00	1	1	0	0	1	0	1	0	1
19:00	1	1	0	0	1	0	1	1	1
20:00	1	1	0	0	1	0	1	0	1
21:00	1	1	0	0	1	0	1	0	1
22:00	1	1	0	0	1	0	1	0	1
23:00	1	0	1	0	0	0	1	0	0
0:00	1	0	1	0	0	0	1	0	0

3.4 Load Profile

Table 4 Load Profile

Time	**Load (kW)**
0	0
1	1.5
2	1.5
3	1.5
4	1.5
5	1.5
6	1.95
7	1.95
8	1.65
9	1.35
10	3.25
11	3.25
12	2.15
13	2.15
14	2.15
15	2.15
16	2.15
17	2.15
18	1.8
19	2.31
20	3.81
21	2.31
22	2.31
23	2.31
24	1.35
Total	50

3.4 Load demand profile

The resulting load demand profile as depicted in figure 9 was obtained by plotting power against time.

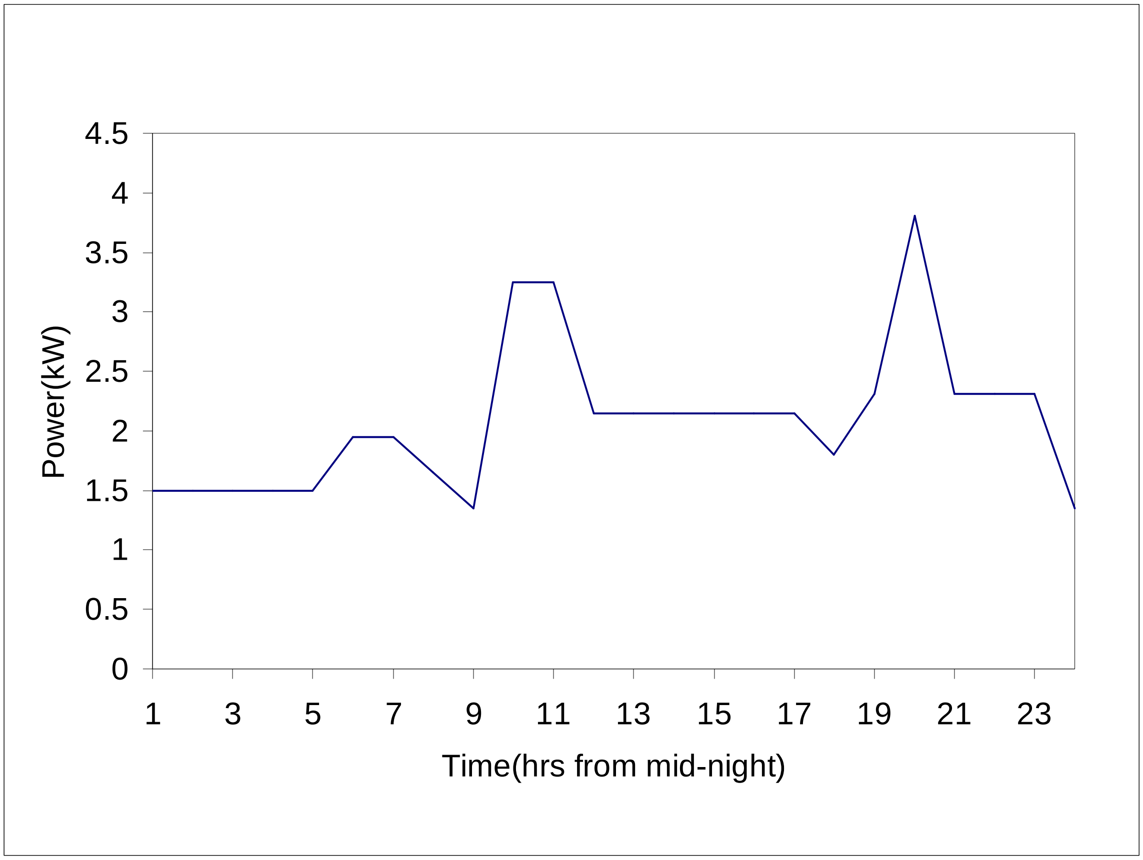

Figure 9 Load Demand Profile For a Typical Rural Clinic

3.5 Sizing of System Components

The system is supposed to operate with solar, diesel generator and battery, and should be able to supply power even during cloudy periods, therefore the diesel generator and the battery should be able to cater for that. There is therefore a minimum battery size to cater for the worst case when environmental conditions are not favorable and in the following section sizing of the battery and the generator set is done. The assumption here is that the diesel generator operates for 20 hours per day.

Table 5 Battery and Diesel generator sizing

TIME	LOAD(KW)	NORMALISED LOAD	CUMMULATIVE NORMALISED LOAD	NORMALISED DIESEL POWER	CUMMULATIVE DIESEL SUPPLY	DISCREPANCY
0	0		0	0	0	0
1	1.5	0.0300	0.0300	0.0500	0.050	-0.02
2	1.5	0.0300	0.0600	0.0500	0.100	-0.04
3	1.5	0.0300	0.0900	0.0500	0.150	-0.06
4	1.5	0.0300	0.1200	0.0500	0.200	-0.08
5	1.5	0.0300	0.1500	0.0500	0.250	-0.1
6	1.95	0.0390	0.1890	0.0500	0.300	-0.111
7	1.95	0.0390	0.2280	0.0500	0.350	-0.122
8	1.65	0.0330	0.2610	0.0500	0.400	-0.139
9	1.35	0.0270	0.2880	0.0500	0.450	-0.162
10	3.25	0.0650	0.3530	0.0000	0.450	-0.097
11	3.25	0.0650	0.4180	0.0000	0.450	-0.032
12	2.15	0.0430	0.4610	0.0000	0.450	0.011
13	2.15	0.0430	0.5040	0.0000	0.450	0.054
14	2.15	0.0430	0.5470	0.0500	0.500	0.047
15	2.15	0.0430	0.5900	0.0500	0.550	0.04
16	2.15	0.0430	0.6330	0.0500	0.600	0.033
17	2.15	0.0430	0.6760	0.0500	0.650	0.026
18	1.8	0.0360	0.7120	0.0500	0.700	0.012
19	2.31	0.0462	0.7582	0.0500	0.750	0.0082
20	3.81	0.0762	0.8344	0.0500	0.800	0.0344
21	2.31	0.0462	0.8806	0.0500	0.850	0.0306

The first column in table 5 shows time for the day while the next one shows the load which is taken from table 4. This load can be normalized by dividing the hourly load by the total daily load to get the next column. The following column is obtained by finding the cumulative normalized load.

Diesel power was normalised on an hourly basis to give the next column by diving by the product of the number of hours of operation. The cumulative diesel power was done using the same principle as for cumulative load to give the next column and the last column shows the discrepancies between the cumulative supply and the cumulative demand.

To size the diesel generator, the diesel power required is found by dividing the total daily load by the product of the number of hours of operation and the battery efficiency. Thus the power is normalized to get 50/20 = 2.5kW. This power has to be divided by a factor of 0.85 to cater for battery inefficiency and this was normalised.

Required power = 2.5/0.85 = 3kW

After considering such factors as temperature derating of 30%, Altitude derating of 10% and a power factor of 95% then the required power is divided by the product of 0.7, 0.9 and 0.9 to give the rated power of 4.9. The next size of generator was then taken as 5kVA The rest time for the diesel generator is during the day to enable maintenance of the system to take place during day time.

Battery storage is required to smoother the high fluctuation of the discrepancy between the supply and demand. In this strategy, which was called the Night Strategy in this research, the worst case was considered where the diesel generator was meeting all the power demand. In order to size the storage battery capacity, graphs of cumulative normalized diesel power against time and cumulative normalized load against time were plotted and superimposed to get maximum deficit and maximum surplus power as shown in figure 10.

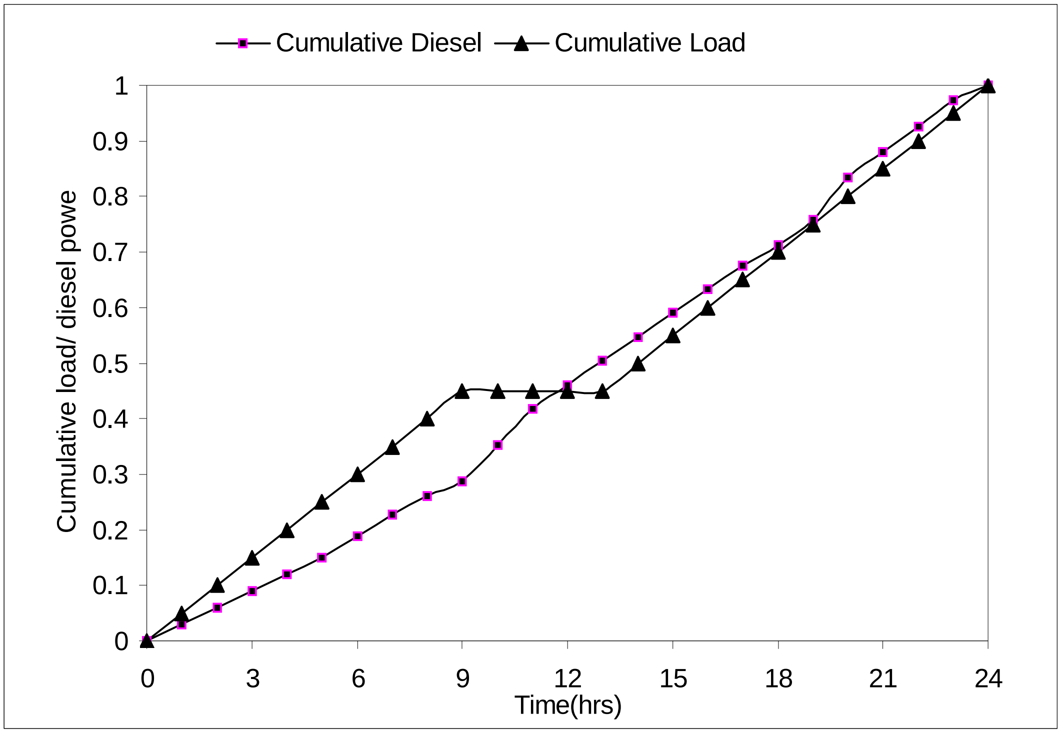

Figure 10 Cumulative normalized load and diesel power against time

The total of the maximum deficit and surplus gives the storage, which has to be divided by the allowable depth of discharge, which is 0.5 in this research. The result is further divided by the battery discharging efficiency and multiplied by the daily load to give the minimum battery storage of 50*0.5 = 25 kWh.

3.6 The Study Model For The PV-Diesel-Battery Power Supply System Performance Simulation

The model used in this study, for simulating the performance of the PV-Diesel-Battery power supply system, is an improvement of an earlier model by Hove (2000). The improvements of the present model, over the earlier model, include; ability to simulate hourly diesel generator load ratio thus enabling the calculation of specific fuel consumption and generator maintenance schedule; a battery life model for estimating battery life depending on charge-discharge history; and flexibility on the choice of the diesel generator dispatch strategy. The model makes an hour-by-hour audit of the energy flows in the system, taking into account the variability of the load; the environmental driving forces (solar radiation and ambient temperature); the battery state of charge; and the diesel generator dispatch strategy. Different hourly performance characteristics of the power supply system can be calculated by the model, such as the PV generator energy output; the hourly battery energy gain (charge or discharge); the hourly solar or diesel contribution to the load; the hourly diesel generator load ratio and fuel consumption; the fraction of the battery charge life spent in the hour in question; and other performance characteristics. The salient features of the model are outlined in the following sections.

3.6.1 Photovoltaic Generator Output

The hourly energy output from the PV generator of given area, *A*, is given by:

$$Q_{PV} = \eta_{PV} \bullet \mathrm{A} \bullet I_{PV} \tag{10}$$

In Equation (1), η_{PV} is the efficiency of the PV generator, which can be expressed as a function of the hourly solar irradiation incident on the PV array, I_{PV} (kWh/m^2), and the ambient temperature, T_a, as well as the test parameters of the PV generator at Standard and Nominal Cell Operating Temperature (NOCT) conditions. The expression for η_{PV} derived by Hove (2000) was used:

$$\eta_{PV} = \eta_r \left[1 - 0.9\beta(I_{PV} / I_{PV,\mathrm{NOCT}})(\mathrm{T}_{c,\mathrm{NOCT}} - \mathrm{T}_{a,\mathrm{NOCT}}) - \beta(\mathrm{T}_a - \mathrm{T}_r)\right] \tag{11}$$

η_r is the PV generator efficiency measured at reference cell temperature, T_r, i.e. under Standard test conditions (25^{o}C). β is a temperature coefficient for cell efficiency (typically 0.004 to 0.005/^{o}C), $I_{PV,\mathrm{NOCT}}$ is the averaged hourly solar irradiation incident on the array at Nominal Operating Cell Temperature (NOCT) test conditions (0.8 kWh/m^2), $\mathrm{T}_{c,\mathrm{NOCT}}$ (typically 45^{o}C), $\mathrm{T}_{a,\mathrm{NOCT}}$ (20^{o}C), are respectively, the cell and ambient temperatures at NOCT test conditions.

The hourly solar irradiation incident on the PV array is a function of time of day, expressed by the hour angle; the day of the year; the tilt and azimuth of the PV array; the location of the PV array site as expressed by the latitude; as well as the hourly global solar irradiation and its diffuse fraction. The actual expression depends on the so-called sky model (a mathematical representation of the distribution of diffuse radiation over the sky dome) preferred. In the study, the simplified isotropic diffuse formula suggested by Collares-Pereira and Rabl (1979) was used because it can be applied with a simple data set that is easily obtainable in Zimbabwe.

$$I_{PV} = (I_h - I_d)R_b + I_d \tag{12}$$

In Equation (3), I_h and I_d are, respectively, the hourly global and diffuse irradiation in kWh/m^2. R_b is geometric factor representing the ratio of beam irradiance incident on a tilted plane to that incident on horizontal plane. It was calculated using a standard formula from solar geometry literature (Hove and Gottsche, 1999)

Monthly average hourly meteorological data, global irradiation, diffuse irradiation and ambient temperature were used as inputs in evaluating Equations (10), (12) and (13) of the performance simulation model. The evaluation was performed at the mid-point of each hour of the day, on the "average day" of each month defined by Klein (1977).

3.6.2 Battery Energy

The battery is charged by the PV generator and/or by the diesel generator and is discharged to make good supply deficit by the PV and diesel generators. The hourly battery charge or discharge depends on the size of the hourly load, L_o, relative to PV-generated (Q_{PV}) plus diesel-generated (Q_D) power, as well as the battery state of charge.

The battery discharges if $L_o > (Q_{PV} + Q_D)$ and the battery is not empty.

The amount of battery discharge, *Bgain*, is limited, by the charge regulator, to the maximum allowable rate of discharge. Hourly battery discharge satisfying the above conditions is written:

$$Bgain(-ve) = -\min[L_o - (Q_{PV} + Q_D);\ Bcap/T_{\min};\ Blevel - (1-DOD_{\max})Bcap] \tag{14}$$

$Bcap$ = Battery capacity [kWh]
$Blevel$ = Battery energy level at beginning of hour in question [kWh]
$T_{\min}$ = minimum time the battery is allowed to discharge from full capacity to empty [hours]
$DOD_{\max}$ = maximum allowable depth of discharge

The battery charges if $L_o < (Q_{PV} + Q_D)$ and the battery is not full. The corresponding hourly battery charge gain is:

$$Bgain(+ve) = \min[(Q_{PV} + Q_D) - L_o; Bcap/T_{\min}; Bcap - Blevel] \quad (15)$$

In addition the battery energy due exclusively to the PV generator, *Bgain-PV*, is calculated using equations similar to (4) and (5) with appropriately set conditions.

3.6.3 Solar Fraction

The hourly solar fraction- the fraction of the hourly load contributed by solar energy- is calculated as follows:
The hourly energy contributed to the load by solar energy, L_s, is the sum of the PV hourly output and the battery discharge attributable to solar energy, *Bgain-PV*. It is limited by the diesel generator supply deficit, L_o-Q_D.

$$\begin{aligned} Ls &= \min\{Q_{PV} + Bgain\text{-}PV(\text{-ve}); L_o - Q_D) && \text{if Lo} > Q_{PV} + Q_D \\ &= Q_{PV} - Bgain\text{-}PV(\text{+ve}) && \text{otherwise} \quad (16) \end{aligned}$$

The daily solar contribution to the load is the sum of the hourly contributions, and the daily solar fraction is the ratio of the daily solar contribution to the daily load. The monthly solar fraction is equal to the daily solar fraction for the average day, and the annual solar fraction is the weighted average (according to number of days in each month) of the monthly solar fractions.

3.6.4 Battery Life Estimation Model

The model is also able to estimate the lifespan of the battery based on manufacturer's data on battery life cycles for varying depth of discharge and variation of battery capacity with time to discharge (discharge current).

In the battery model used, the ratio of the effective discharge (d_{eff}) of the battery, for any discharge event, to the actual observed discharge (d_{actual}) depends on:

1) the ratio of the average depth of discharge of the battery during the discharge event (D_A), to the manufacturer's rated discharge (D_R), D_A/D_R.
2) the ratio of the rate of discharge during the discharge event to the manufacturer's rated discharge rate, I_A/I_R.

The relationship is:

$$d_{eff} / d_{actual} = \mathrm{f1}(D_A/D_R) \times \mathrm{f2}(I_A/I_R) \qquad (17)$$

where the functions f1 and f2 are obtained from curve fitting equations of the relations between manufacturer's battery life-cycle versus depth of discharge, and that on amp-hour capacity versus time to discharge.

The battery life, in units of the discharge event duration (1 hour in the present case), is the rated charge life (amp-hours) divided by the effective discharge in each discharge event.

3.6.5 Diesel Generator Dispatch Strategy and Load Ratio

The criteria employed for turning on/off the diesel generator set (the dispatch strategy) was made a variable in the model. It affects the hourly energy flow pattern in the power supply system; the variation of battery state of charge; the amount of usable PV energy at any given time; the hourly load ratio of the diesel generator; etc. In this study two diesel generator dispatch strategies were considered:

1) the diesel generator is turned on at night OR when the incident solar irradiance is low (below a certain threshold, say $I_{PV} < 0.08$ kWh/m^2)

i.e. Q_D = rated diesel power if $\text{abs}(\omega) > \omega_s$ OR $I_{PV} < 0.08$ kWh/m^2
= 0 otherwise,

where Q_D is the hourly diesel energy output, ω is the hour angle and ω_s is the sunset hour angle.

2) the diesel generator energy dispatch is load-following; it is turned on when the load exceeds a certain prescribed value (e.g. $L_o > 0.8\ L_{bar}$) AND it is greater than the PV power output ($L_o > Q_{PV}$)

i.e. Q_D = rated diesel power if $L_o > 0.8\ L_{bar}$ AND $L_o > Q_{PV}$
= 0 otherwise,

where L_{bar} is the average hourly load.

3.6.5.1 Load Ratio

The model relates load ratio with specific fuel consumption therefore it can calculate the fuel consumption for any load ratio.

3.6.5 Input Data Required by the Model

Electricity is be generated either by photovoltaic array or by diesel generators or both. A battery bank is used to store excess electricity from the PV array and the diesel generators. In order to determine the size of the PV array and other variables there was then need to design a model that could simulate various operations. The major constraint is that solar radiation is not constant, thus the model is designed to be able to simulate variations in solar radiation. Simulation can be done for every day of the year requiring too much data so monthly averages of hourly radiation are used in this approach. For diffuse and global radiation either use data derived from model for calculation of daily average values from various texts or we use readily available statistical data from the meteorological center. Radiation on a tilted surface is calculated for each hour of the day for the average day of the month .

Various conditions were created in order to come up with an operational model. The average meteorological data are assumed to occur on Klein’s average day (Klein, 1977). Solar radiation data shown in table, global and diffuse radiation shown in table as well as the ambient temperature shown in table for Bulawayo were obtained from meteorological department as statistical data.

Table 6 Monthly Average Hourly Solar Radiation Over Bulawayo For The Year 1999

Month	**Time**	**06:00**	**07:00**	**08:00**	**09:00**	**1000**	**1100**	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**Total**
January	Global	0.03	0.42	1.00	1.61	2.06	2.44	2.8	2.61	2.25	1.94	1.61	1.1	0.55	0.08	20.51
	Diffuse	0.03	0.26	0.54	0.79	1.03	1.24	1.31	1.21	1.06	0.87	0.71	0.48	0.28	0.06	9.87
February	Global	0.01	0.29	0.88	1.41	2.05	2.43	2.68	2.74	2.45	2.25	1.77	1.10	0.40	0.08	20.48
	Diffuse	0.01	0.19	0.50	0.74	1.02	1.20	1.33	1.24	0.99	0.78	0.64	0.41	0.18	0.02	9.25
March	Global	0.01	0.27	0.87	1.56	2.15	2.59	2.58	2.56	2.60	2.06	1.44	0.75	0.19	0.00	19.63
	Diffuse	0.01	0.20	0.54	0.78	1.03	1.13	1.15	1.16	0.99	0.76	0.55	0.30	0.09	0.00	8.69
April	Global	0.00	0.15	0.79	1.56	2.27	2.64	2.87	2.80	2.51	2.13	1.48	0.76	0.12	0.00	20.08
	Diffuse	0.00	0.07	0.26	0.41	0.45	0.53	0.61	0.71	0.67	0.58	0.43	0.24	0.07	0.00	5.03
May	Global	0.00	0.11	0.69	1.39	2.07	2.51	2.69	2.60	2.28	1.84	1.22	0.51	0.03	0.00	17.94
	Diffuse	0.00	0.04	0.18	0.28	0.33	0.36	0.38	0.35	0.35	0.34	0.25	0.15	0.02	0.00	3.03
June	Global	0.00	0.02	0.44	1.13	1.76	2.23	2.36	2.36	2.13	1.68	1.13	0.50	0.03	0.00	15.77
	Diffuse	0.00	0.02	0.14	0.25	0.32	0.36	0.4	0.42	0.38	0.35	0.27	0.14	0.01	0.00	3.06
July	Global	0.00	0.03	0.41	1.01	1.65	2.13	2.27	2.30	1.99	1.63	1.07	0.47	0.04	0.00	15.00
	Diffuse	0.00	0.02	0.17	0.37	0.53	0.61	0.66	0.59	0.56	0.47	0.32	0.17	0.02	0.00	4.49
August	Global	0.00	0.13	0.67	1.40	2.05	2.53	2.71	2.66	2.34	1.88	1.26	0.63	0.08	0.00	18.34
	Diffuse	0.00	0.04	0.19	0.33	0.42	0.46	0.52	0.55	0.54	0.43	0.32	0.19	0.04	0.00	4.03
September	Global	0.00	0.19	0.85	1.58	2.23	2.69	3.01	2.98	2.73	2.21	1.51	0.78	0.15	0.00	20.91
	Diffuse	0.00	0.10	0.31	0.46	0.54	0.62	0.62	0.60	0.62	0.53	0.43	0.28	0.08	0.00	5.19
October	Global	0.01	0.38	1.08	1.89	2.58	3.08	3.26	3.17	2.79	2.32	1.61	0.98	0.28	0.00	23.43
	Diffuse	0.01	0.19	0.40	0.59	0.73	0.78	0.79	0.80	0.75	0.62	0.52	0.36	0.14	0.00	6.68
November	Global	0.04	0.46	1.18	1.85	2.44	2.88	3.00	2.99	2.61	2.28	1.67	1.00	0.36	0.02	22.78
	Diffuse	0.03	0.23	0.41	0.59	0.63	0.68	0.86	0.77	0.68	0.58	0.51	0.35	0.16	0.02	6.50
December	Global	0.07	0.42	1.1	1.81	2.41	2.9	3.01	2.77	2.56	2.26	1.66	1.02	0.48	0.06	22.53
	Diffuse	0.03	0.20	0.44	0.60	0.72	0.79	0.92	0.95	0.85	0.85	0.66	0.42	0.22	0.04	7.69

Table 7 Mean hourly ambient temperature for Bulawayo for the period 1975 - 1990

Time	July	August	September	October	November	December	January	February	March	April	May	June
1:00	7.0	9.1	12.5	15.8	16.5	16.7	16.7	16.5	15.2	15.5	9.7	7.2
2:00	6.6	8.8	12.1	15.2	16.1	16.4	16.4	16.2	14.9	13.1	9.5	6.9
3:00	6.3	8.4	11.6	14.8	15.8	16.1	16.1	15.9	14.0	12.9	9.2	6.7
4:00	6.1	8.2	11.2	14.5	15.6	15.9	15.9	15.7	14.4	12.7	9.0	6.5
5:00	6.1	6.1	11.2	14.4	15.5	15.9	15.8	15.7	14.3	12.7	9.0	6.4
6:00	6.0	8.0	11.1	14.8	16.2	16.4	16.0	15.6	14.2	12.6	8.9	6.4
7:00	6.4	9.2	13.7	17.6	18.2	18.1	17.8	17.1	15.7	14.0	10.0	7.0
8:00	10.8	13.4	17.1	20.0	20.0	19.7	19.4	18.9	18.0	16.9	13.9	11.0
9:00	13.8	16.0	19.3	22.0	21.6	21.0	20.8	20.4	19.7	19.1	16.5	13.9
10:00	15.7	17.9	21.3	23.9	22.9	22.2	22.0	21.7	21.2	20.8	18.3	15.7
11:00	17.0	19.4	22.8	25.2	24.0	23.2	23.0	22.8	22.3	22.0	19.6	17.1
12:00	18.1	20.6	24.0	26.3	24.7	23.9	23.7	23.6	23.2	22.9	20.5	18.1
13:00	18.9	21.4	22.8	27.1	25.2	24.3	24.3	24.2	23.8	23.5	21.2	18.8
14:00	19.3	21.9	25.3	27.5	25.2	24.5	24.5	24.5	24.1	23.9	21.5	19.2
15:00	19.4	22.4	25.4	27.5	25.1	24.3	24.5	24.4	24.1	23.9	21.5	19.3
16:00	19.1	21.8	25.0	27.0	24.7	23.9	24.2	24.1	23.8	23.5	21.2	18.9
17:00	18.0	20.8	24.0	25.9	23.8	23.3	23.6	23.5	23.0	22.4	19.9	17.6
18:00	14.4	17.5	21.1	23.7	22.4	22.2	22.5	22.3	21.4	19.8	16.1	13.6
19:00	11.0	13.9	17.5	20.8	20.3	20.4	20.6	20.3	18.9	17.0	13.2	10.8
20:00	9.6	12.4	16.0	19.3	19.0	19.0	19.2	18.8	17.6	15.7	12.0	9.0
21:00	8.9	11.6	15.1	18.5	18.4	18.3	18.4	18.1	16.9	15.1	11.4	8.8
22:00	8.3	10.9	14.5	17.8	17.8	17.9	17.9	17.7	16.4	14.6	10.9	8.4
23:00	7.8	10.3	13.8	17.1	17.4	17.4	17.5	17.2	15.9	14.2	10.4	7.9
0:00	7.3	9.7	13.1	16.4	16.9	17.1	17.1	16.9	15.6	13.9	10.1	7.5
Mean	11.7	14.2	17.6	20.5	20.1	19.9	19.9	19.7	18.7	17.6	14.3	11.8

3.6.6 PV Array Parameters

Input parameters for the PV array are as shown in table 8.The latitude for the site, in this case for Bulawayo is –20.2^0 as it is in the southern hemisphere and the angle of tilt was chosen to be equal to the latitude while the azimuth angle in this case is zero (north facing) for maximizing the year – round radiation income as stated in various texts. The reference efficiency of the state of art PV arrays as well as the temperature coefficient is as shown in the same table. The area A is obtained by inputting the standard area (A/A_o) which is found by dividing the area by A_o which refers to the array area that would be required to satisfy the daily load if the array delivered a constant power throughout the day at reference efficiency and reference radiation conditions.

Table 8 PV Array Parameters

Parameter	**Value**
Tilt (deg)	20.2
Azimuth (deg)	0
Latitude (deg)	-20.2
Standard Area, A/A_o	1.5
Area (m^2)	26
Reference Efficiency	0.12
Temperature Coeffient/^{0}C	0.005

The tilt angle in degrees represents array tilt angle from the horizontal while the angle of latitude refers to the location of the site; positive North and negative South. Another parameter is the efficiency of the array at reference conditions; radiation 1000 W/m^2, and the temperature coefficient for efficiency [$^0C^{-1}$].

3.6.7 Battery Parameters

Table 9 Battery Parameters

Parameter	**Value**
B_{cap}/L_{day}	2
Capacity (kWh)	100
Allowable DOD	0.5
D_R	0.2
CR20(A-H)	100
Battery efficiency	0.85
Battery voltage	24

Battery parameters are as shown in table 8 .Battery voltage for the system is 24. The effective battery capacity is normalized by divided by the daily load to give the standard battery capacity, B_{cap}/L_{day} . The allowable depth of discharge (DOD) given in the table limits the amount of battery discharge, B*gain.*

3.6.8 Diesel Generator set Parameters

Table 10 Diesel Generator set Parameters

Parameter	**Value**
Rated Power (kVA)	5
Power factor /efficiency	0.55
Specific fuel Consumption (kWh/l)	2
Low radiation cut-in (kWh/m^2)	0.08

Table 10 shows the diesel generator set parameters as they are used in the model. The power factor is inputted to come up with the rated power of the generator while 80W is the radiation level at which the generator starts to operate in the load following strategy. The efficiency of the power conditioning equipment, specifically the PV controller is taken as 90%.

CHAPTER 4

Results and Analysis

4.1 Introduction

This section looks at the outputs from the model and their analysis. Comparisons of the outputs from the two energy dispatch strategies are made in order to determine the most suitable strategy for the location and the given load profile.

4.2 Load Sharing

The following Figures 11 – 14 generally show how the load is shared in the PV-Diesel-Battery Hybrid System. The load share is plotted against time for cases where the load is partially met and where the load is satisfied completely for both the Night and the Load-Following Strategies**.** In figure 11 where the load is not satisfied 100% on the Night Strategy, a typical day output shape is depicted which shows the fractions of the load met directly by the PV array, the battery and the diesel generator. For this case, where the area of the PV array is small there is little or no wastage of PV array energy, as evidenced by the neat shape of the PV energy supply curve during the day when diesel genset is off. The situation is different with the Load Following Strategy in which the diesel generator comes into operation at any time to complement the insufficient energy. There is therefore more PV energy wastage as the diesel generator interferes with energy supply once the load is above 80% of the load and the PV energy is less than the load. This is shown in figure 12.

4.2.1 Load Sharing for unsatisfied load

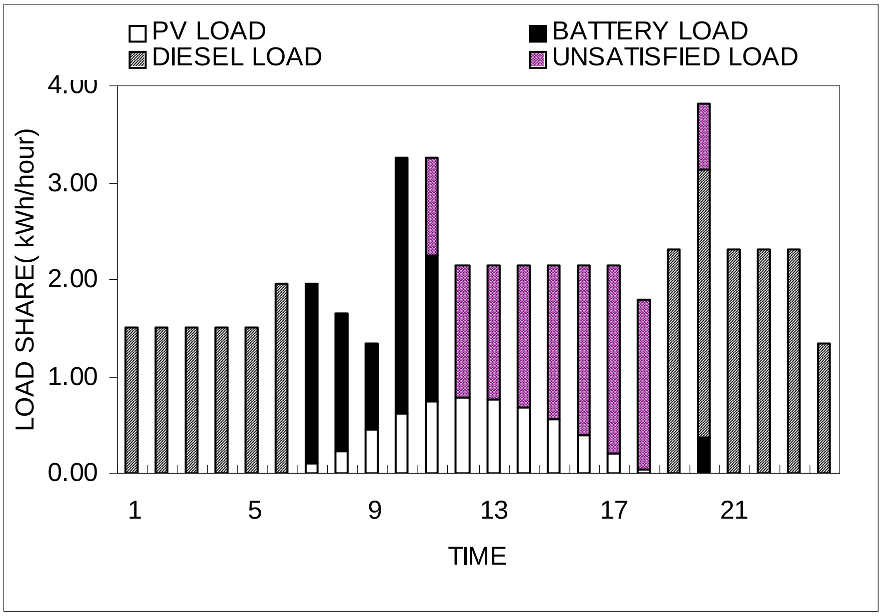

Figure 11 Unsatisfied Load for the Night Strategy

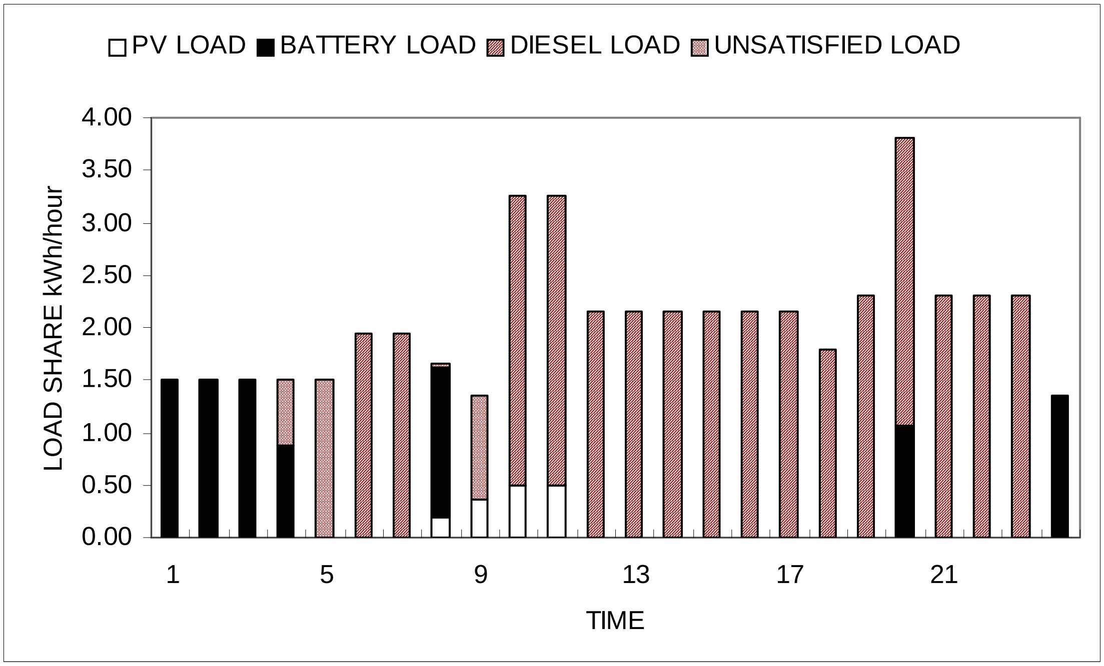

Figure 12 Unsatisfied Load for the Load Following Strategy

4.2.2 Load Sharing for 100% Load **Satisfaction**

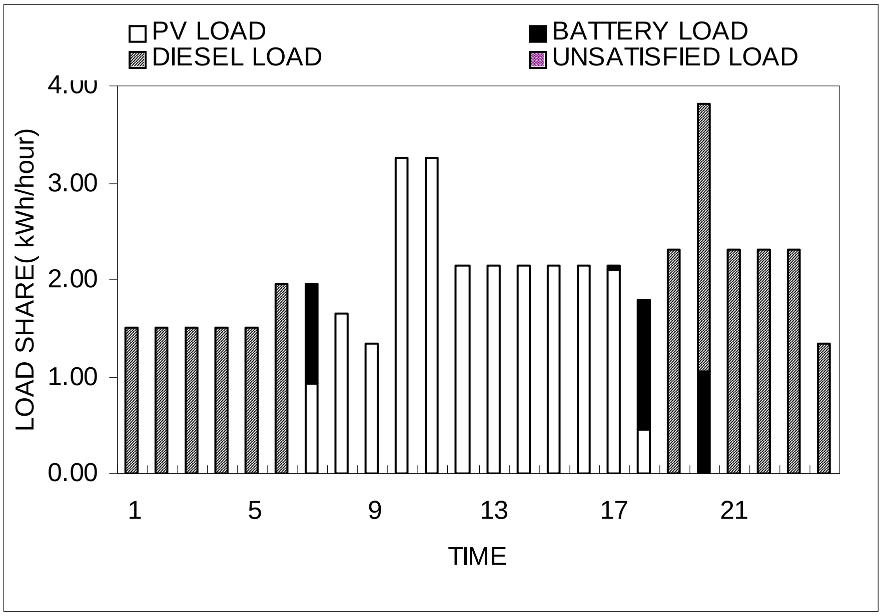

Figure 13 Load Sharing for the for the Night Strategy

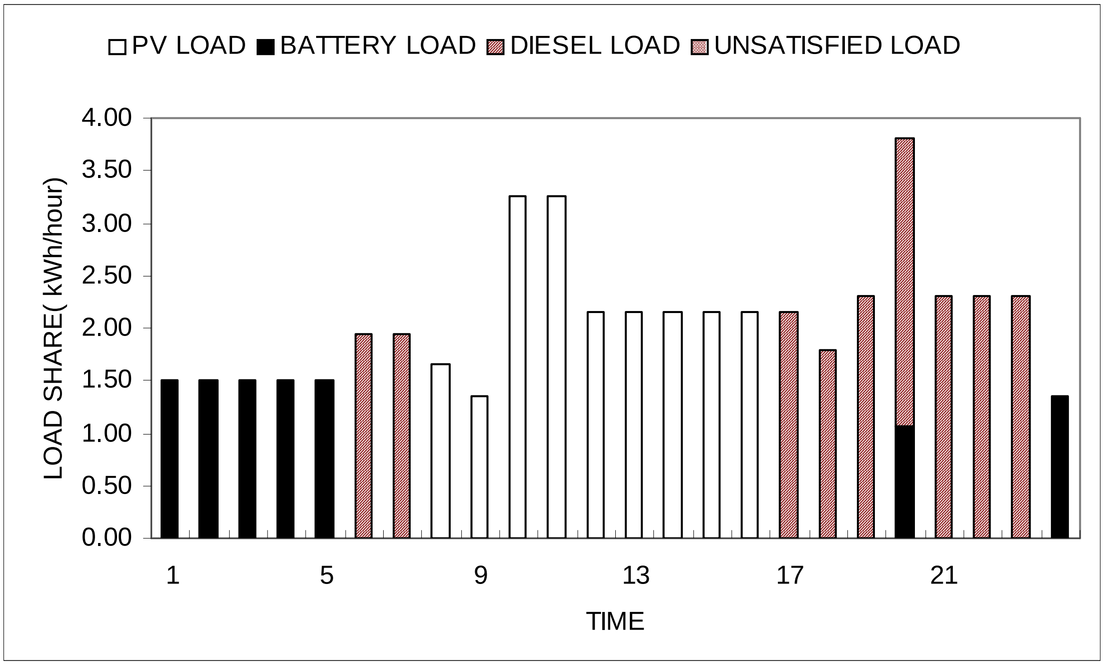

Figure 14 Load Sharing for Load following Strategy

As the PV array is increased adequately, the load can be completely satisfied by the power supply. For the Night Strategy the load sharing picture is shown in figure 13 where the battery comes in to share the load with the PV array. Figure 14 shows that for the Load Following Strategy the diesel comes in any time depending on the loading conditions to share the load. However in both cases solar energy is wasted hence the solar energy output picture is not seen.

4.3 Effect of Normalised Area on Annual Solar Fraction and Diesel Consumption

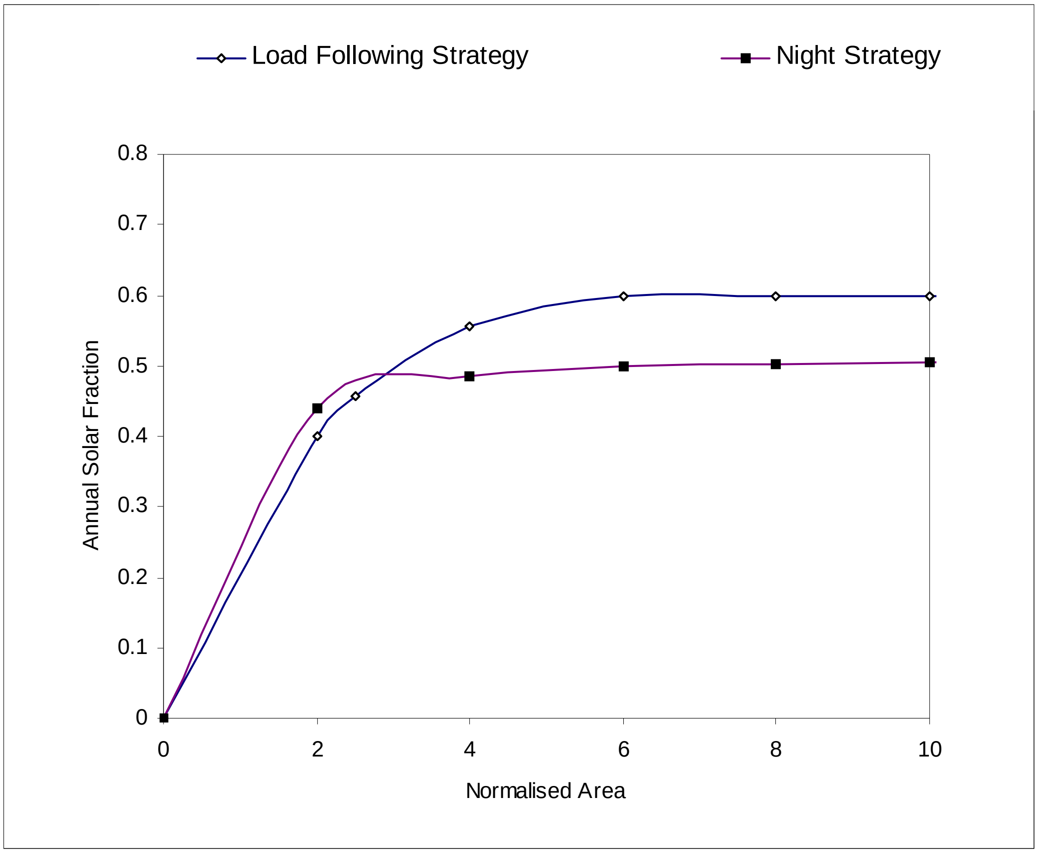

Figure 15 Effect of Normalized Area On Annual Solar Fraction

In figure 15 the annual solar fraction was plotted against the normalised area A/A_o for both the Night and Load Following Strategies, where A is the PV array area and A_o refers to the array area that would be required to satisfy the daily load if the array delivered a constant power throughout the day at reference efficiency and reference radiation conditions. It is given by the equation:

$Ao = L_{day} /(\eta_r * G_{ref} * 24)$

Where L_{day} is the daily load and nr is the efficiency of the array at reference conditions and G_{ref} is the reference solar radiation, 1000 W/m^2.

The curves for solar fraction against normalized area for both strategies show in general that solar fraction increases with increase in normalized area. The marginal increase of solar fraction with normalized area however diminishes as normalized area increases, resulting in an elbow shaped curve. For values of normalized area to the left of the elbow the marginal increase in solar fraction is relatively much higher than for values of normalized area to the right of the elbow.

Comparing the solar fraction against normalized area curves for Load Following and the Night Strategies, it is clear that the load following curve lower lies generally above the corresponding Night Strategy curve which is above the Load Following Strategy for low values of A/A_o but the dominance switches over as the normalized area is increased. The Night Strategy curve reaches the saturation point on the elbow at a much lower A/A_o value than for the Load Following curve resulting in the Load Following Strategy having a greater solar fraction for large normalized areas. Optimal normalized area for the Load Following Strategy is therefore larger than for the Night Strategy. The Load Following Strategy favours a bigger solar array, which means more use of solar energy.

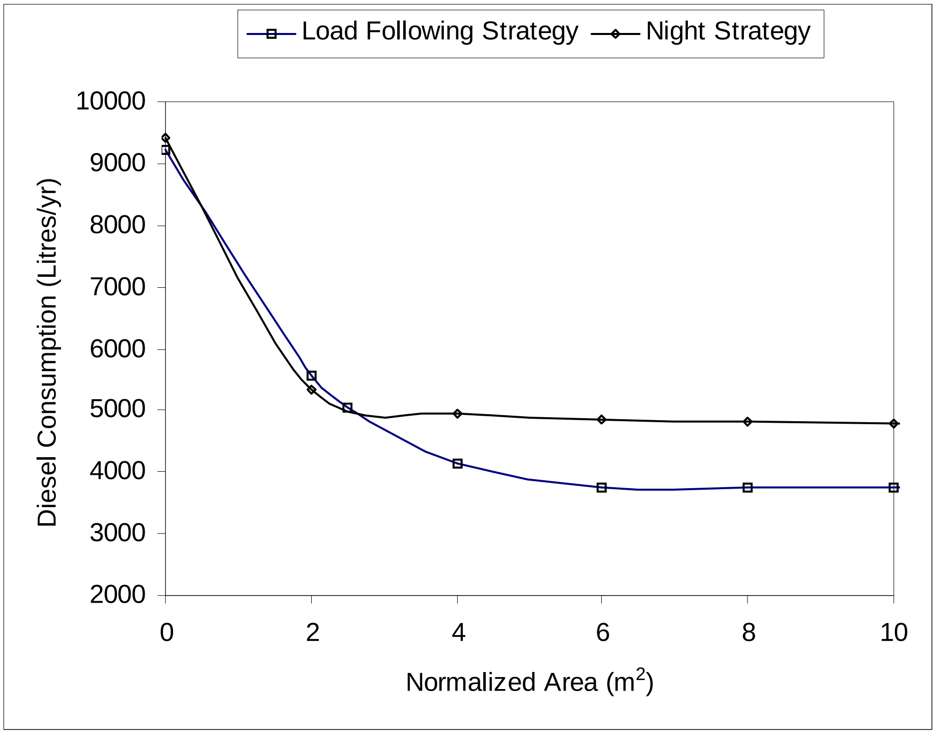

Figure 16 Diesel consumption against Normalized Area

Figure 16, shows the diesel consumption against normalized area curves for both strategies and these depict that diesel consumption decreases as the PV area increases and this should be expected as a larger area implies a larger solar fraction and reduction of the fraction of the load, which is taken by the diesel.

4.4 Relationship Between Normalised Area and Battery Life

From the graphs shown in figure 17 it is clearly seen that battery life generally increases with area. However, for the same areas the battery life is much less for the Load Following Strategy compared to the Night Strategy.

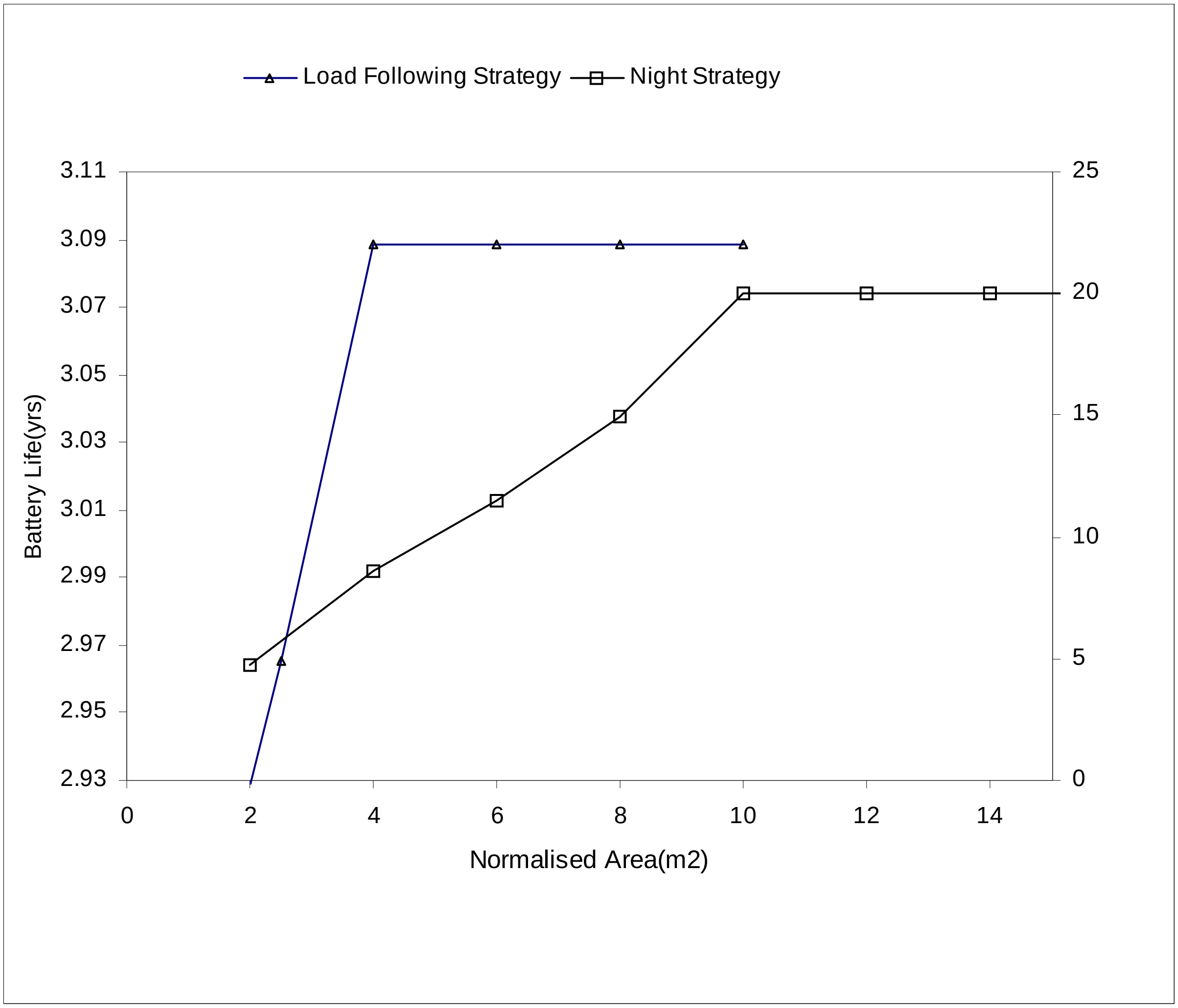

Figure 17 Relationship between Normalized Area and Battery Life

The reason for this can be easily explained by figures 18 and 19.

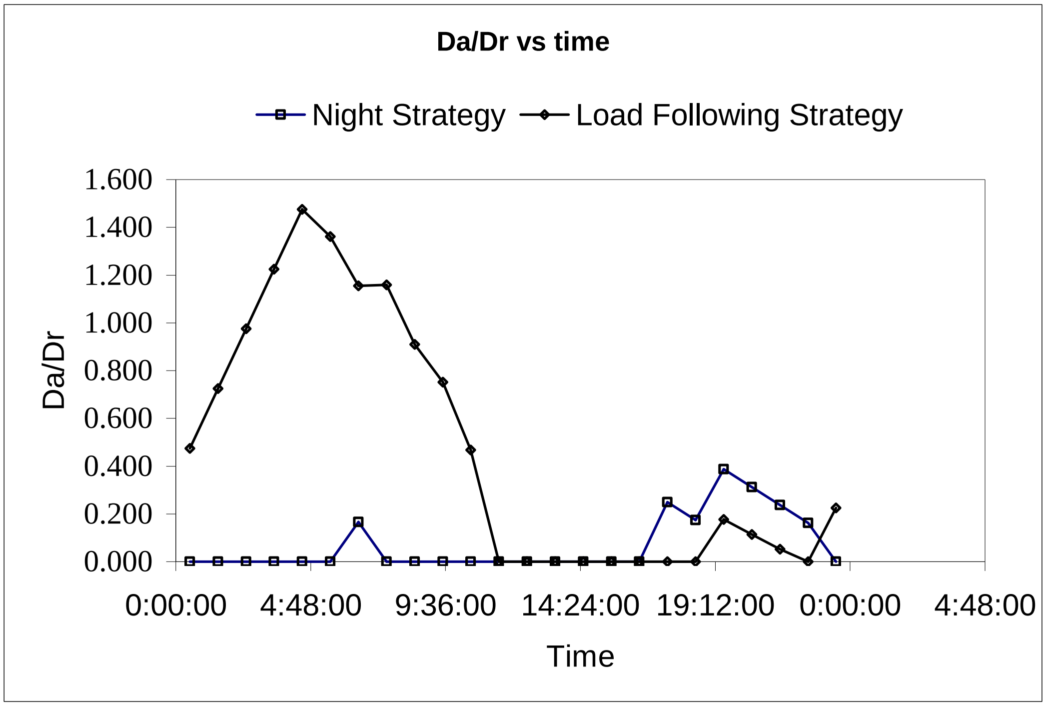

Figure 18 Actual Depth of Discharge of the battery over the Rated Depth of Discharge

Figure 18 shows for atypical day, the variation of the ratio D_A $/D_R$ (actual depth of discharge of the battery over the rated depth of discharge) with time. It is clear that for the Load-Following strategy the depth of discharge is generally higher than that for the night strategy (battery is more severely discharged).

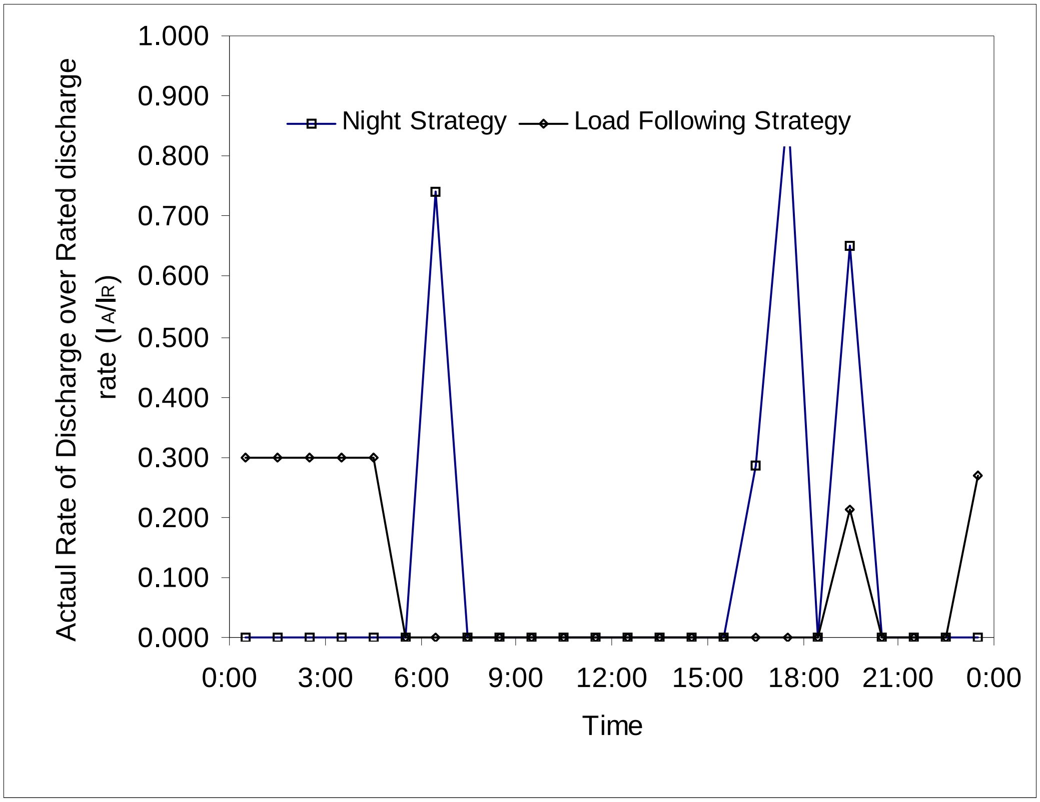

Figure 19 Actual Rate of Discharge over Rated Rate of discharge against Time

The curves shown in figure 19 shows that although actual rate of discharge is less than the rated discharge rate for both strategies, for larger areas it is higher for most of the time for the Load Following Strategy implying that the battery is discharged more than for the Night one. The explanation given above generally reflect that battery life depends mostly on the depth of discharge and the rate of discharge.

4.5 Relationship between Battery Capacity and Battery Life

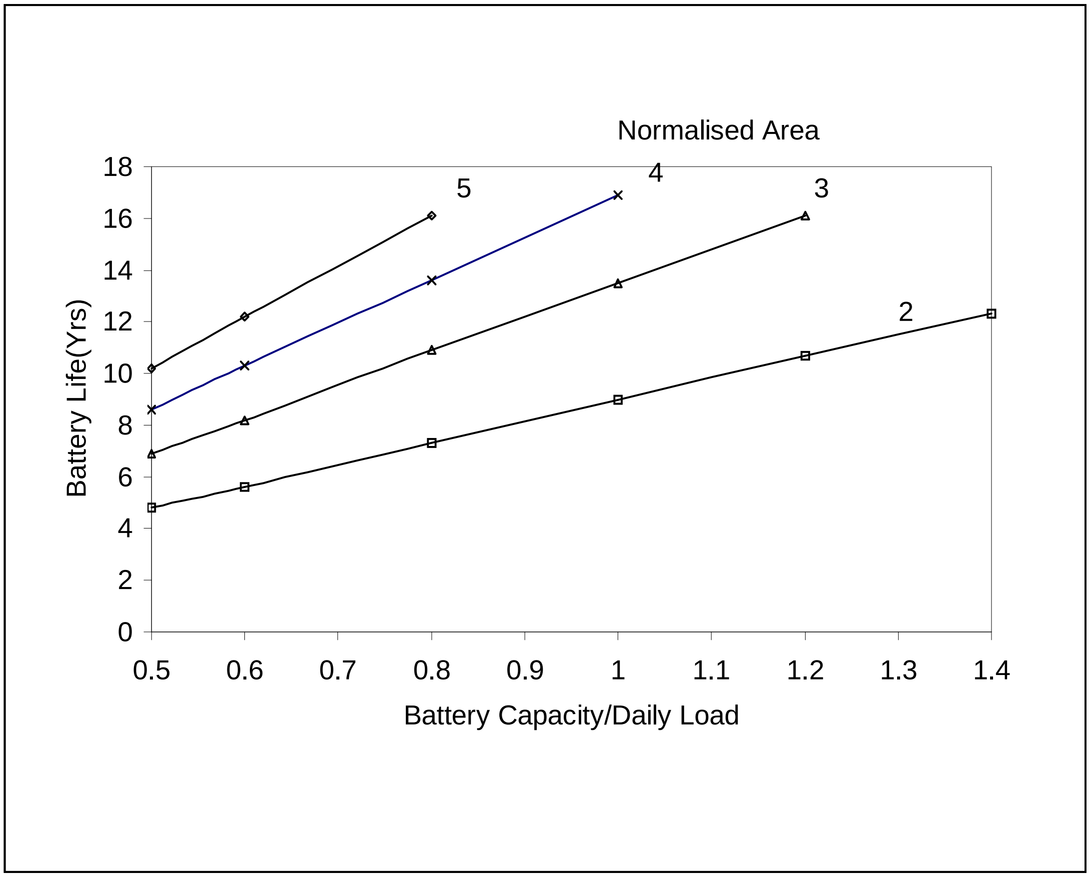

Figure 20 Relationship Between Battery Capacity and Battery Life for the Night Strategy

The graphs shown in figure 20 indicate an increase in battery capacity results in an increase in battery life for any given area. An increase in battery capacity also means an increase in the initial cost but since the life also increases, it means there is less replacement and cost. The overall cost depends on economic parameters such as discounting rate and life cycle costs. The area is decided on by the elbow while an increase in battery life is expected because the battery is charged frequently by a bigger area so that the depth of discharge is always low. For a chosen area the increase is due to fact that as the battery capacity increases the depth of discharge decreases. Also the ratio the ratio of the rate of discharge during the discharge event) to the manufacturer's rated discharge rate, (I_A/I_R), is less for a large battery than for a smaller battery.

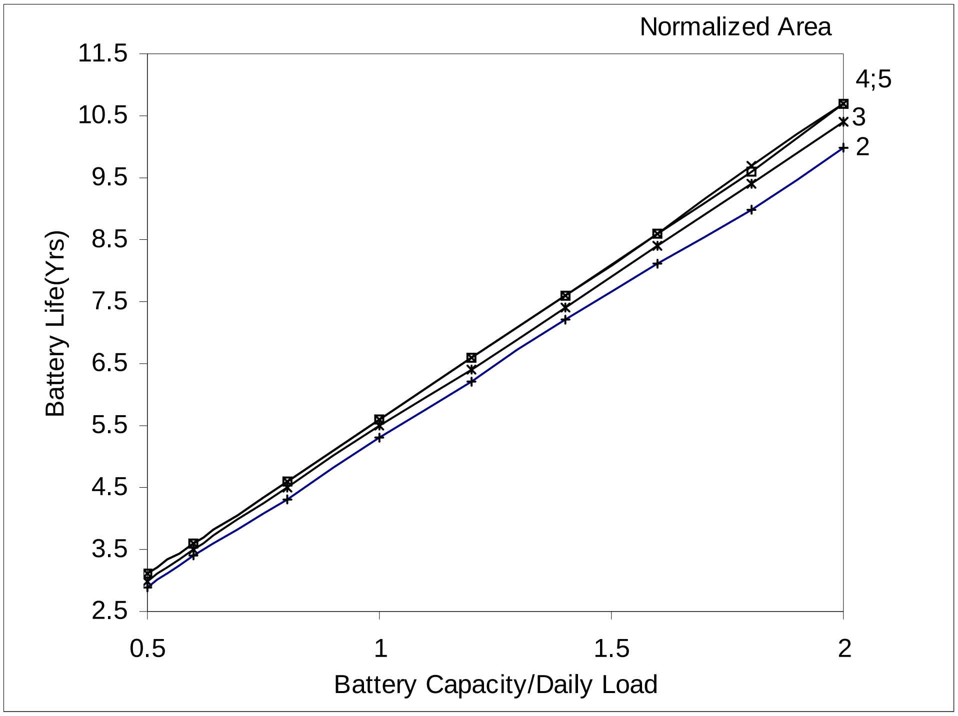

Figure 21 Relationship Between Battery Capacity and Battery Life for the Load Following Strategy

For the Load Following Strategy, the graphs shown in figure 21 also depict that battery life increases as the capacity is increased but in this case this is less dependent on area. This increase is again expected because the ratios of IA/IR are less for larger areas than for smaller areas.

4.6 Effect of Solar Fraction on Diesel Consumption

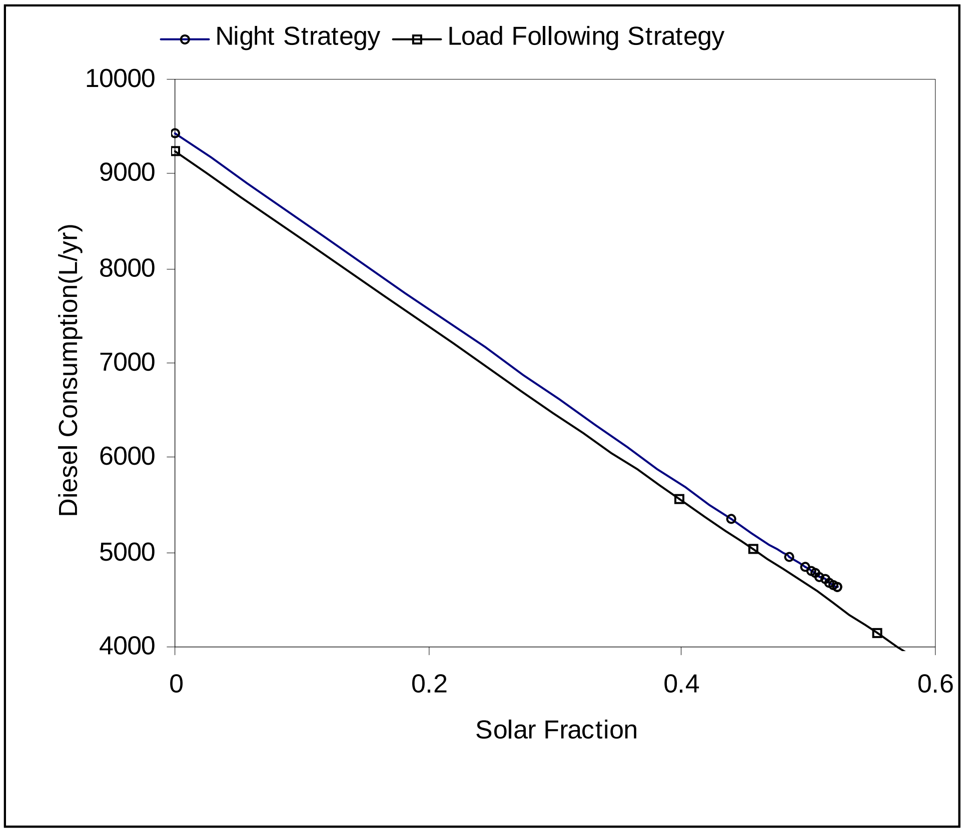

Figure 22 Effect of Solar Fraction on Diesel Consumption

The graphs shown depict that diesel consumption decreases as solar fraction increases but consumption is higher on the Night than on the Load Following Strategy implying that generally the Load Following Strategy is more fuel-economical to employ than the Night Strategy. This can be explained by the graphs shown in figure 22, which show the load ratio against time for each hour of the day with other things being the same.

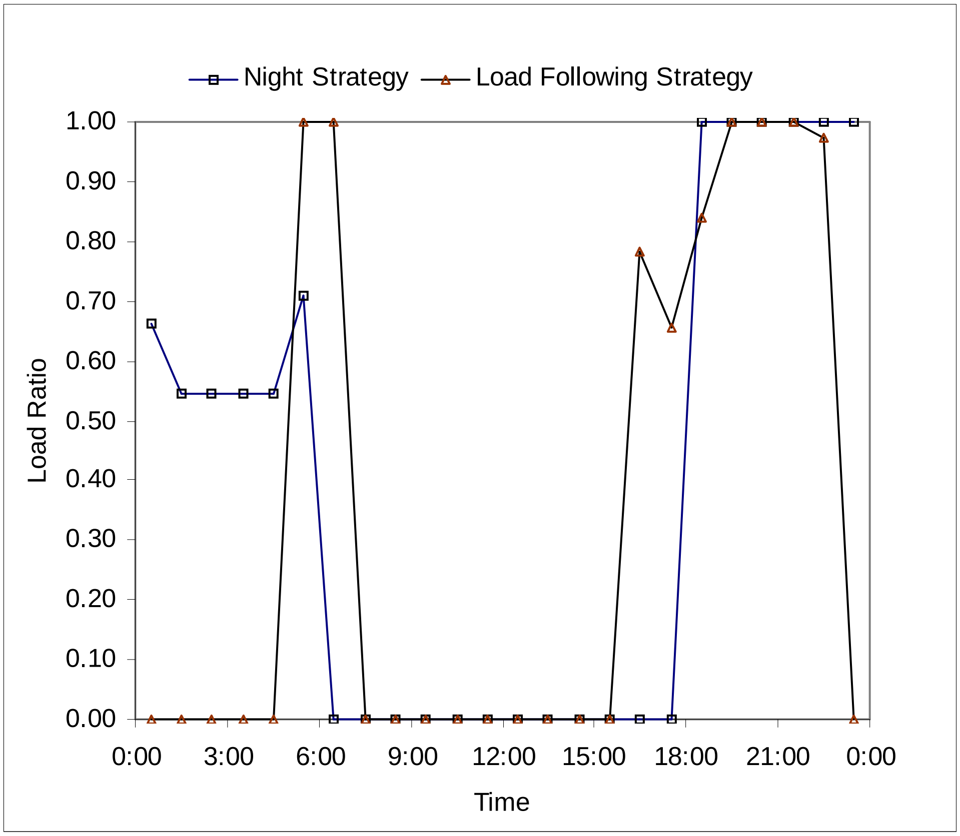

Figure 23 Variation of Load Ratio with Time

In figure 23, it is shown that the load ratios are generally high for most of the times for the Load Following Strategy implying less fuel consumption while for the Night Strategy it is less than one which implies that the specific fuel consumption is less hence more diesel is consumed because of the low load ratios. This is expected as it follows the behavior of the typical specific fuel consumption versus load ratio.

4.6 Variation of Nominal and Effective diesel running hours with Normalized Area

Effective diesel running hours refers to the number of hours when the diesel generator set is run at part load and then the model penalizes the system by increasing the running hours. This is achieved using the equation:

$N_{eff} \quad = \quad N_{full}*4\text{^}(1-LR)$

where N_{eff} refers to the effective running hours, N_{full} refers to the number of hours the generator set is run at full load and LR is load ratio

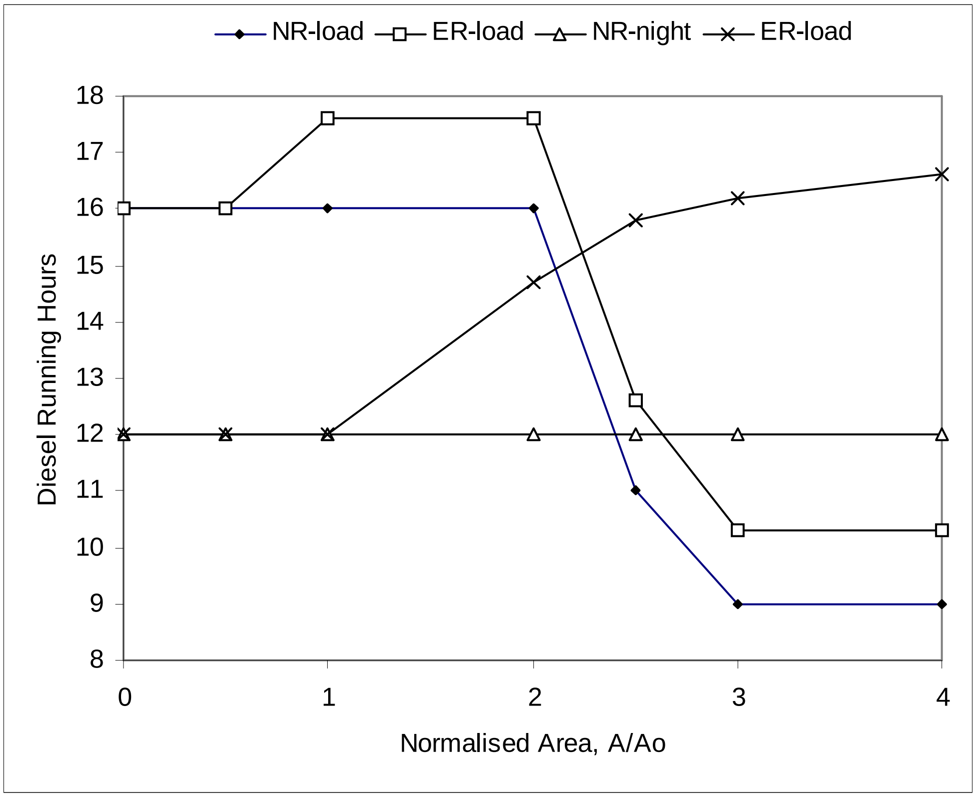

Figure 24 Variation of Nominal and Effective diesel running hours with Normalized Area

Figure 24 shows that for the load following strategy nominal diesel running hours are not constant, they vary because the diesel engine is switched on depending on the switching conditions. The effective diesel running hours are in general more than the nominal running hours and they decrease as the solar array increases; this strategy uses more fuel for lower solar array areas. For the night strategy, the nominal running hours are constant which is expected. The effective running hours depend on the load ratio and they vary for the night strategy as the normalized area increases. The load ratio is lower implying more fuel consumption.

4.7 Discussion on Findings

The outputs of the model showed that the optimal PV area for the Night Strategy smaller area than the Load Following strategy but it also consumes more fuel. This was shown by curves for solar fraction and diesel consumption versus normalized area. It was found that the solar fraction increased with normalized area with a decreasing marginal increase such that the solar fraction versus normalized area curve showed a distinct elbow, which formed a basis for sizing of the PV array. This implies that it is not beneficial in terms of solar fraction to continue increasing the size for the PV array beyond the value of area represented by the elbow value.

The Load Following Strategy was found to be more efficient than the Night Strategy at higher solar fractions and areas with relatively less fuel consumption. The Diesel Consumption against normalized area curves for both strategies showed that diesel consumption decreases as the PV area increases and this should be expected as a larger area implies a larger solar fraction and reduction of the fraction of the load, which is taken by the diesel.

Another observation was that the effective diesel running hours are more for the Night than for the Load Following Strategy and this has an effect on the maintenance costs of the diesel generator. Since the diesel engine was found to consume more fuel and run for more hours, it follows that the Night Strategy incurs more maintenance costs than the Load Following Strategy and is not environmental friendly in terms of emissions into the atmosphere.

Another observation was that for the battery model used, battery life increased with increase in battery capacity and this was due to reduced depth of discharge of the battery. This should be expected since the ratio of the rate of discharge during the discharge event) to the manufacturer's rated discharge rate, I_A/I_R, is less for a large battery than for a smaller battery.

Battery life was also found to increase with area mainly because the battery was not allowed to deeply discharge at larger areas. The battery bank and array sizes were larger for the Load Following Strategy than for the Night Strategy and this has got some cost implications that need to be evaluated by an economic analysis. This also implies that it is difficult to determine the better of the two energy dispatch strategies without carrying out an economic analysis which is beyond the scope of this research.

4.8 Conclusion

This chapter mainly focused on the presentation and analysis of the model outputs, the next section will look at the optimal sizing of the generator components for a typical load profile and whether conditions.

CHAPTER 5

OPTIMAL SIZING OF THE PV/DIESEL/BATTERY HYBRID SYSTEM

5.1 Introduction

In this section some of the results from the simulation model are used in the final design of the PV/Diesel/Battery hybrid system. The optimal sizes of the PV array, battery, battery charger and inverter are thus going to be determined.

5.2 Sizing the PV array

Figure16, which shows solar fraction and diesel consumption against normalized area was used as the design chart for sizing the PV array. As explained earlier on, for values of normalized area to the left of the elbow the marginal increase in solar fraction is relatively much higher than for values to the right of the elbow. It is therefore not beneficial in terms of increasing the solar fraction to continue increasing the PV array size beyond the “elbow value”. After the elbow, to the right the marginal increase is very small therefore it is no longer beneficial to increase the solar fraction and this is analogous with the law of diminishing returns in economics. In other words the value at the elbow can be taken as the optimal normalized area.

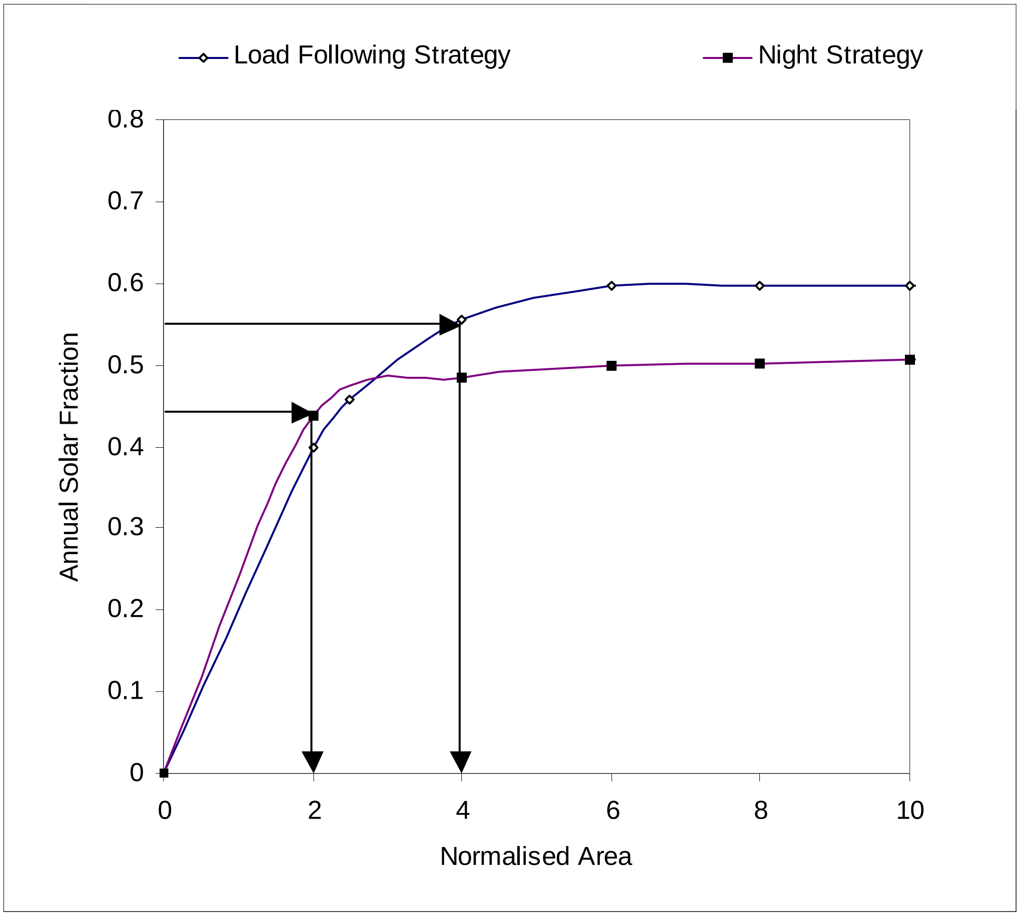

Figure 25 **Design Chart for PV array size**

Using the curves for solar fraction against normalized area and considering that the most cost effective points are found around the elbow of the graph , the most appropriate point chosen is where there is a solar fraction of 55% and normalized area of 4 on the Load Following Strategy as it is the one that gives the most solar fraction and a correspondingly lower diesel consumption. On the Night Strategy the chosen point is where there is a solar fraction of 44% and standard area of 2.

From an engineering intuition the optimum size of the PV array occurs at the elbow of the solar fraction versus normalized area curve which provides the basis for sizing the PV array in this study. Comparing the two energy dispatch strategies used in this study, the elbow of the solar fraction versus normalized area curve for the Night Strategy occurs at lower values of normalized area than for the Load Following Strategy indicating that more solar fraction and larger areas can be utilized by employing the Load Following Strategy. Graphs for diesel consumption also indicate that the Load Following Strategy may be more economical since diesel consumption is shown to decrease more as the area increases. Therefore through economic analysis, which is not within the scope of this research, a decision can be reached on the better strategy to adopt for the site.

5.2.1 PV modules and Electrical Configuration

From obtained values of A/A_o, since area and power are interchangeable the following formula is used to find the corresponding power:-

where $A = (A/A_o)A_o$

P = no*Go*A

For the load Following Strategy

$A = (69.4/4)*4 = 69.4\ m^2$

P =0.12*1000*69.4

= 8328W

From Kyocera Batteries a Kyocera KC200GT PV panel was chosen with the following specification:-

Maximum power 200W

Maximum current 7.61A

Maximum voltage 26.3V

The number of modules is found by diving the total power output by the power output of the chosen PV module.

Number of modules at 200Wp = 8328/200

= 42

Number of modules in series is found by dividing the system voltage by the module voltage at maximum power.

Number of modules in series = 24/26.3

= 1

Number of modules in parallel is found by diving the total number of modules by the number of modules in series.

Number of modules in parallel = 42/1 = 42

For the Night Strategy

$A = (34.7/2)*2 = 34.7\ m^2$

P = 0.12*1000*34.7

= 4164W

Number of modules at 200Wp = 4164/200 = 21

Number of modules in series = 24/26.3

= 1

Number of modules in parallel =21/1

= 21

5.3 Sizing the battery

Generally as battery size increases the initial capital cost increases but the life also increases therefore the battery is replaced less frequently. For a smaller battery size the initial capital costs are lower but the battery is replaced more frequently therefore the size can be best determined through economic analysis which is beyond the scope of this research.

The graphs shown in figure 8a can be used to give a rough estimate of the size by choosing the desired battery life. Considering that in practice solar batteries last been 3 and 7 years depending on their use, battery life was limited to six years in this research.

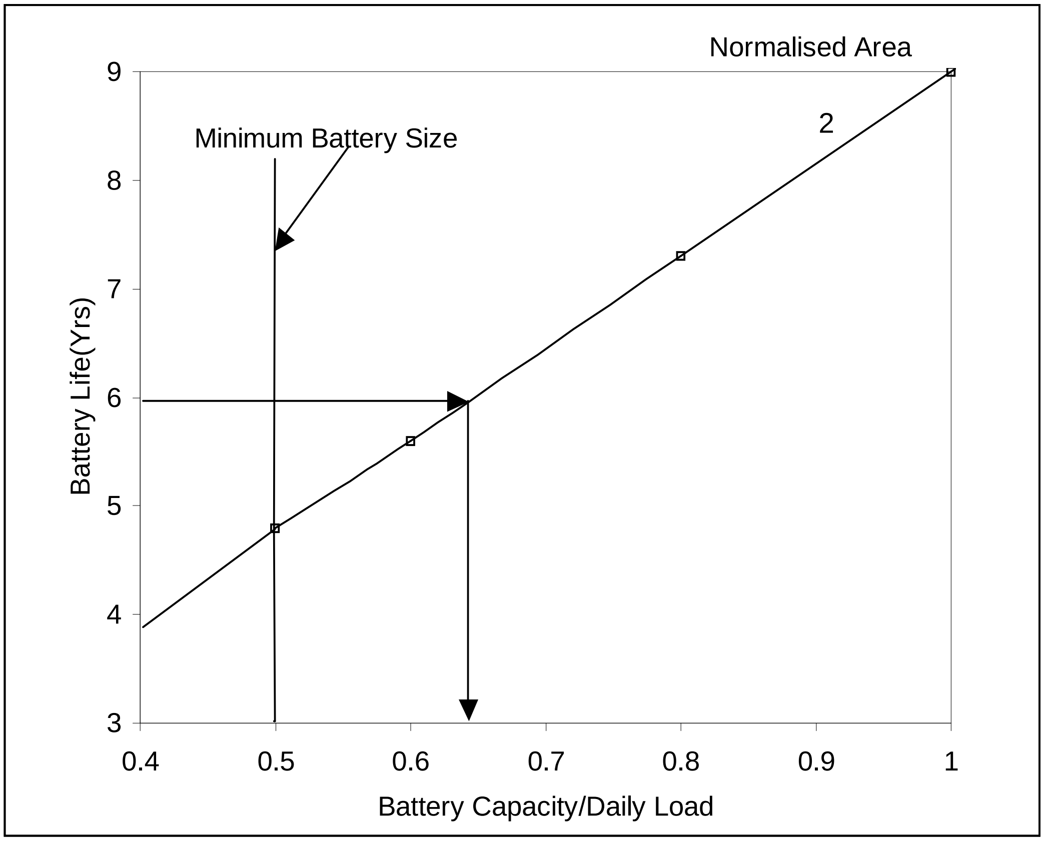

Figure 26 Design Chart for Battery Capacity

This limit disqualifies areas greater than 2 in figure 26 giving a normalized battery capacity of 0.65 which gives a battery capacity of 32.5kWh. For the Load Following Strategy graphs shown in figure 27 give a normalized battery capacity of 1.09 which gives a battery capacity of 54.5kWh for any array size. From the analyses of figures 26 and 27, it therefore follows that without knowing economic parameters like discounting for the system, the size is determined by the minimum battery size which is 25kWh in this case or by fixing the battery life to a number of years, say 6 years before replacement.

5.4 Specifications for the battery bank

To size the battery bank using the determined battery capacities for the two strategies if the capacity of each battery at a 20 hour charging rate is 625Ah, the following steps are followed:

1. Convert the kWh to Ah capacity by dividing by the system voltage
2. Divide the total battery capacity by the Ah rating for the batteries. This rounded off to the nearest whole number gives the number of batteries in parallel needed.
3. Divide the system voltage by the battery voltage to get the number of batteries in series needed.
4. Multiply the number of batteries in parallel by the number of batteries in series to get the total number of batteries required.

The above step were followed to size battery banks for the two strategies.

5.4.1 Night Strategy

For Battery capacity/daily load of 0.65, a battery capacity of 32.5kWh is obtained from the model.

1. 32500/24 = 1355Ah
2. 1355/625 = 3 batteries in parallel
3. 24/12 = 2 batteries in series
4. 3*2 = 6 batteries

5.4.2 Load Following Strategy

For Battery capacity/daily load of 1.09, a battery capacity of 54.5kWh is obtained from the model.

1. 54500/24 = 2271 Ah
2. 2271/625 = 4 batteries in parallel
3. 24/12 = 2 batteries in series
4. 4*2 = 8 batteries

Batteries were selected from solar battery company.

5.5 Sizing the inverter

The inverter is sized based on peak power and in this case the peak power is 3810 watts. To find the power rating to match the inverter specifications the peak power is multiplied by a factor of 1.2 to account for inverter loss. Therefore

Power Rating of inverter = 3810*1.2 = 4572 watts

An inverter with the following specifications was chosen:

Model ML5500-24, 24 Volt DC to 110 Volt AC inverter, 5500Watts continuous, 7000Watts peak

Inverters selected from Plamy Power Inverter Company.

5.6 Sizing the charge Controller

Critical factors when selecting a charge Controller are the system voltage and the maximum rate of charge of the batteries. In this case the system voltage is 24. The capacity at a 20-hour charging rate is 625Ah

For the charge controller the first step is to convert the total kWh to Ah capacity by dividing by the system voltage then divide by the current rating of the battery to get the charge controller current rating. In this case this gives for

1. The Night Strategy

   32500/(24*20) = 68A Therefore a 100A charge controller was chosen

2. The Load Following Strategy

   54500/(24*20) = 114A. Therefore a 200A charge controller was chosen from Kyocera Company.

5.7 Sizing and Operating Parameters for the two dispatch strategies

Table 11: Parameters for the two dispatch strategies

Parameter	**Night Strategy**	**Load Following Strategy**
Sizing Parameters		
PV Array size(A/Ao)	2	4
Battery size (Bcap/Lday)	0.65	1.09
Inverter (Wp)	4600	4600
Charge Controller (A)	100	200
Diesel Generator set (kVA)	5	5
Operation Parameters		
Solar fraction	44%	55%
Diesel consumption (L/yr)	5346	4143
Battery life (yrs)	6	6
Effective Diesel Running Hours	14.7	10.3

Table shows the sizing and operation parameters of the two dispatch strategies used in this research. It shows that the PV array size for the Night Strategy is half of that for the Load Following Strategy while the battery capacity is 65% less. The inverters are of the same size since the inverter is sized based on peak power which is the same for the given load profile. The charge controller rating is 50% more for the Load Following Strategy. The relative sizes of the components have implications on the capital costs of the two energy dispatch strategies. The Load Following Strategy thus have more capital costs.

Considering the operation parameters it is clearly seen that the effective diesel running hours and fuel consumption are higher for the Night Strategy than for the Load Following Strategy.. Effective diesel running hours have an effect on the maintenance costs of the diesel generator set such that more running hours mean more frequent maintenance. It therefore follows that the Night Strategy requires more maintenance than the Load Following Strategy. Diesel consumption has an implication on the operation costs of the systems which implies that the Load Following Strategy may be desirable in developing countries like Zimbabwe where capital is a problem. The Night Strategy thus consumes more diesel and requires more maintenance meaning that it may be desirable if diesel is cheap since most developing countries including Zimbabwe import fuel.

Capital costs are high for the load following strategy which may not be affordable but they are more fuel savings. In the Zimbabwean context, since the capital items and fuel are important, it is difficult to judge which of the two strategies is better from an economic point of view only but other factors can be considered such that the load following strategy requires complex electronic of controls which might be difficult to operate in rural areas with untrained manpower while the night strategy can be operated easily by untrained staff and is therefore more appropriate for rural areas.

From an environmental point of view the load following strategy is advantageous over the night one. It has low fuel consumption and less running hours, which means less fuel is burnt at higher efficiency resulting in less greenhouse gas emissions.

5.8 Conclusion

This section mainly looked at the sizing of the optimal components of the PV/Diesel/Battery hybrid power supply system, the next section will focus on the conclusions and recommendations.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This section looks at the conclusions and recommendations that are made based on the findings of the research.

6.2 Conclusions

The outputs of the model reflected that the designed model can make an hourly audit of energy flows and after inputting things like solar radiation data, temperature data, average day of the month, tilt angle, normalized area and capacity among other inputs, can output things like solar fraction, diesel fraction, load satisfied, diesel running hours and battery life among other outputs. The battery life versus battery capacity/daily load curve can be used to choose the battery capacity by selecting a desired battery replacement time (battery life), with a limit for the minimum battery capacity provided by the requirement that it should be able to smoother hourly load fluctuations on a day with no solar radiation.

Based on the findings, it can be concluded without economics that the best strategy is the Load Following Strategy since it has lower diesel running hours and diesel consumption when compared with the Night one. The lower running hours imply lower costs in terms of diesel generator maintenance and fuel costs. Although this strategy favours relatively larger areas and bigger battery capacities implying higher initial costs, the solar fraction utilized is also higher and battery life is increased making it a better option in terms of the payback period. However, because of the complexity of the controls involved, which may need immediate attention by technical experts in the event of a malfunction, the Night Strategy was considered as the more appropriate strategy in this research as it can be operated manually by a non- technical operator. It can also be concluded that the dispatch strategy is an important factor in deciding the size of system and the economics.

The decision on the better energy dispatch strategy will depend on various economic parameters, for instance, on the fuel price relative to the capital cost of the battery, or the PV array.

6.3 Recommendations

Basing on the above findings and conclusions, it can be therefore be recommended that:

- To size components of hybrid systems, simulation models are required to simulate all combinations and avoid design of sub-optimal systems
- An economic analysis is required for both exact determination of the generator component size and the energy dispatch strategy.
- For a start a simple strategy that operate at night (Night diesel generator strategy), is recommended for developing countries like Zimbabwe since it can be operated manually and does not require complicated electronic controls.
- Further studies, should focus on the economics and more simple and efficient energy dispatch strategies.

REFERENCES

Urmee, T., Harries, D. and Schlapfer, A. 2009 *"Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific"* Renewable Energy Journal, Vol. 34, 2009, pp 354–357.2.

Ackermann, T. (ed). 2005 "Wind power in power systems" Jon Wiley & Sons, Ltd.

Nayar CV et. al 1993 *Novel Wind/Diesel/Battery Hybrid Energy System* Solar Energy Vol 5 No 1 pp 65-78 1993. USA

Karnavas, Y.L., and Papadopoulos, D.P.: 1999 *"Maintenance oriented Algorithm for economic operation of an autonomous diesel electric station"* Electric Power Systems Research, Vol.5, 1999, pp109-122.

Kaikhurst, E. T. 1998 "Village Electrification an Evaluation of Options in remote Area Systems" The World Directory of Renewable Energy Suppliers and services

Gabrovska, K., Wagner, A. and Mihailov, N. 2004 *"Software System for Simulation of Electric Power Processes in Photovoltaic-Hybrid System"* International Conference on Computer Systems and Technologies - CompSysTech'2004. 17-18 June 2004, Rousse,Bulgaria

Haupt, R.L and Haupt S.E 1998 Practical Generic Algorithms. John Wiley and Sons, Inc, New York

Beyer, H.G., Rüther, R. and. Oliveira, S.H.F.2003 *"Adding PV-generators without storage to medium size stand alone diesel generator sets to support rural electrification in Brazil"* ISES Solar World Congress, Göteborg, June 2003, pp16-19.

Patel M., Pryor T.L. 2001 "Monitored Performance Data from a Hybrid RAPS System and the Determination of Control Set Points for Simulation Studies", Proceedings of ISES Conference, Adelaide, Nov 2001

Schienbein, L and Reich, E.: "Market, Cost, and Technical Analysis of Vertical and Horizontal Axis Wind Turbines: Market Demand for Small Wind". May 2003, Global Energy Concepts, LLC, Kirkland, Washington. http://www.greenhouse.gov.au/markets/mret/pubs/12_remote.pdf

Nain H. Afgan, Maria G. Carvalho 2008 *Sustainability assessment of a hybrid energy system Energy Policy*, Volume 36, Issue 8, August 2008, Pages 2903-2910

Wichert, B 1997 "*PV-diesel hybrid energy systems for remote area power generation- A review of current practice and future developments*", Renewable and Sustainable energy Reviews, Vol. 1, No. 3, 1997, pp. 209-228.

Drouilet S.(1997) A battery life prediction method for hybrid power applications

Duffie JA, Bechaman WA Solar engineering of thermal processes. John Wiley and Sons, 1991.

Lenzen M. 1999 *Greenhouse gas analysis of solar-thermal electricity generatio*n. Solar Energy 65(6):353-368, 1999

Lopez R.D. and Agustín J.L.B, 2004 *Design and control strategies of PV–Diesel systems using genetic algorithms, Solar Energy* **79** (2004), pp. 33–46.

Al-Alawi A.and Islam S. M, 2004: *Demand side management for remote area power supply systems incorporating solar irradiance model* Renewable Energy Volume 29, Issue 13, October 2004, Pages 2027-2036

Islam, S.M., 1999. Improving Operational Cost in a Hybrid System by Optimal Sizing and Control Design, A Short Course On: PV/Diesel/ Hybrid Systems, Australian Cooperative Research Centre For Renewable Energy, Curtin University of technology, Australia

SOPAC Miscellaneous Report 406: 2005 Hybrid Power Systems and their potential in the Pacific Islands

Hove T.and Gottsche J. *Mapping global, diffuse and beam radiation over Zimbabwe,* Renewable energy 1999;18:53

Collares –Pererra M, Rabl A. *The average distribution of solar radiation hourly correlations between diffuse and hemispherical radiation and between daily and insolation values* Solar Energy 1979; 22:15

Klein, S.A. *Calculation of monthly average insolation on titled surfaces*. Solar energy 1977;19:325

Hove T. 2000 *A method for predicting long-term average performance of photovoltaic systems.* Renewable Energy 21 (2000) 207-229.

http://www.energymatters.com.au/renewable-energy/solar-power/stand-alone-power-systems/

Behrendorff, G, 1999, Queensland Remote Area Power Supply (RAPS) Trials, 5th Renewable Energy Technologies and Remote Area Power Supplies Conference 1999, Cairns.

Rural and Remote Area Power Supplies for Australia, Department of Primary Industries and Energy, 1993, Australian Government Publishing Service, Canberra

http://www.ecs.umass.edu/mie/labs/rerl/hy2/theory/pdf/users.pdf Last accessed 12/06 2006

Henerica Tazvinga
Tawanda Hove

Photovoltaic / Diesel / Battery hybrid power supply system

Generator component sizing and energy performance analysis

VDM

A solar-based power supply system, such as a Photovoltaic-diesel-battery system, is a particularly attractive option for decentralised power supply in southern Africa where solar radiation is ubiquitous in most countries. Such systems can make a positive contribution to the sustainability of rural communities in developing countries that do not have access to electricity grid as they address shortfalls of stand- alone systems. However, a lot more design effort and expertise is required for optimising the sizing and operational strategy of the PV-diesel-battery hybrid system than is required for single-source systems. This book presents the development and application of a simple spreadsheet-based mathematical model for sizing and performance prediction of a PV-diesel-battery autonomous power supply system. The model can be used to compute the energy performance of systems with different combinations of component sizes, for two different diesel generator dispatch strategies. The model could be useful in sizing hybrid systems to supply whole villages, schools and clinics in remotely located rural areas where there is no access to grid electricity.

Henerica Tazvinga, Tawanda Hove
Henerica Tazvinga, MSc: Studied Renewable Energy at the University of Zimbabwe. Lectured at Chinhoyi University of Technology Fuels and Energy Department Zimbabwe; Researcher at Council for Scientific and Industrial Research, South Africa.

9 783639 284966 978-3-639-28496-6