An-Najah National University
Faculty of Graduate Studies

COMPUTER – AIDED DESIGN AND PERFORMANCE EVALUATION OF PV-DIESEL HYBRID SYSTEM

Prepared by
Mo'ien Ali Ahmad Omar

Supervisors
Prof. Dr. Marwan M. Mahmoud
Dr. Imad Ibrik

Submitted in Partial Fulfillment of the Requirements for the Degree of Master in Clean Energy and Energy Conservation Engineering, Faculty of Graduate Studies, at An-Najah National University, Nablus, Palestine.

2007

COMPUTER – AIDED DESIGN AND PERFORMANCE EVALUATION OF PV-DIESEL HYBRID SYSTEM

Prepared by
Mo'ien Ali Ahmad Omar

This thesis was defended successfully on 1/12/2007 and approved by:

Committee Members	Signature
1. Prof. Dr. Marwan M. Mahmoud	-------------------
2. Dr. Imad Ibrik	-------------------
3. Dr. Abdel-Karim Daud	-------------------
4. Dr.Waleed Al-Kokhon	-------------------

TO

MY PARENTS

MY WIFE (AMAL)

MY BROTHERS AND SISTERS

ACKNOWLEDGMENT

I would like to express my sincerest gratitude to my adviser Prof. Dr. Marwan Mahmoud who has always been providing kindest support, encouragement, and guidance throughout the accomplishment of this dissertation. I would like also to thank Dr. Imad Ibrik, whom I can refer to as my second advisor; he has given me an opportunity to learn more in this work.

I also like to thank my wife, Amal for her programming advice and encouragement. I also like to thank my parents and my family for their encouragement.

Lastly, I would like to thank my friends and colleagues in clean energy and conservation engineering program for their encouragement.

Table of Contents

List of Tables

List of Figures

COMPUTER – AIDED DESIGN AND PERFORMANCE EVALUATION OF PV-DIESEL HYBRID SYSTEM

Prepared by
Mo'ien Ali Ahmad Omar

Supervisors
Prof. Dr. Marwan M. Mahmoud
Dr. Imad Ibrik

Abstract

The present work presents a methodology to design and analyze the performance of a PV-Diesel Hybrid Power Systems using computer aided design. Analysis carried out in terms of several designs and different economic parameters based on life cycle cost and cost annuity. It was found that for Palestine the PV-Diesel Hybrid Power Systems are economically more feasible than using diesel or PV- stand alone systems. Different scenarios were tested technically and economically until the most appropriate one was found. A respective computer program, which simulates the operation of hybrid system on an hourly basis, was developed and can be a helpful tool to design a PV– Diesel Hybrid Power Systems appropriate from techno-economical view points for rural areas in Palestine.

CHAPTER ONE

INTRODUCTION

1. Introduction

Electricity is one of the fundamental necessities for every day's life. However off grids regions in Palestine still use diesel generators for short periods (5-7 hours/day). Most of these diesel generators are oversized. Initial cost of diesel generators may be comparatively low, but the long term cost can be high due to running cost (fuel consumption & maintenance requirements).In Palestine the price of diesel fuel supplied from "Dor alon Israel fuel company " is high since it amounts to 1 $/liter.

Using hybrid systems (combination of PV- Diesel –Battery storage) is recognized as a viable alternative to conventional diesel generator or stand alone PV-Battery system.

Such systems will improve the quality of life and make power supply to operate 24 h/day and reduce the environment pollution emissions from diesel generator.

The major concern in design of such systems is sizing system components and mange diesel generator operation to satisfy the load demand economically. The software package developed in this thesis can be used to simulate and design such a system.

The goals of this work are summarized in the followings:

1-Contribution to the development program of rural areas in Palestine.

2-Encourage the use of renewable energy sources.

3- Reduce the environment pollution.

4-Development of reliable alternative energy sources.

5-Development of a PV-Diesel hybrid system appropriate from techno-economical view points for rural areas in Palestine.

The research approach is as follows:

1-Select accurate and practical mathematical models for characterizing PV module, diesel generator and battery storage.

2-Design the software package for simulating PV/Diesel energy source.

3-By using the above computer simulation the optimum system configuration can be determined for the conditions in Palestine by comparing the performances which meet the load demand with minimum cost.

CHAPTER TWO

HYBRID ENERGY SYSTEM

2. Hybrid Energy System.

A stand-alone PV system with another integrated power source is called a PV-hybrid system. Meeting the full requirements of the load demand with stand-alone PV –system is too expensive especially under worst –case weather conditions. Hybrid system provides better economics as the storage requirements are low and investment costs are minimized.

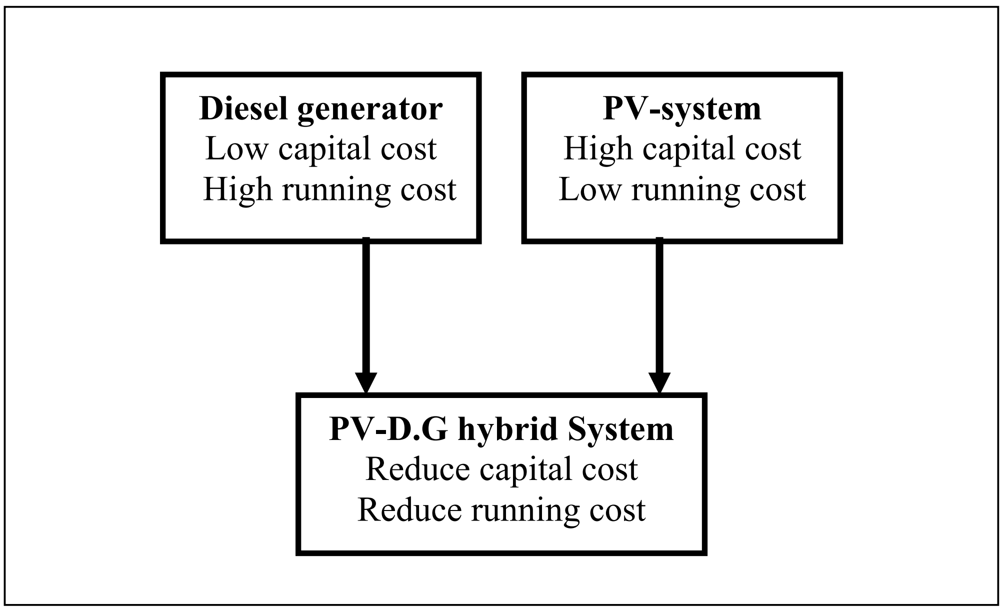


Figure (2.1): Comparison of Hybrid systems with stand-alone systems.

2.1. Configurations of hybrid system

Hybrid systems can be categorized according to their configuration as [1]

• **Series hybrid system**

In the series hybrid system (Figure 2.2), the energy from diesel generator and a PV array are used to charge a battery bank. The diesel generator is connected in series to the inverter to supply the load. The diesel generator cannot supply the load directly. The inverter converts DC voltage from the battery to AC voltage and supplies it to the load. The capacity of the battery bank and inverter should be able to meet the peak load demand. The capacity of diesel generator should also be able to meet the peak load and charge the battery simultaneously.

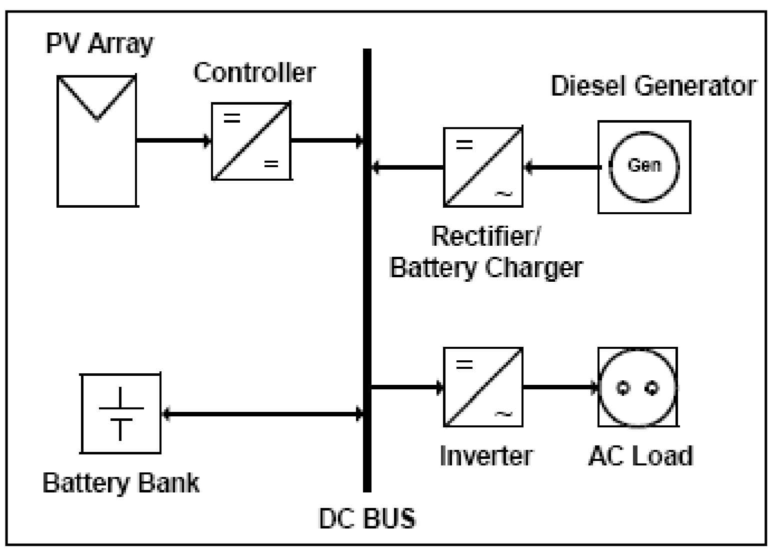


Figure (2.2): Series PV-diesel generator hybrid system.

• Switched hybrid system

The switched hybrid system (Figure 2.3), the battery bank can be charged by the diesel generator and the PV array. The load can be supplied directly by the diesel generator. If the diesel generator output power exceeds the load demand, the excess energy will be used to recharge the battery bank. During period of low electricity demand, the diesel generator is switched off and the load is supplied by the PV Array, together with stored energy from the battery bank. When comparing the overall conversion efficiency, switched systems is more efficient than the series system.

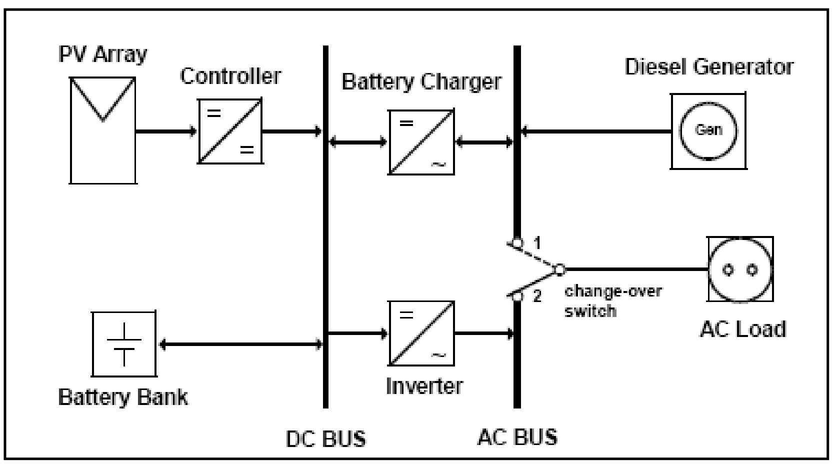


Figure (2.3): Switched PV-Diesel generator hybrid system.

• Parallel hybrid system

A parallel hybrid system is show in Figure 2.4. The diesel generator can supply the load directly. The PV array and the battery bank are connected in series with the bi-directional inverter to supply the load. During low electricity demand, excess energy from PV array is used to recharge the battery bank. The bi-directional inverter can charge the battery bank when excess energy is available from the diesel generator. Several advantages of this configuration include meeting load demand in an optimal way, reduction in the rated capacities of the diesel generator, battery bank, inverter and PV are possible, in addition meeting the peak loads.

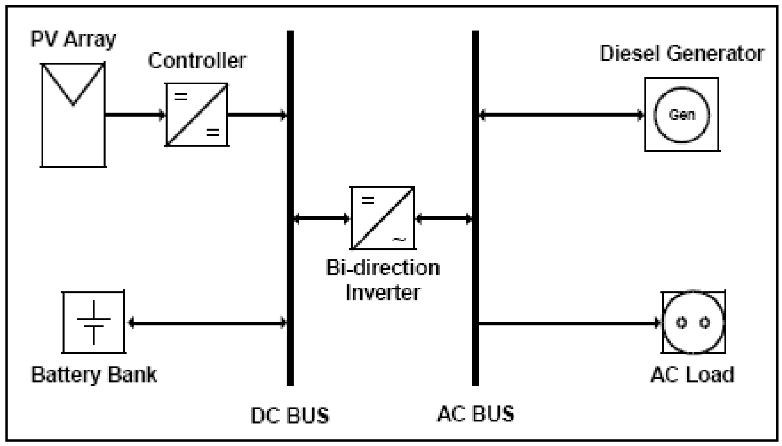


Figure (2.4): Parallel PV-Diesel generator hybrid system.

Switched hybrid system configuration was selected as a case study in this work.

CHAPTER THEREE

SOLAR RADIATION

3. Solar radiation

For PV system, solar radiation is the most important data for preliminary design and sizing of a PV power system.

3.1. Geographical location of Palestine

Palestine is located between the longitudes 34.15° and 35.40° east and between the latitudes 29.30° and 33.15° north as shown in Figure 3.1.

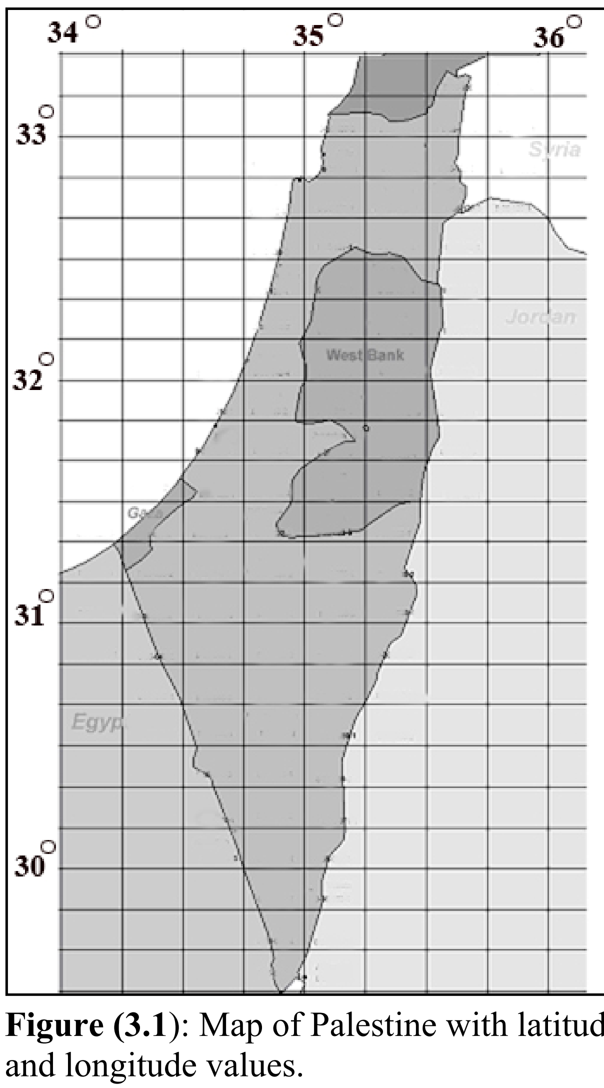


Figure (3.1): Map of Palestine with latitude and longitude values.

Palestine has a high solar energy potential, where the daily average of solar radiation intensity on horizontal surface is 5.4 kWh/m^2, while the total sunshine hours amounts to a bout 3000 and this is enough to produce solar energy in a sustainable way [2].

Table (3.1): Monthly average solar radiation (kWh/m^2-day) in Palestine [3].

Month	kWh/m^2-day
1	2.89
2	3.25
3	5.23
4	6.25
5	7.56
6	8.25
7	8.17
8	8.10
9	6.30
10	4.70
11	3.56
12	2.84

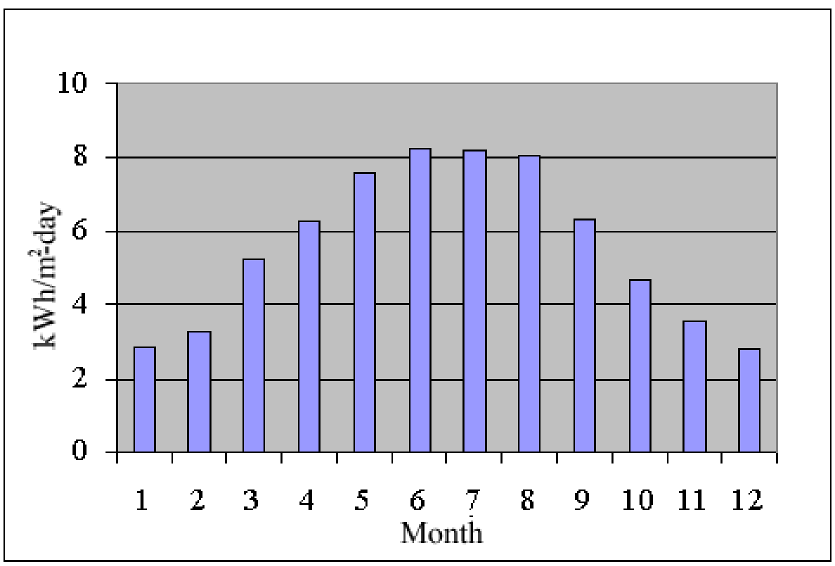


Figure (3.2): Monthly average solar radiation in Palestine.

3.2. Sun tracking

Sun tracking by tilting the PV – array allows to receive the maximum solar radiation. Moreover it limits the difference between the maximum and minimum of the power output of PV-array.

Tilt angle is the angle between the surface of the PV-array and the horizontal axis, where as the azimuth angle is the angle between the normal of the tilted array and the geographic south.

Fixing tilt angle at a certain angle all year to the latitude value (32º) in Palestine increase the solar energy collected by modules. Seasonal changes of tilt angle of solar modules collect higher solar energy than those of the fixed solar modules.

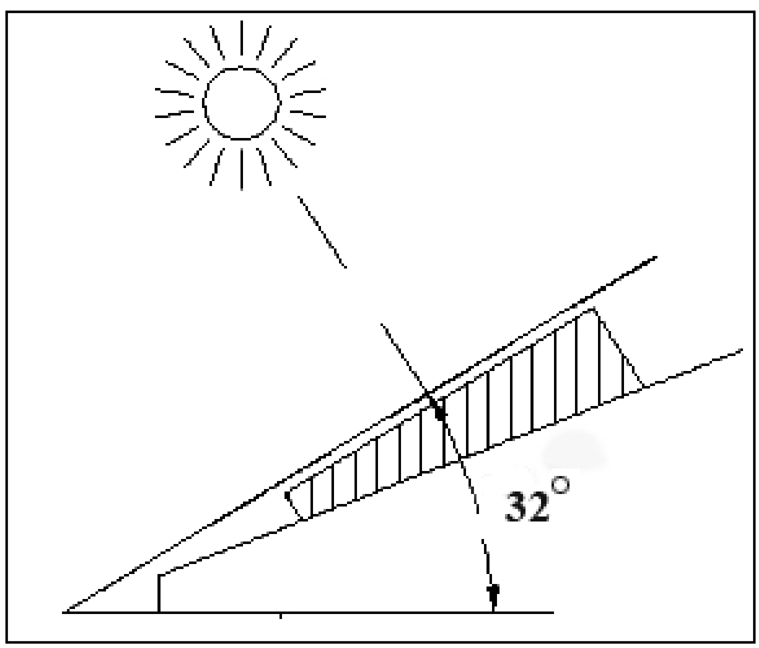


Figure (3.3): PV-array facing south with tilt angle 32º**.**

The tilted angle β is fixed seasonally as follows:

β =L+10 =32 +10 =42 during winter period.

β =L=32 during spring and autumn period.

β = L-10 =32-10=22 during summer period.

CHAPTER FOUR

COMPONENTS OF HYBRID SYSTEM

4. Components of hybrid system

This chapter will describe the different components of PV-diesel hybrid power system to give an understanding of components and some aspects of their operation.

4.1. Photovoltaic modules

Photovoltaic means direct conversion of sun light to DC electricity. The history of photovoltaic goes back to the year 1839, when Becquerel discovered the photovoltaic effect [4].

Bell laboratories produced the first solar cell in 1954, the efficiency of this cell was about 5 %, and cost was not a major issue, because the first cells were designed for space applications [4].

In the following years solar cell efficiency increased while the cost have decreased significantly as shown in figure 4.1 .

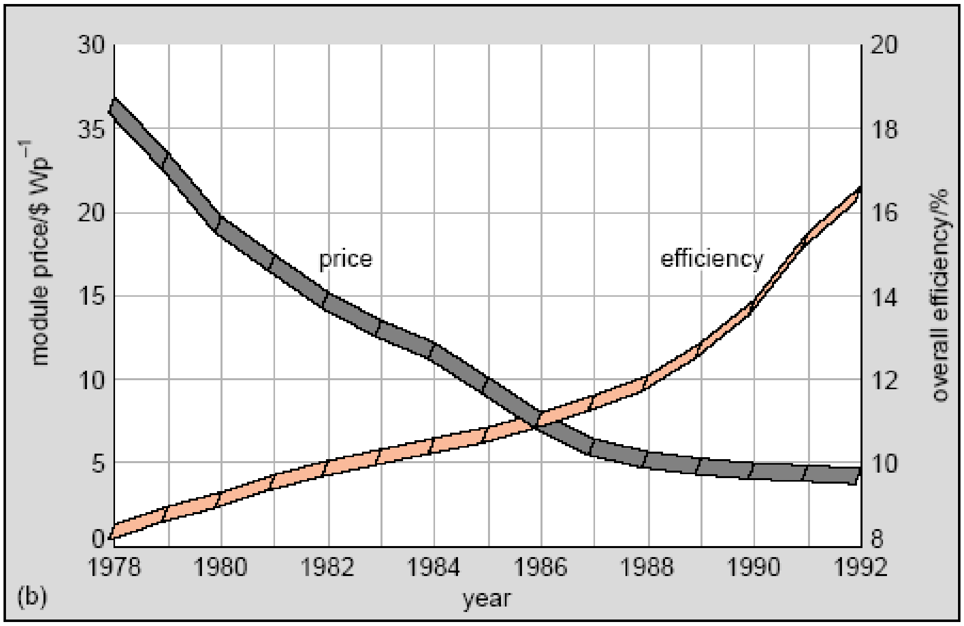


Figure (4.1): Increases in PV module efficiency, and decreases in cost per peak watt, 1978–92 [5].

Photovoltaic offers the highest versatility among renewable energy technologies, one advantage is the modularity .All desired generator sizes can be realized from milliwatt range for the supply of pocket calculator to megawatt range for the public electricity supply [4]. PV module production increased since 1979 as shown in figure 4.2.

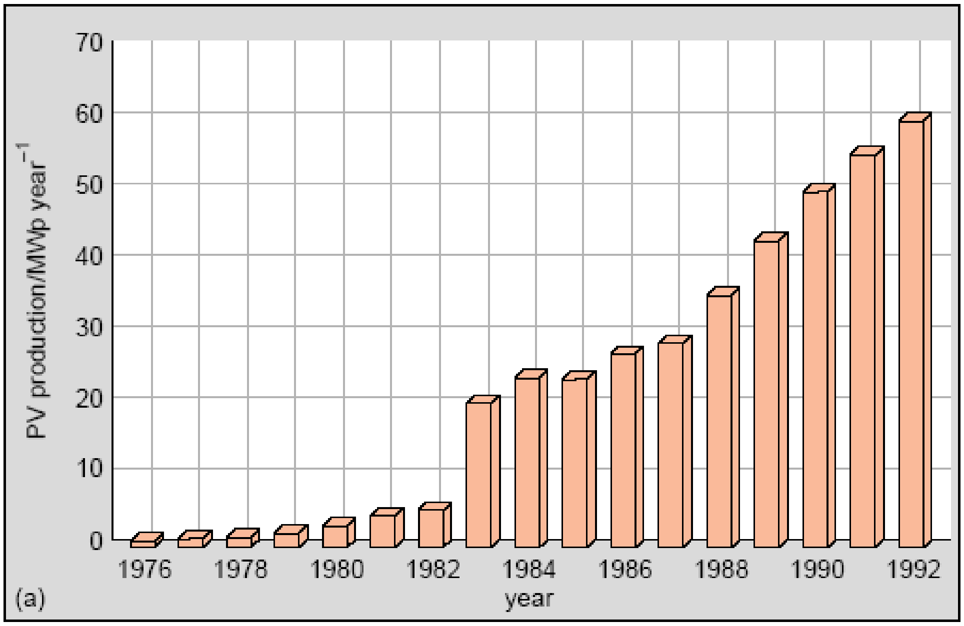


Figure (4.2): PV module production since 1976 [5].

Many photovoltaic applications are available for consumers such as water pumping, communication station, water desalination, street lighting, hybrid power system and many other applications.

4.1.1. PV operating principle

A PV cell is made of at least two layers of semiconductor material. One layer has a positive charge, the other negative. When light strikes the surface of the cell, some of the photons from the light are absorbed by the semiconductor atoms, freeing electrons from the cell's negative layer to flow through an external circuit and back into the positive layer. This flow of electrons produces electric current. Figure 4.3 shows the solar cell construction, the sandwich of semiconductor materials produce electricity directly from the sunlight without any moving parts.

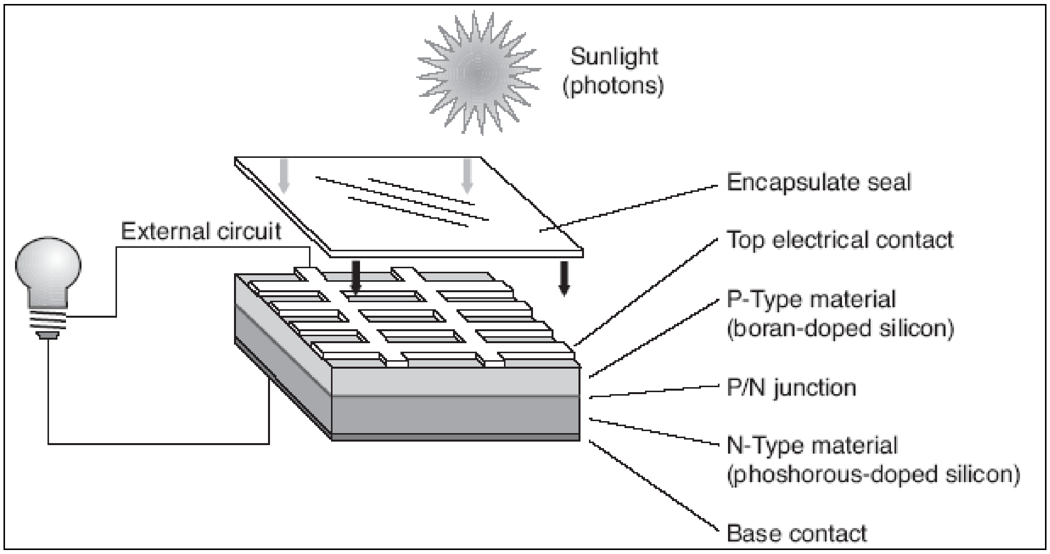


Figure (4.3): Basic solar cell construction [6].

In principal, a solar cell is a large-area silicon diode. Figure 4.4 shows Equivalent circuit diagram of an ideal solar cell.

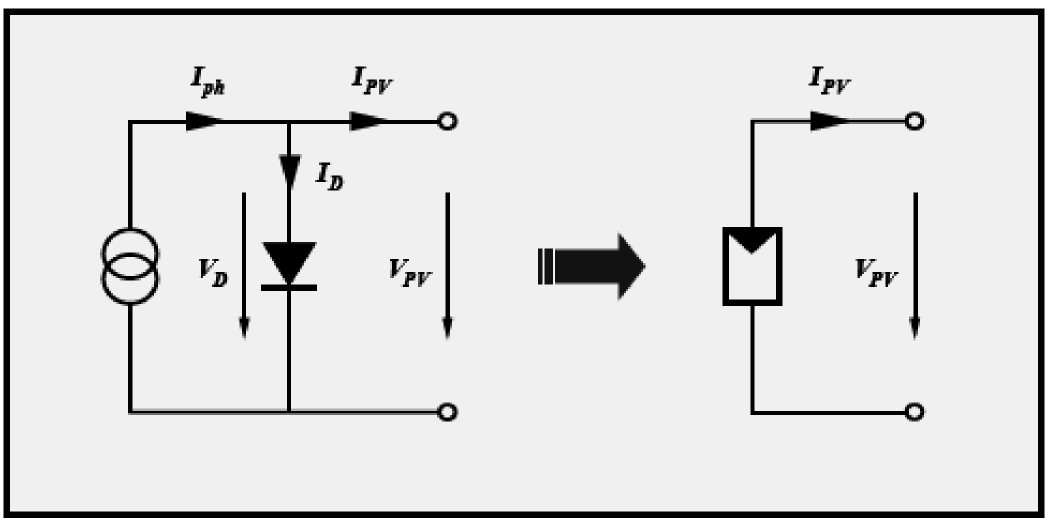


Figure (4.4): Equivalent circuit diagram of an ideal solar cell.

The mathematical function of an ideal illuminated solar cell is illustrated in the following equation:

$$I_{pv} = I_{ph} - I_d = I_{ph} - I_o \cdot \left(e^{\frac{qV}{KT}} - 1 \right) \qquad \textbf{(4-1)}$$

Where:

I_{PV} : Load current [A]

I_{ph} : photocurrent [A]

I_O : dark current [A] or saturation current

q : Elementary charge [e =1.6*10^{-19} As]

V : voltage [V]

K : Boltzmann constant [8.65*10^{-5}eV/K]

T : diode temperature [K]

4.1.2. STC and I-V curve

The rated power of a solar cell or a module is basically reported in "peak watts" [Wp] and measured under internationally specified test conditions, namely Standard Test Conditions (STC), which refers to global radiation 1000 W/m^2 incident perpendicularly on the cell or the module, cell temperature 25 °C and AM 1.5 (AM: air mass).

Photovoltaic modules have current voltage relationship which is represented in I-V curve.

Figure 4.5 shows a single 100 cm^2 silicon PV cell connected to a variable electrical resistance R, together with an ammeter to measure the current (I) in the circuit and a voltmeter to measure the voltage (V) developed across the cell terminals. Let us assume the cell is being tested under standard test conditions.

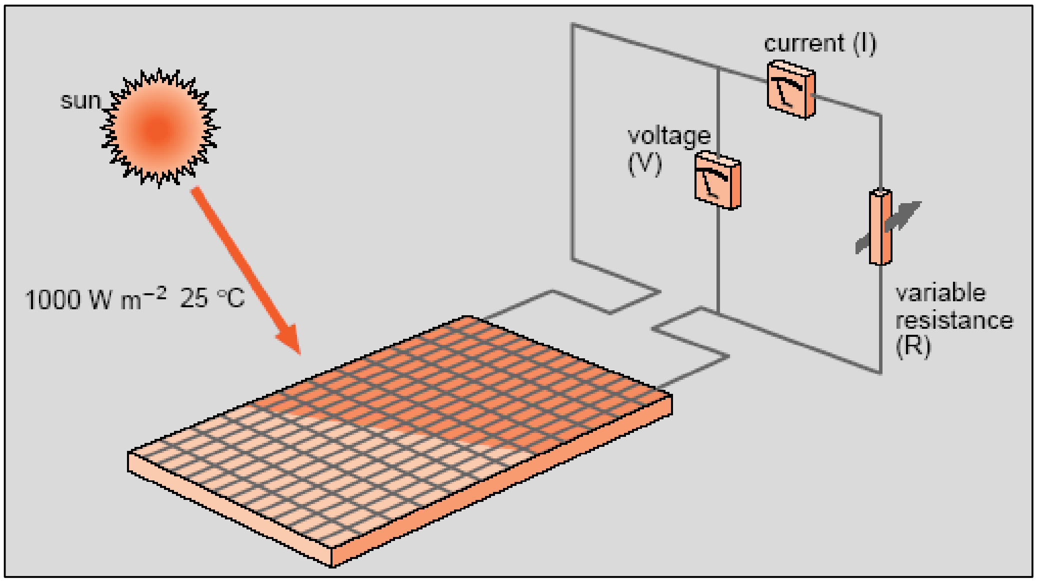


Figure (4.5): PV cell connected to variable resistance, with Ammeter and Voltmeter to measure variations in voltage and current as resistance varies.

When the resistance is infinite (i.e. open circuited) the current in the circuits at its minimum (zero) and the voltage across the cell is at its maximum, known as the 'open circuit voltage' (V_{oc}). At the other extreme, when the resistance is zero, the cell is in effect 'short circuited' and the current in the circuit then reaches its maximum, known as the 'short circuit current (I_{sc}).

If we vary the resistance between zero and infinity, the current (I) and voltage (V) will be found to vary as shown in Figure 4.6, which is known as the ‘I-V characteristic’ or ‘I-V curve’ of the cell. It can be seen from the graph that the cell will deliver maximum power (i.e. the maximum product of voltage and current) when the external resistance is adjusted so that its value corresponds to the maximum power point (MPP) on the I-V curve [5].

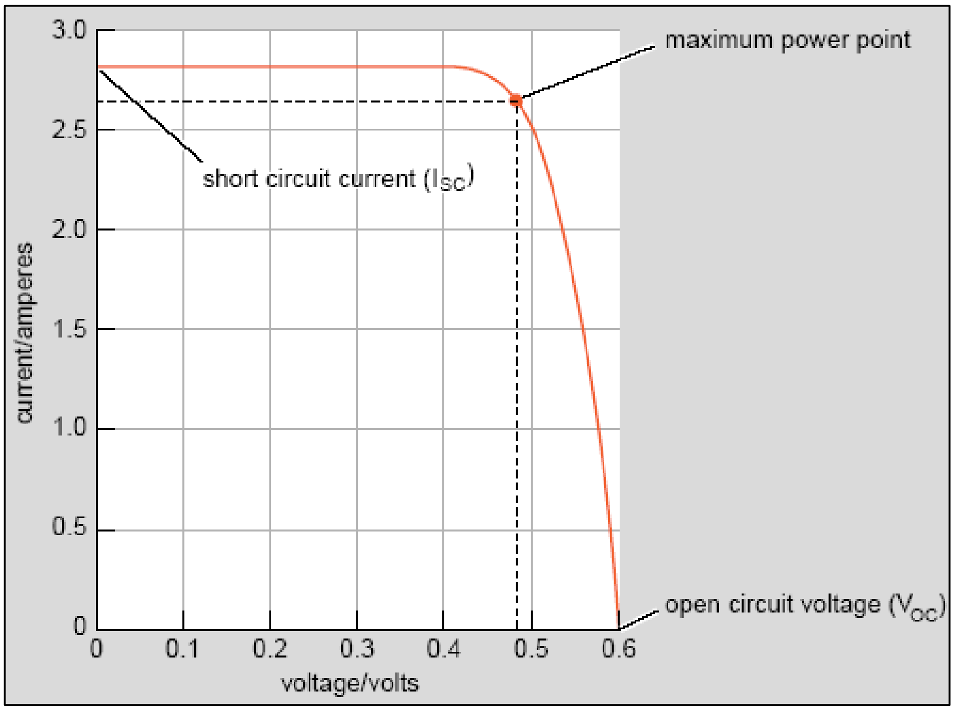


Figure (4.6): (I-V) characteristics of a typical silicon PV cell under standard test conditions.

4.1.3. Effect of solar radiation on PV performance

The irradiance will affect the current generated by a solar cell, the higher the irradiance the higher the current. The effect of irradiance on voltage is minimal .The change in Irradiance can be calculated, the manufacturer’s standards will provide the user with a short-circuit current, which can be recalculated for the new irradiance value by equation (4-2).

$$I_{sc}(G) = (I_{sc}\ rated@1000W/m^2) \times (G/G_{stc}) \qquad \textbf{(4-2)}$$

Where

I_{sc}**:** short circuit current

G: the actual radiation

G_{stc}: standard test condition value of radiation (1000W /m²)

Figure 4.7 shows the effect of radiation variation at PV module consisting of 36 cells of mono crystalline silicon [Siemens, SR50] at constant temperature.

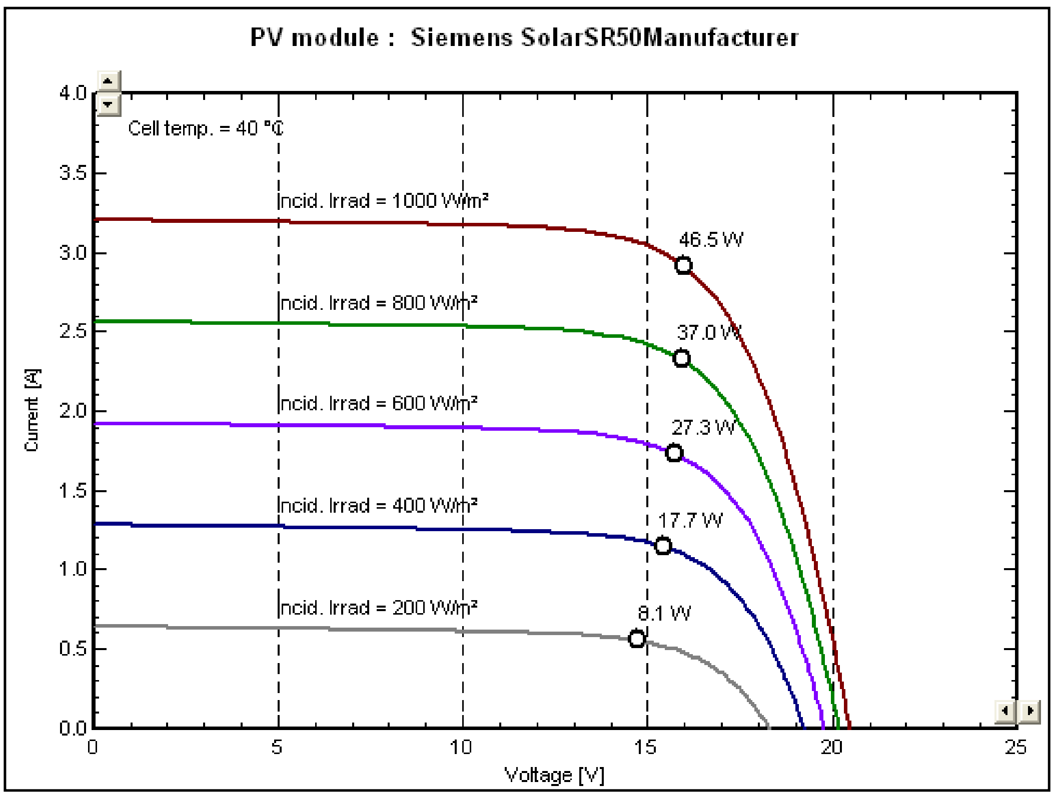


Figure (4.7): PV module (I-V) curve with variation of solar radiation and constant temperature [7].

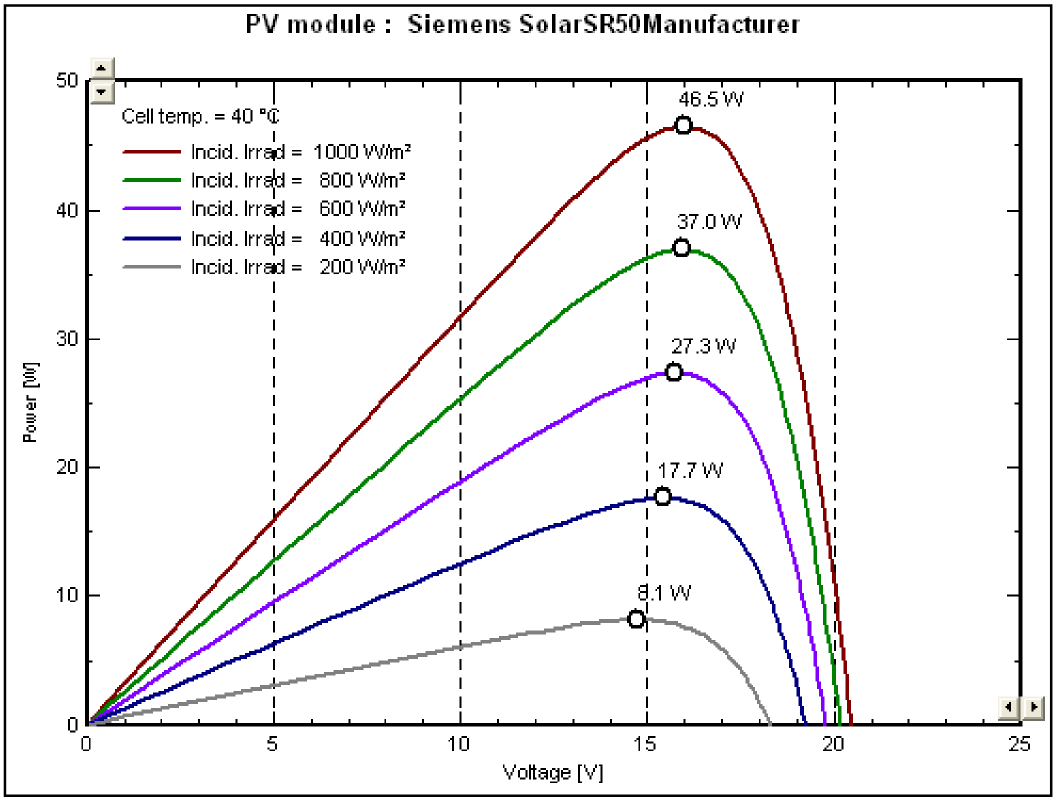


Figure (4.8): PV module (P-V) curve with variation of solar radiation and constant temperature [7].

4.1.4. Effect of temperature on PV performance

Solar cells vary under temperature changes; the change in temperature will affect the power output from the cells. The voltage is highly dependent on the temperature and an increase in temperature will decrease the voltage. Each solar module will have manufacturing standards; the normal operating cell temperature (NOCT) should be among these standards. The NOCT is the temperature the cells will reach when operated at open circuit in an ambient temperature of 20^oC at AM 1.5 irradiance conditions, G = 0.8 kW/m^2 and a wind speed less than 1 m/s. For variations in ambient temperature and irradiance the cell temperature (in ^oC) can be estimated quite accurately with the linear approximation that

$$T_C = T_A + \left(\frac{NOCT - 20}{0.8}\right) \times G \qquad \textbf{(4-3)}$$

The combined effects of irradiance and ambient temperature on cell performance merit careful consideration. Since the open circuit voltage of

a silicon cell decreases by 2.3 mV/^{o}C, the open circuit voltage of a module will decrease by 2.3n mV/^{o}C, where n is the number of series cells in the module. Hence, for example, if a 36-cell module has a NOCT of 40^{o}C with VOC = 19.40 V, when G = 0.8 kW/m^2, then the cell temperature will rise to 55^{o}C when the ambient temperature rises to 30^{o}C and G increases to 1 kW/m^2. This 15^{o}C increase in cell temperature will result in a decrease of the open circuit voltage to 18.16 V, a 6% decrease. Furthermore, excessive temperature elevation may cause the cell to fail prematurely [8].

Figure 4.9 shows the effect of temperature variation at PV module consisting of 36 cells of mono crystalline silicon [Siemens, SR50] at constant radiation.

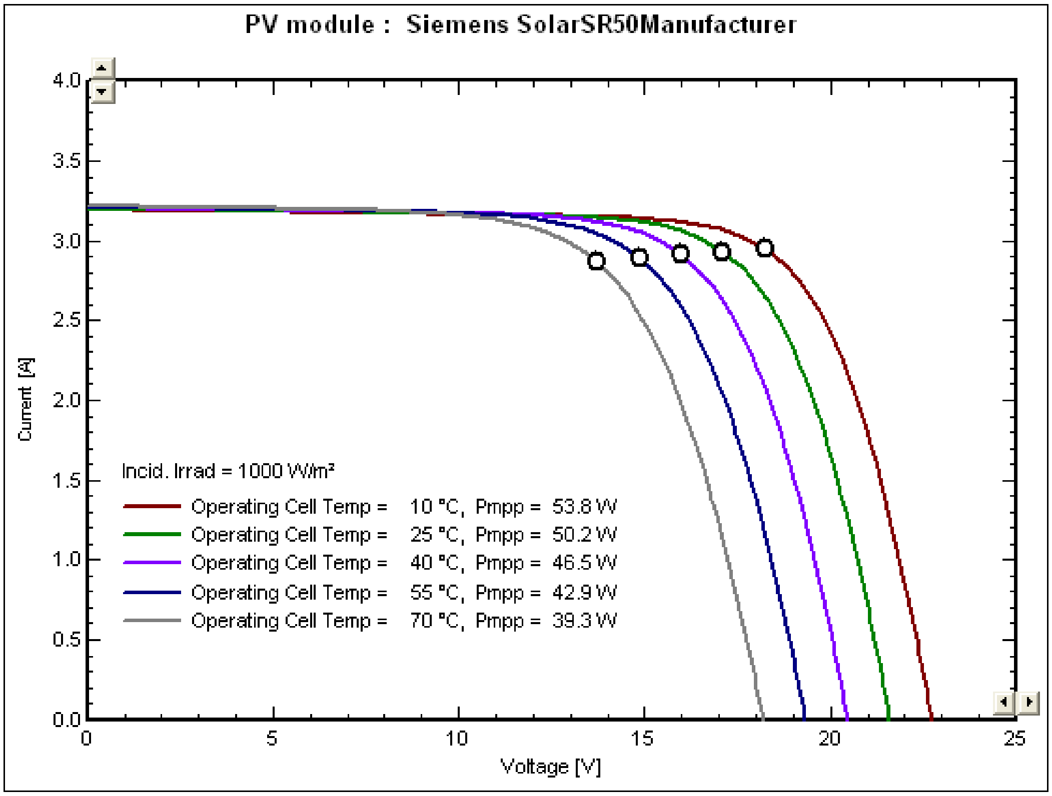


Figure (4.9): PV (I-V) curve with variation of temperature and constant radiation [7].

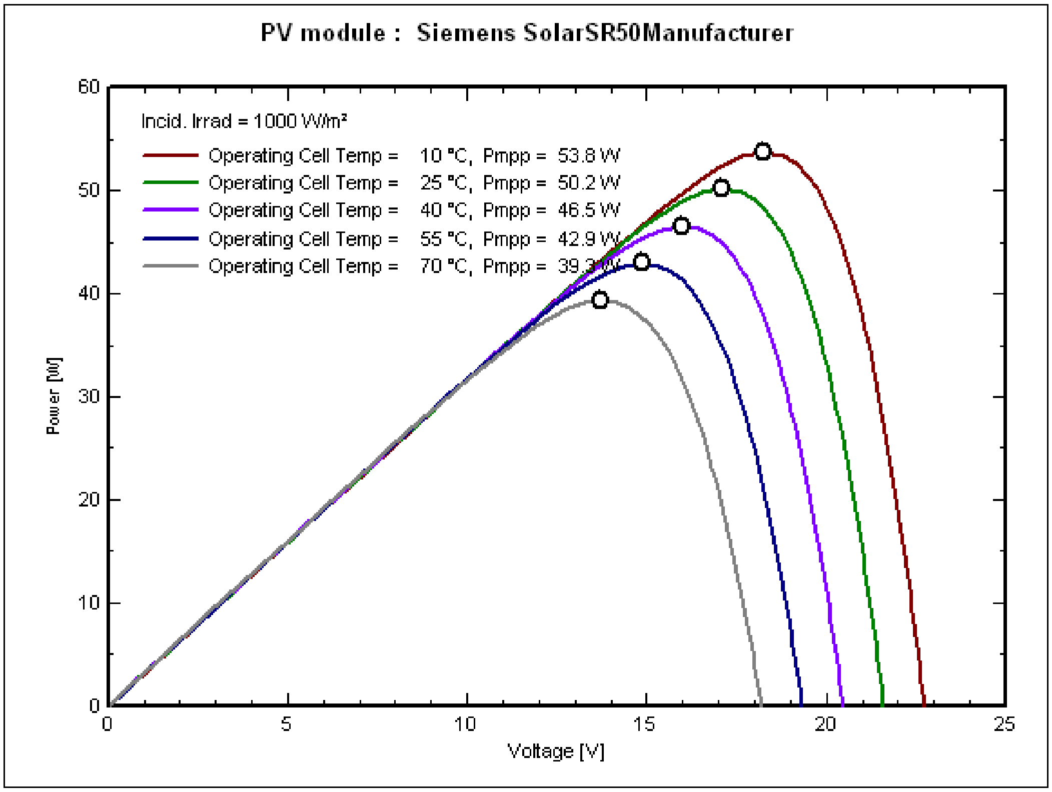


Figure (4.10): PV (P-V) curve with variation of temperature and constant radiation [7].

4.1.5. PV-cell types

There are many types of PV cells for instance mono-crystalline, poly-crystalline, amorphous silicon, compound thin-film, and thick-film and high-efficiency cells. The figure 4.11 illustrates some examples of commercially available PV cells.

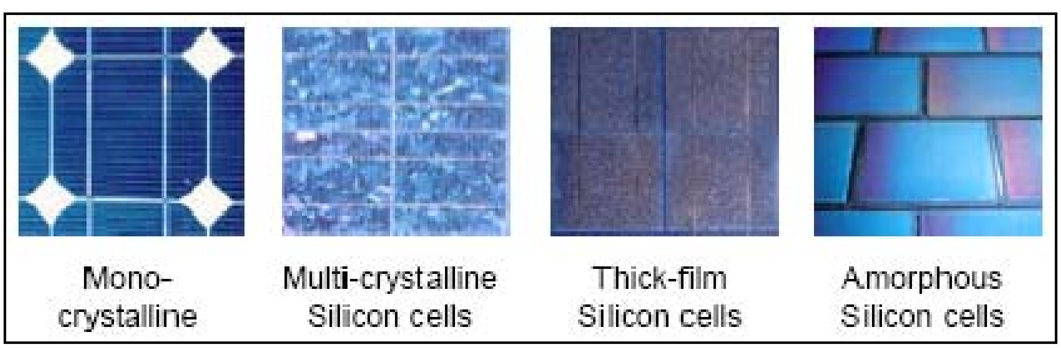


Figure (4.11): different types of PV cell

-Main characteristics of different PV cell types

- Single-crystal silicon
  - 15% efficient, typically
  - expensive to make (grown as big crystal)
- Poly-crystalline silicon
  - 10–12% efficient
  - cheaper to make (cast in ingots)
- Amorphous silicon (non-crystalline)
  - 4–6% efficient
  - cheapest per Watt
  - called "thin film", easily deposited on a wide range of surface types
  - efficiency degradation with time

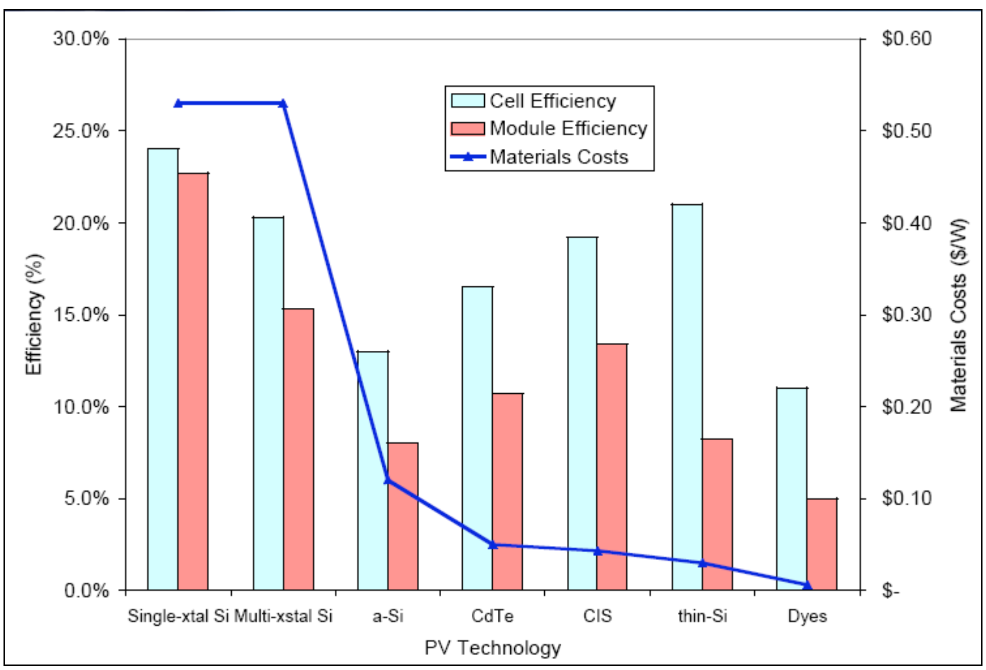


Figure (4.12): Comparison of PV Technologies [9]

4.1.6. PV performance model

As mentioned first the electrical behavior of PV cell is function of the incident solar radiation and cell temperature, our model considered cell temperature, incident solar radiation, and parameters provided by manufacturers; temperature coefficient of maximum power, K_T, is ordinarily negative, typical values for K_T are about -0.4% / ^{o}C for single and poly – crystalline silicon and -0.1 to -0.2% / ^{o}C for amorphous silicon [10].

The maximum power temperature coefficient is one parameter in a simple and widely used expression for estimating PV output [10]

$$P_{out}=P_r\ (G/G_{ref})\ x\ [1+ K_T\ (T_{module} - T_{module,ref})] \qquad (4\text{-}4)$$

Where
P : power, kW
G : radiation, (W/m^2)
K_T : Temperature coefficient of maximum power (1/ ^{o}C)
ref : reference conditions (G=1000 W/m^2,T=25 ^{o})

Empirical equation (4-5) used to find module temperature from ambient temperature and solar radiation.

$$Tmodule = T\ ambient + 0.0256\ x\ G\ (t) \qquad (4\text{-}5)$$

Model inputs:

The inputs affect the output power of PV panel:

Rated power of panel.

Maximum power temperature coefficient.

Ambient temperature (hourly).

Solar radiation (hourly).

Model outputs:

The output of this model after simulation is the output power of PV module at desired conditions hourly.

4.2. Diesel generator

Diesel generators are widely used as alternative energy sources for remote off-grid areas mainly due to their low capital costs. In a hybrid system it is mainly included to supply power during extended periods of low solar radiation and supply peak power in order to reduce the array size as well as the battery bank.

4.2.1. Diesel generator in hybrid system.

The utilization of diesel generator in hybrid systems is dependent on the percent of energy delivered to the load by the PV system, system with high PV contribution, the diesel generator is used mainly as a backup source and will not necessarily started daily. Diesel generator becomes the main source and runs many hours every day if the PV contribution is low. In this case the fuel and maintenance cost should be optimized to decrease the cost of energy generated from the system. Finally diesel generator runs from time to time if PV – contribution is medium.

4.2.2. Diesel generator operating characteristics

- **Rotation speed**

The Corresponding speeds of 50 Hz generators are 3000 rpm and 1500 rpm synchronous generators obtained from the following equation.

$$120 \times f = n \times P \qquad \textbf{(4-6)}$$

Where:

n : speed (rpm)

f : frequency

P : number of poles

The 3000 rpm units are 2-pole machines and are of simpler construction, resulting in lower acquisition cost. The 1500-rpm machines are 4-pole machines and are somewhat more expensive, but more common in the larger sizes or heavy duty units.

In general, the higher the rpm, the more wear and tear on the bearings. This means more frequent maintenance requirements. Two-pole generators are thus most convenient for use in relatively light duty applications that require less than 400 hours per year of operation. Four-pole generators are recommended when more than 400 hours of operation per year are anticipated [8].

- **Fuel types**

Diesel engines differ from gasoline engines in that they do not have spark-plugs to ignite the fuel mixture, and work at much higher pressures. Diesel engines need less maintenance that gasoline engines, and they are more efficient [11].

- **Efficiency and fuel consumption**

Electrical and mechanical losses are present in all generators.

However, the greatest losses in a generator system are attributable to the prime mover engine. The efficiency of diesel generator is proportional to the size of the operated load by the diesel generator .Manufactures endeavor to produce maximum efficiency at somewhere between 80-90 % of rated full load.

Figure 4.13 shows approximate plots of efficiency vs. percent of rated electrical load

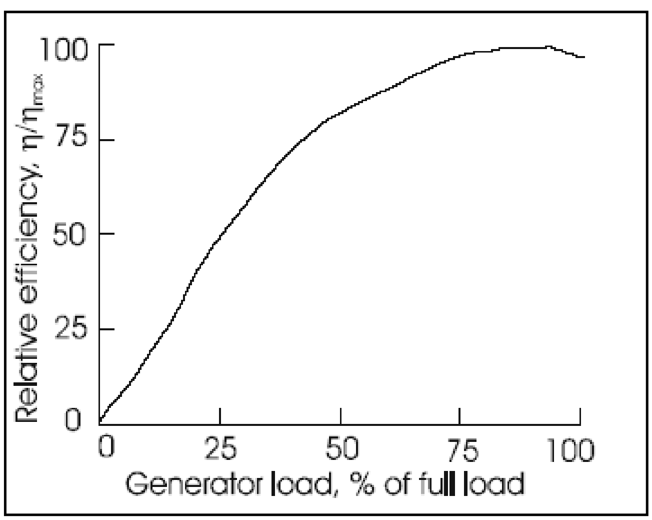


Figure (4.13): Diesel generator overall efficiency vs. rated load.

As seen in Figure 4.13 the efficiency of a diesel genset is higher at the higher loading rate, and is lower at the lower loading rate.

4.2.3. Diesel fuel consumption model

There are two fuel consumption models reviewed in this section linear model by Uhlen and nonlinear model Nayar.

Linear model : Skarstein and Uhlen (1989) (after Reiniger et al.,1986) have presented a relation among various models of diesel gensets in which F_i is a constant and F_o is proportional to the rated power of the genset :

$F = F_i \times P_{out} + F_o$

$Fi = 0.246$ liters/kWh

$Fo = B \times P_r$

$B = 0.08415$ liters/kWh

The equation of fuel consumption becomes:

$$\mathbf{F=0.246 \times P_{out}+0.08415 \times P_r} \qquad \textbf{(4-7)}$$

Where

F = fuel consumption (L/h).

P_{out} = actual operating electric output power (kW).

P_r = rated electric power of diesel generator (kW).

The Figure 4.14 illustrates the linear relation of diesel fuel consumption with electrical output power.

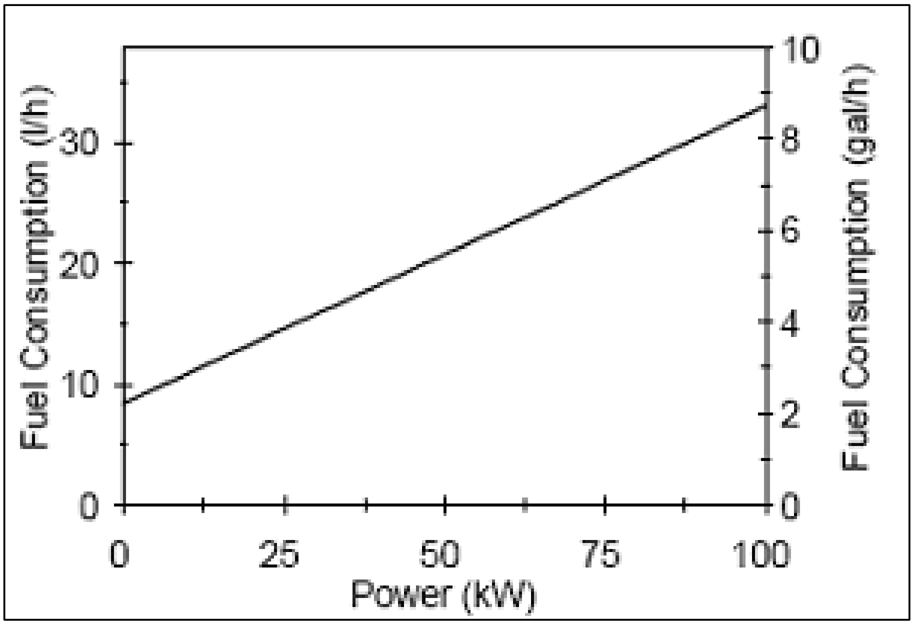


Figure (4.14): Linear diesel fuel consumption per hour.

Nonlinear model: Figure 4.15 Illustrates the normalized specific fuel consumption characteristic for plant in the size of 20-40kVA this measured by [12].

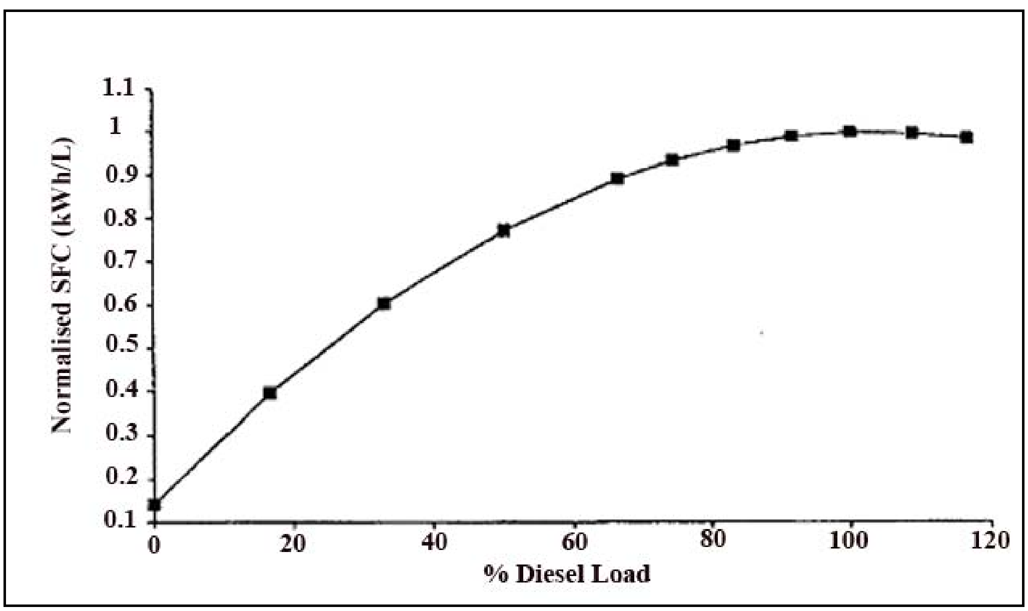


Figure (4.15): Specific fuel consumption characteristic for plant in the size of 20-40 kVA.

From the above two models we can calculate hourly fuel consumption of diesel generator.

For Example If the rated power of D.G is 40 kW, and the load factor =50 %

The calculation from linear model, equation (4-7) results the following.

P_{out} = 20 kW

P_r = 40 (kW)

F= 8.286 L/h

Calculation from Nonlinear model: using Figure 4.15 to find the value of the SFC for specific diesel generator operating power. Fuel consumption rate is equal the operating power divided by SFC.

At 20 kW output power, normalized SFC = 0.78.

SFC=3kWh/Liter x 0.78 =2.34 kWh/liter.

Fuel consumption at 50 %; 20 kW.

F = P/SFC = 20/2.34 = 8.547 L/hour.

The tow results nearly the same, linear model is used in this work.

4.2.4. Life cycle of diesel and regular maintenance requirements

A diesel generator can operate for between 5000–50 000 hours (average 20000 hours), depending on the quality of the engine, whether it has been installed correctly, and whether O&M has been properly carried out [11]

Regular maintenance and low load operation are the main factors affect the diesel generator life.

- **Regular maintenance**

Diesel engines require routine maintenance for long –life service. The normal maintenance requirements are about the same as owing a diesel powered vehicle –oil, oil filter and fuel filter in tropical and cold climates. It is advisable to have a water fuel separation filter system installed, water or moisture in diesel fuel can be damaging to a diesel engine because the water properties create advanced ignition and accelerated detonation.

The engine will need oil change every 100 to 250 hours depending on the dust conditions. Companies recommend to change the oil filter every time where engine oil will be changed.

Air filter need to be changed as required depending on how much dust is in the air, Diesels need a lot of clean air to operate properly and will collapse if the air filter is dirty. Manufacturers recommend checking the air filter at least every 100 hours .In industrial environment checking is recommended each 50 hours.

Fuel filter are normally changed every 200 to 250 hours depending on how clean the fuel and dust condition [13].

- **Low load operation.**

Other factor affects the diesel generator life is the low load operation which defined as when the engine operates for a prolonged period of time below 40 – 50 % of rated output power [13].

During periods of low loads, the diesel generator will be poorly loaded with the consequences of poor fuel efficiency and low combustion temperatures. The low temperatures cause incomplete combustion and carbon deposits (glazing) on the cylinder walls, causing premature engine wear. Therefore To avoid glazing we operate the diesel generator near its full rated power.

4.2.5. Pollutant emissions

Number of kg of CO2 produced per liter of fuel consumed by the diesel generator depends upon the characteristics of the diesel generator and of the characteristics of the fuel, and it is usually falls in the 2.4–2.8 kg/L range [14].

4.2.6. Mathematical model for diesel generator

A linear diesel fuel consumption model that relates the diesel fuel consumption to the electrical power output is considered in this study:

$F = 0.246 \times Pout+0.08415 \times Pr$

Model inputs:

P_{out} = actual operating electric output power (kW)

P_r = rated electric power of diesel generator (kW)

Model outputs:

Fuel consumption (liter/hour)

4.3. Storage battery in PV power system

Except in PV powered water pumping systems, storage batteries are indispensable in all PV power systems operating in standalone mode to act either as a power buffer or for energy storage.

The PV generator is neither a constant current nor a constant voltage source. The maximum power output of the generator varies according the solar radiation and temperature conditions [15].

In the early morning or late afternoon, the PV generator may not be able to meet the load demands especially with short high current peaks such as during motor-startup. A battery which is constant voltage source acting as a power buffer between the PV generator and the load, will compensate for the limitation of the generator. When solar radiation is higher than needed to meet the load requirement, excess energy is stored in the battery to supply power to the load during night and cloudy days of low solar radiation [15].

4.3.1. Battery types

The two battery types that have been used for PV systems are lead–acid and nickel–cadmium. Due to higher cost, lower cell voltage (1.2 V), lower energy efficiency and limited upper operating temperature (40 ◦C),

Nickel – cadmium batteries have been employed in relatively few systems. Their use is based mainly on their long life with reduced maintenance and their capability of standing deep discharge without damage . The lead–acid battery will remain the most important storage device in the near future, especially in PV systems of medium and large size [15].

4.3.2. Lead acid battery

The lead-acid battery is still the most common for relatively economical storage of relatively large quantities of electrical energy, and will probably remain so for at least for the next few years [8].

4.3.3. Lead acid battery function and structure

A battery is made up of two or more electrochemical cells interconnected in an appropriate series/parallel arrangement to provide the required operating voltage and current levels. The familiar 12V lead–acid battery used in automobiles consists of six 2-V cells connected in series and packaged .in a rubber or plastic case [15].

Battery has two electrodes, in the charged state, the positive electrode consists of lead dioxide Pbo_2 and the negative electrode of pure lead (Pb), a membrane embedded in a plastic box separates the two electrodes.

Diluted Sulphuric acid (H_2SO_4) fills the empty space between the two electrodes, a fully charged lead -acid battery has an acid density of about 1.24 Kg/liter at temperature of $25C^o$, and the density changes with the temperature and charge state [4].

The over all reaction is given by the following equation.

$$Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$$

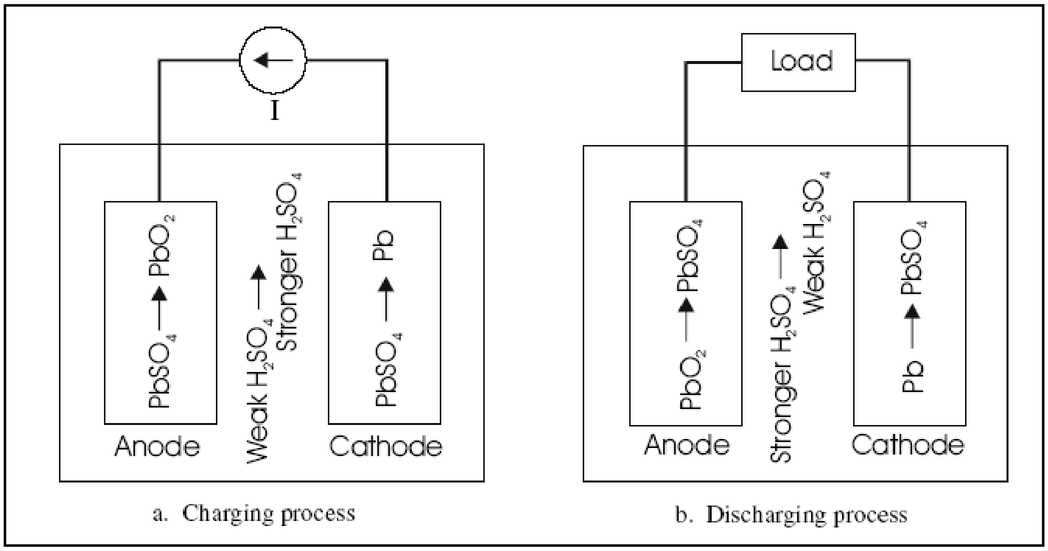


Figure (4.16): Charge and discharge of the lead-acid cell.

4.3.4. Lead acid battery characteristics

- **Voltage, specific gravity and state-of-charge**

The nominal voltage of a lead–acid cell is 2V, while the upper and lower limits of discharging and charging open circuit voltage at 25 ◦C cell temperature are 1.75 and 2.4V, which corresponds to 10.5 and 14.4V for a 12V battery (respectively). The maximum acceptable battery cell voltage decreases linearly with increasing cell temperature as illustrated in Figure 4.17 [15].

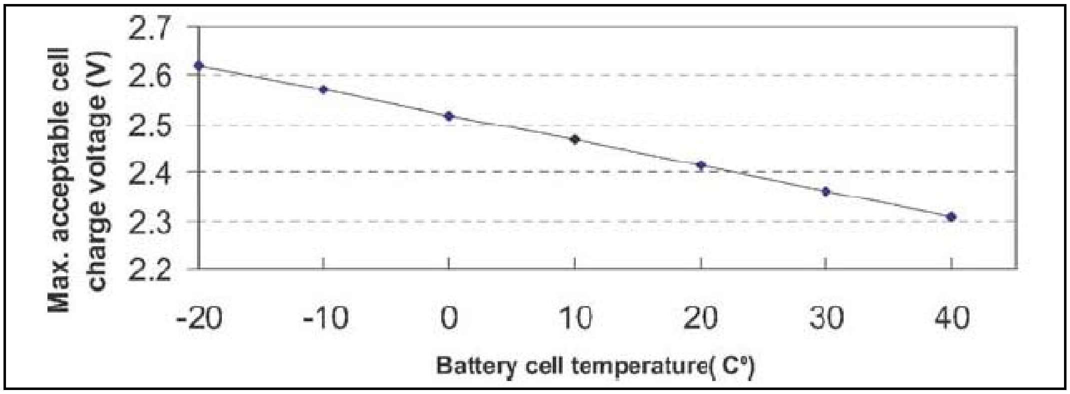


Figure (4.17): Battery cell voltage in function of cell temperature [15].

The specific gravity of the acid solution of the battery decreases slightly with increasing temperature. Cell voltage and specific gravity of the acid solution are mainly a measure for the state-of-charge of the battery cell as recognized in table 4.1.

Table (4.1): Typical open circuit voltage and specific gravity for a lead–acid cell at temperature 26.7^{o} C [15].

Battery voltage	Cell voltage	Specific gravity	State-of-charge
(12 V) (V)	(V)	(g/cm^3)	(charge level) (%)
12.7	2.116	1.265	100
12.4	2.066	1.225	75
12.2	2.033	1.190	50
12	2	1.155	25
11.9	1.983	1.120	10

- **DOD and SOC**

The depth of discharge (DOD) is the obverse of state-of-charge. Cell voltages almost linearly with depth of discharge until a point called cut-off-voltage is reached .Battery cells should not be operated beyond the cut off voltage, because further discharge will result in increasing the internal resistance of the battery and can result in permanent damage. On other hand, overcharging the batteries until gassing leads also to cell damage. So we must use charge controller or regulator.

- **Self of discharge**

Lead–acid battery cells are available with either pure lead or lead–calcium grids to minimize the self-discharge rate.

All lead–acid cells have some loss in capacity on standing due to internal chemical reactions. Figure 4.18 presents typical self discharge rates for a cell containing antimony or calcium grids. Self-discharge rate, increases with increasing cell temperature and remain relatively low for cell with lead calcium grids.

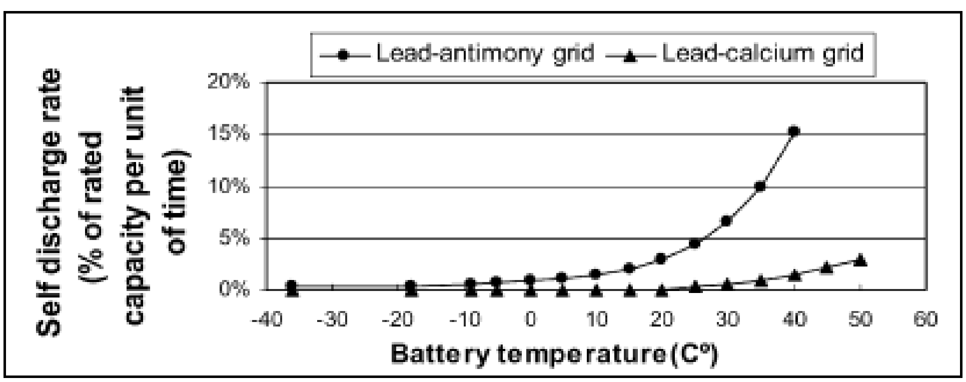


Figure (4.18): Lead–acid battery self discharge rate in function of cell temperature [15].

4.3.5. Storage capacity and efficiency

Batteries are commonly rated in terms of their Ampere– hour (Ah) or Watt–hour (Wh) capacity. Ah-capacity is the quantity of discharge current available for a specified length of time valid only at a specific temperature and discharge rate. For example, a 12V battery rated at 100 Ah over 20 h can deliver 5 Ah for 20 h (C20 rate) is equivalent to 1.2 kWh of energy (12V × 100 Ah). At 5 h discharge rate, the same battery will deliver a maximum of 70 Ah equivalents to 0.8 kWh of energy (C5 rate).

The discharge curve in Figure 4.19 illustrates the relationship between Ah-capacity and discharge current for a typical 100 Ah/12V lead–acid battery. High discharge current would result in reduction of the battery capacity and will shorten its life . In addition, the Watt–hour capacity (Wh) or energy capacity is the time integral of the product of discharge current and voltage from full charge to cutoff voltage. Battery capacity increases about 1% for every 1^{o} C increase in temperature.

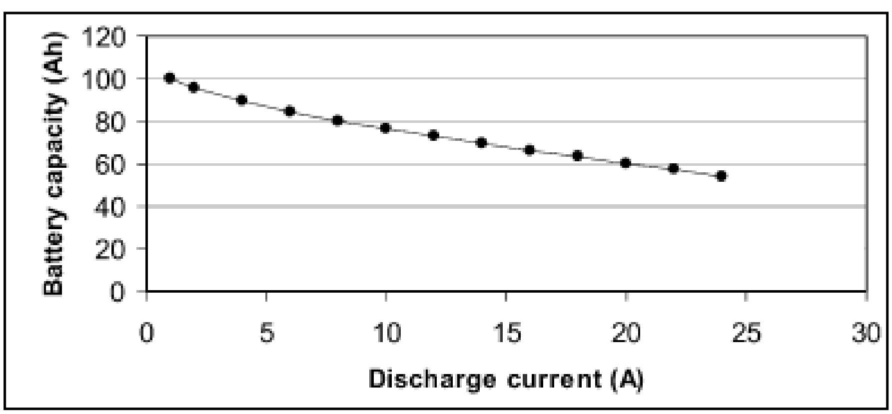


Figure (4.19): The Ampere–hour capacity of a lead–acid battery in function of the discharge current [15].

Lower temperature results in decreasing the capacity due to slower chemical reactions. The Ampere–hour efficiency of a battery cell (η_{Ah}) is the ratio of the number of Ampere–hours obtainable during discharge to that required to restore it to its original condition. The value for a lead–acid cell is about 90%. Based on Table 4.1, the voltage of a battery cell depends on its state-of-charge. Therefore, its Watt hour efficiency takes the voltage variation during charging and discharging into account, and amount to about 75%.

4.3.6. Battery life cycle time

Battery lifetime in cycles depends on the depth of discharge during normal operation. Figure 4.20 shows how the depth of discharge affects the number of operating cycles of a deep discharge battery.

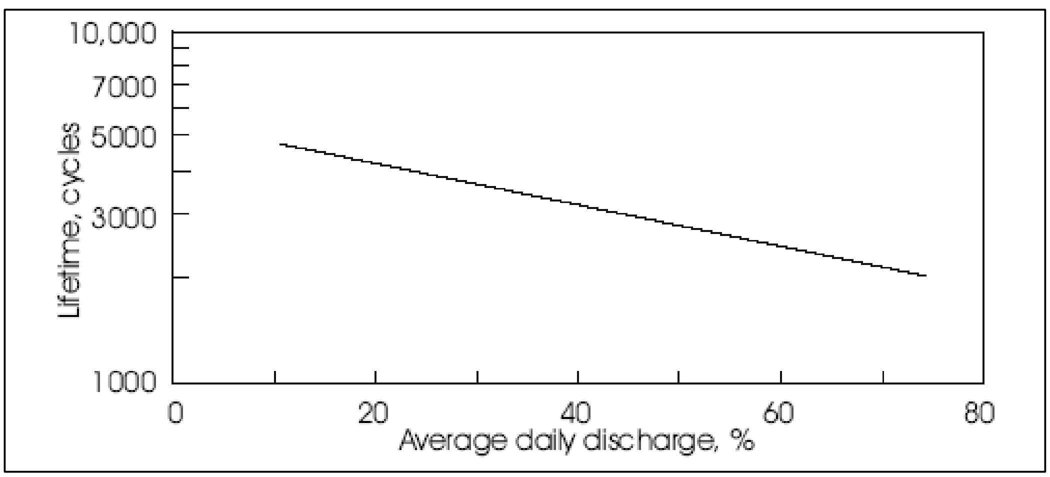


Figure (4.20): Lead-acid battery lifetime in cycles vs. depth of discharge per cycle [8].

Deep discharged lead acid batteries can be cycled down to 20% of their initial capacity [8].

4.3.7. Fast and slow charge and discharge

The higher discharge rates results in less charge being available as energy to a load.

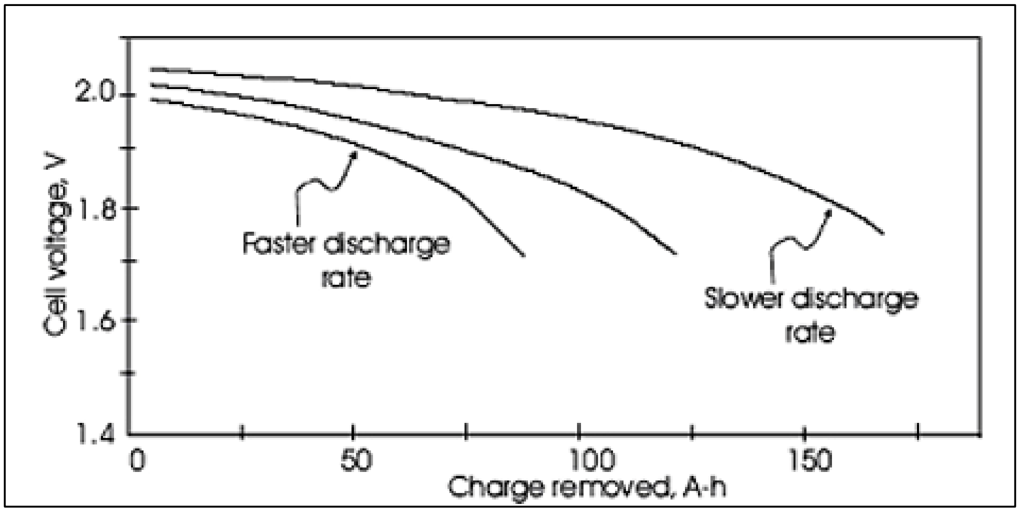


Figure (4.21): Effect of discharge rate on available energy from a lead-acid battery [8].

At higher charging rates a smaller fraction of the charging energy is used for charging and a larger fraction is used to heat up the battery.The battery can be fully charged at higher charging rates, but it takes more energy at higher charging rates to obtain full charge [8].

4.3.8 Operation conditions of battery in hybrid PV-system

Energy from batteries is needed whenever the renewable energy is insufficient to supply the load. On the other hand, energy is stored whenever the supply from the renewable energy system exceeds the load demand. The minimum storage level is limited to 20% of what is available in the battery before the discharging cycle begins [16].

The battery operation between E_{bmin} and E_{bmax}

$E_{bmin} <= E_b (t) <= E_{bmax}$

$E_{bmin} = (1\text{-}DOD)*E_b$

Where:

E_b: is the nominal capacity of battery bank.

DOD: depth of discharge.

4.3.9. Battery model:

Charging mode:

The charge capacity of battery bank at the time t at charging state can be expressed as

$$\mathbf{E_b (t) = E_b (t-1) \times (1-\sigma) + (E_{PV} (t) - E_L (t)/\eta_{inv}) \times \eta_{Batt}} \qquad \textbf{(4-8)}$$

On the other hand, the battery bank is in discharging state, assumed the discharge efficiency of battery bank is 1.

Discharging mode:

The charge capacity of battery bank at the time t at discharging state can be expressed as

$$\mathbf{E_b (t) = E_b (t-1) \times (1-\sigma) - (E_L (t)/\eta_{inv} - E_{PV} (t))} \qquad \textbf{(4-9)}$$

E_b (t) and E_b (t-1) are the charge capacity of battery bank at the time t and (t-1) , respectively, σ is hourly self discharge rate assumed is zero , $E_{PV}(t)$ is energy from PV array , $E_L(t)$ is load demand at the time t , η_{inv} and η_{Batt} are the efficiency of inverter and charge efficiency of battery bank respectively [17].

4.4.Charge controller (regulator)

In nearly all systems with battery storage, a charge controller is an essential component to protect the battery against deep discharge and excessive overcharge. The charge controller must shut down the load when the battery reaches a prescribed state of discharge and must shut down the PV array when the battery is fully charged.

The controller should be adjustable to ensure optimal battery system performance under various charging, discharging and temperature conditions. Battery terminal voltage under various conditions of charge, discharge and temperature has been presented in Figure 4.22.

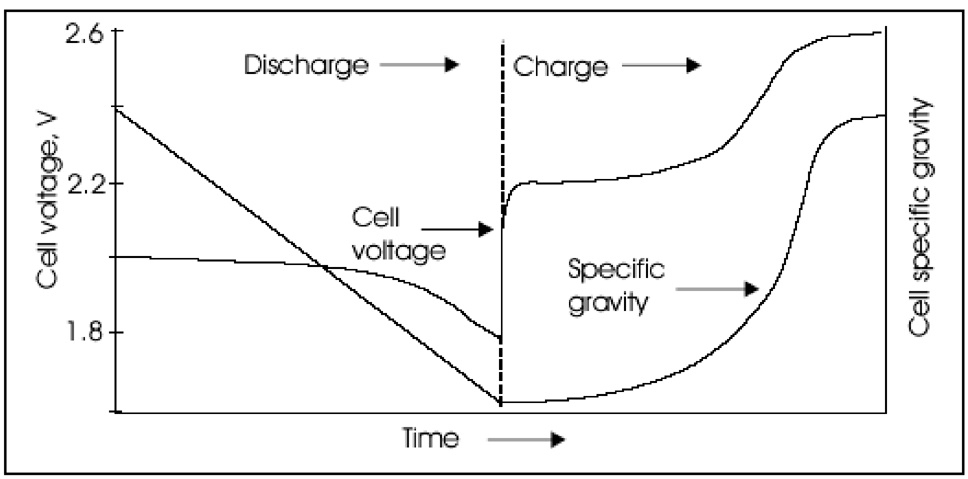


Figure (4.22): Variation of cell electrolyte specific gravity and cell voltage during charge and discharge at constant rate [8].

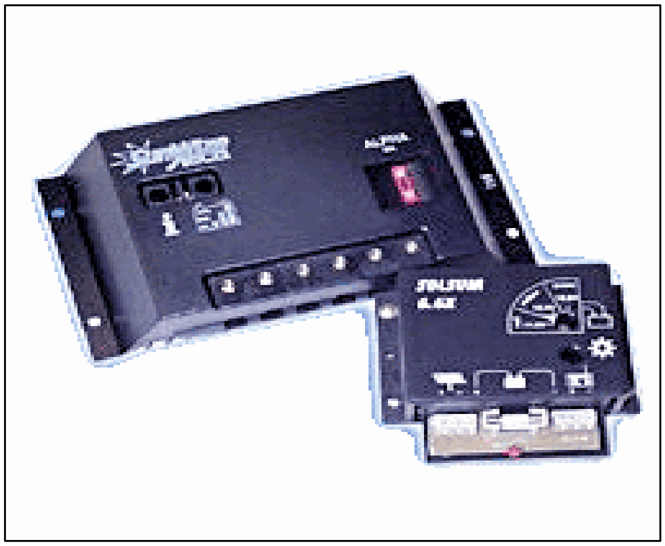
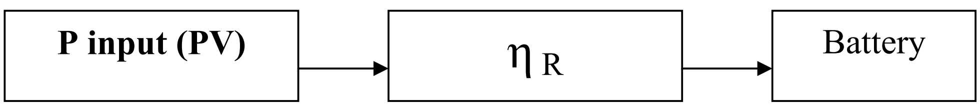


Figure (4.23): Charge regulator.

4.4.1. Controller model

Each Regulator can be characterized by power and efficiency.



Model inputs:

Input power from PV : P_{pv}

Efficiency of charge regulator : η_R

Model outputs:

Output power of regulator : P_{Ro}

$$P_{Ro} = \eta_R \times P_{pv} \qquad \textbf{(4-10)}$$

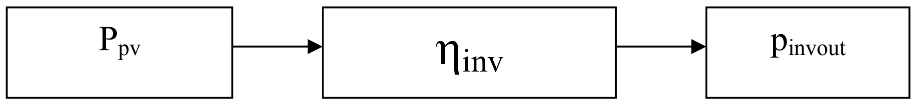
4.5. Inverter

Depending on the requirements of the load, a number of different types of inverters are available. Selection of the proper inverter for a particular application depends on the waveform requirements of the load and on the efficiency of the inverter. Inverter selection will also depend on whether the inverter will be a part of a grid-connected system or a stand-alone system. Many opportunities still exist for the design engineer to improve the inverters, since inverter failure remains one of the primary causes of PV system failure.

Figure (4.24): Inverter

4.5.1 Inverter Model

Each inverter can be characterized by power and efficiency.



Model inputs:

Input power from PV: P_{pv}

Efficiency of inverter: η_{inv}

Model outputs:

Output power of inverter : P_{invout}

$$P_{invout} = \eta_{inv} \times P_{pv} \qquad \textbf{(4-11)}$$

CHAPTER FIVE

SIZING OF SYSTEM COMPONENTS

5. Sizing of system components

It is important to determine the correct size of system components,

If the system is oversized, it will be more expensive without increasing the performance level. However if the system is too small, the system will not be able to reach load demand.

5.1. Load

Load profile estimation is an important criterion for sizing and design the power supply system. It varies with respect to the performance of the villagers or consumers. For example in Palestine villages the large loads are at around midday (washing, fans...), and the largest occurring at evening. Villagers stay in their homes (lights, TV, appliances).After 10 PM the load is very low because most of the appliances are off except refrigerators

5.2. Sizing of PV Panel

The peak power of the PV generator to cover the total load demand is obtained as in equation (5-1).

$$P_{pv} = \frac{E_L}{\eta_v \times \eta_R \times PSH} \times S_F \qquad \textbf{(5-1)}$$

Where E_L is the daily energy consumption in kWh, PSH is the peak sun hours (PSH= 5.4); η_R, η_V are the efficiencies of charge regulator and inverter respectively (η_R 0.92, η_V 0.9) and S_f is the safety factor for compensation of resistive losses and PV-cell temperature losses S_f=1.15 [2].

5.3. Sizing the battery block

The storage capacity of a battery block for such PV power systems is considerably large. Therefore, special lead–acid battery cells (block type) of long life time (>10 years), high cycling stability-rate (>1000 times) and capability of standing very deep discharge should be selected [2]. Such battery types are available but at much higher price than regulars batteries. The Ampere hour capacity (C_{Ah}) and Watt hour capacity (C_{wh}) of the battery block, necessary to cover the load demands for a period (day) without sun, is obtained as in equation (5-2) [2].

$$C_{wh} = \frac{E_L \times AD}{\eta_v \times \eta_B \times DOD} \qquad \textbf{(5-2)}$$

AD is the autonomy days: period of time (day) necessary to cover the load demands by the battery without sun.

5.4. Sizing of charge regulator

The charge regulator (CR) is necessary to protect the battery block against deep discharge and over charge. Input/output ratings of CR are fixed by the output of the PV array and the battery voltage.

5.5. Sizing of inverter

The input of inverter has to be matched with the battery block voltage while its output should fulfill the specifications of the electric grid supplying the load.

5.6. Sizing of diesel generator

The ratings of the diesel generator are determined by the load, it must cover the maximum power demand of the village.

CHAPTER SIX

ECONOMICAL ANALYSIS OF HYBRID SYSTEM

6. Economical Analysis of Hybrid System

Hybrid system economical analysis used in this work is based on the use of life cycle cost, cost annuity ($/kWh). Project with lowest cost ($) per production unit (kWh) should be selected. In addition the analysis has been designed for economical comparison of hybrid power system and diesel or PV-battery standalone systems.

Three different types of costs are analyzed and these are:

1. Initial capital cost of purchasing equipment and installation;
2. Recurring costs that occur every year of operation such as fuel and Maintenance costs.
3. Non-recurring costs that may occur on an irregular basis, such as equipment replacement or repairs.

6.1. Present worth factors and present worth [8]

The present worth of an item is defined as the amount of money that would need to be invested at the present time with a return of 100% discount rate in order to be able to purchase the item at the future time.

- Present worth of replacement cost

Present worth factor (Pr) of an item that will be purchased n years later

$$Pr = \left(\frac{1+i}{1+d}\right)^n \qquad \textbf{(6-1)}$$

Where (i: inflation rate, d: discount rate, n: replacement year)

Present worth of replacement item = Pr x replacement cost (6-2)

- Present worth of annual costs

Present worth of recurring expenses such as fuel and maintenance costs

determined by product of annual cost and cumulative present worth factor (Pa).

Letting $$X = \left(\frac{1+i}{1+d}\right)$$

$$Pa = \left(\frac{1-X^n}{1-X}\right)$$

Present worth of annul cost = (Pa x annual cost) (6-3)

6.2. Life cycle cost (LCC)

The life cycle cost (LCC) is defined as the sum of the PWs of all the components. The life cycle cost may contain elements pertaining to original purchase price, replacement prices of components, maintenance costs, fuel and/or operation costs, and salvage costs or salvage revenues.

Calculating the LCC of an item provides important information for use in the process of deciding which choice is the most economical. [8]

LCC = Intial cost + (Pa x Ann.cost) + (Pr x repl.Cost)- (Pr x salvage) (6-4)

The negative sign because salvage value is the revenues at the end of the project.

6.3. Initial cost of hybrid power system

Initial cost include purchasing equipment (PV-panels, Batteries, Diesel generator, inverter, regulator, rectifier, wires and other components used in installation) also includes labors and technicians costs for installation, these costs depend on size and type of a component ,all these costs are summed to give the overall initial cost.

$$\textbf{Initial cost} = \sum \textbf{components cost} + \textbf{installation cost} \qquad \textbf{(6-5)}$$

6.3.1. Initial cost of photovoltaic modules.

PV-modules available in different sizes and types, the size of PV characterized by their peak watt at STC (rated power).The price of peak watt is the same for mono or poly crystalline but the installation or structure cost will differ depending on the installed PV area. Figure 6.1 shows the relation between (W_p) and ($\$/W_p$) for modules of BP Solar Panel using multi crystalline silicon cells with different rated power. The ($\$/W_p$) will decrease as the size of module increase [www.affordable-solar.com]

Table (6.1): $\$/W_p$ for different size modules

Module Watt	$/watt
10	12.9
20	11.45
30	8.97
50	6.98
65	6.14
80	5.86
125	5.36
160	4.37

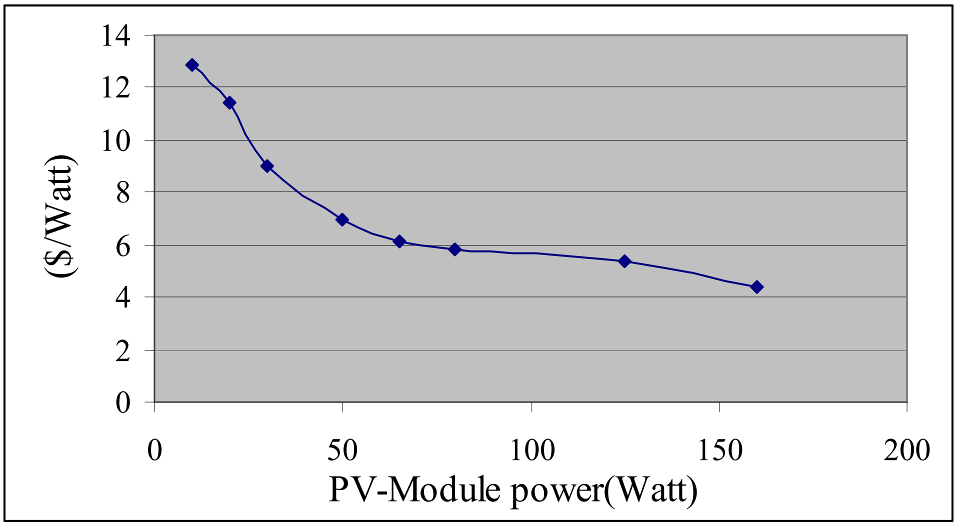


Figure (6.1): Module rated power (watt) vs. ($/watt)

The cost of watt peak can be considered (5 $) per watt peak.

6.3.2. Initial cost of diesel generator

The price of diesel generator depends on diesel generator size, brand and technical characteristics such as speed (rpm), fuel, etc…

Diesel generators kW vs. $/kW shown in Figure 6.2.$/kW decrease while rated power increase. [www.generatorjoe.net]

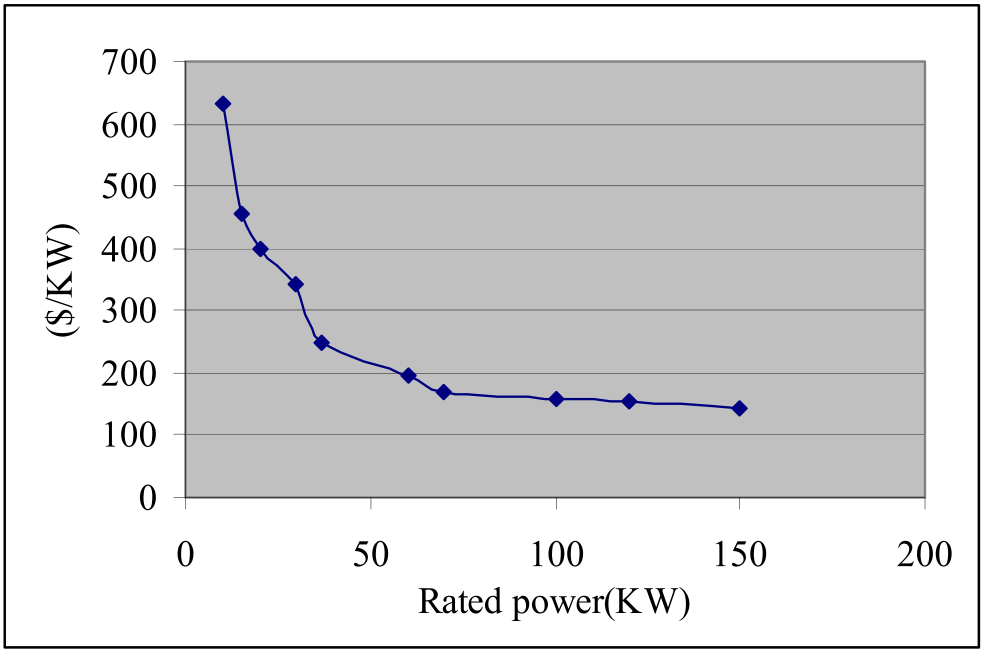


Figure (6.2): Diesel generators rated power (kW) vs. Cost in ($/kW)

6.3.3. Initial cost of batteries

Various battery types exist with different nominal voltage rating (2,4,6,12) volt .The most common ones used in solar system are lead acid batteries of 2 volt per cell (block batteries).This is due to their high cycling stability rate (>1000 times) and capability of standing very deep discharge. Such battery types are available but at much higher price than regular batteries. Table (6.2) show the cost of watt hour rating ($/Wh) vs. Watt hour capacity of Rolls-Surrette Batteries. [www.affordable-solar.com]

Table (6.2): Price of different battery size with same type and brand.

Volt	Ah	Wh	Price ($)	$/Wh
2	1766	3532	644	0.18233
4	546	2184	446	0.204
4	1104	4416	817	0.185
6	546	3276	665	0.203
6	820	4920	915	0.1859
8	546	4368	922	0.211
12	357	4284	821	0.1916

The price in $ per kWh is between (182 to 211) $/kWh

6.3.4 Initial cost of (inverters, regulators, rectifiers)

Cost of these components varies with rated capacity and efficiency and technology. A cost varies widely because of the variation of work principles and/or special options such as digital display or other. For this reason the designer can enter the price of these components manually in software which helps to get exact calculations.

6.3.5. Other initial costs

Shipping costs and accessories needed for installation and system protection, wiring, rooms, should be also considered. These costs depend on the system size and vary with the kind of the project; if it for public use (may be land available free), or for private use.

Capital costs are input into the formula of LCC with a factor of 1.0 since they are assumed to occur in year 0 i.e. before the start of the system operation.

6.4. Hybrid system operation cost

The operation costs considered are incurred after installation in order to run the system for a certain number of years (system life time).

6.4.1. Diesel generator operation costs

Diesel generator operation costs represent the main operation cost in PV-diesel hybrid system. This cost depends on operating hours of the diesel generator.

- The fuel costs in equation (6-6) represent the Present worth of fuel cost [8]

$$\textbf{Present worth of fuel} = \textbf{Ann Fuel cost x } [(1-X^n)/(1-X)] \qquad \textbf{(6-6)}$$

Where, Ann Fuel cost is the annual fuel expenditure, X= [(1+Fe)/ (1+Dr)], Fe represents fuel Inflation, Dr Represents discount rate, and n represents life cycle period in year.

- Recurring maintenance cost depend on the operation hours of diesel generator, Preventive diesel engine maintenance consists of the following operations:
  - General inspection
  - Lubrication service
  - Cooling system service
  - Fuel system service
  - Servicing and testing starting batteries
  - Regular engine exercise

- Maintenance technical requirements ;activity and frequency

Daily services: check fluid levels, and top-up if necessary; start and stop the engine [11].

Weekly services: check the air filter, and clean or replace it if necessary; check oil and fuel leaks; tighten any loose nuts and bolts. Change engine oil Every 250 hours.

Regularly services: clean or replace filters; replace the drive belt. Every 500–2000 hours decarbonize the engine, clean injector nozzles, adjust valves, etc.

Occasionally services: replace engine parts or rebuild engine.

Table 6.3 shows cost and maintenance information on small electrical generators. Note that "small" is defined as sizes less than 100 kW.

Table (6.3): Cost and maintenance information on small electrical generators [8]

Type	Size Range (kW)	Application	Cost ($/W)	Maintenance Intervals		Engine Rebuild,hr
				Oil Ch,hr	Tune-Up,hr	
3600 rpm gas	1-20	Light use	0.50	25	300	2000-5000
1800 rpm gas	5-20	Heavy use	0.75	50	300	2000-5000
Diesel	3-400	Industrial	1.00	125-750	500-1500	6000

We consider in our calculations many types of maintenance such as:

Oil change each 250 hours.

Oil filter replacement each 500 hours.

Air filter replacement each 3000 hours.

Fuel filter replacement each 750 hours .

Overhaul will be carried out each 6000 hour. Overhaul cost is equal to 15 % of diesel generator initial cost. Three times of overhaul then replacement of diesel generator is recommended.

The quantitative expression for life cycle maintenance cost is given by

$$\textbf{PW maintenance} = \textbf{Ann main. cost} \times [(1-X^n)/(1-X)] \qquad (6\text{-}7)$$

Where, Ann main.cost is the annual maintenance cost,

$$X = [(1+Ge)/(1+Dr)]$$

Ge represents general inflation, Dr Represents discount rate, and n represents Period life cycle period in year.

Because yearly operation hours of diesel generator varies with utilization of diesel generator, we assume diesel ON for complete year (8760 hours)

Then calculate annual maintenance cost (Ann. Main. Full) and use this value to calculate real maintenance cost which depends on operating hours per year of diesel generator.

Annual maintenance cost =(Operating hours/8760) x (Ann .Main. Full)

Other type of maintenance represented in monitoring and regular check requires a labor or technician and needs monthly salary depending on living level in Palestine where assume 1200$/year since diesel off in summer .

6.4.2. Battery and PV panels maintenance cost

PV generator requires very little maintenance represented in cleaning the module surface. The batteries in the system will require inspection and topping up, approximately every 3-6 months. So in the hybrid system we should combine these costs with the labor cost used for diesel generator.

6.5. Replacement cost (non-recurring cost)

Batteries are the main components of the system which have to be replaced during the life time of the system.

The equation for non-recurring costs is given by

$$\textbf{PW replacement cost} = \textbf{Item cost x } [(1+Ge)/(1+Dr)]^{Ry} \qquad \textbf{(6-8)}$$

Where, Item cost is the non-recurring expenditure in present day costs, Ge represents general inflation, Dr is the discount rate, and, Ry is the replacement year.

6.6. Economic factors

Different economic factors used in the present economic analysis are life cycle period, discount rate and cost inflation or general inflation. The length of period of the analysis is chosen to be the best service life of the longest-living component. In the case of PV system comparisons, the useful life of a PV module is in the range of 20-30 years, so 20 years is the period chosen for this analysis. The life of a diesel generator is about 24000 hours. The discount rate is the factor that describes the changing value of money over time. It is basically equivalent to the amount of money that we could make with the capital if we choose to invest it in a bank or other investment programs rather than in a power system.

Typical values of discount rate are in range 7-15%. 8 % is used in this analysis. Cost inflation, also called inflation is used to account for the fact that components and services traditionally get more expensive over time. For remote power systems this applies to fuel, maintenance costs and replacement parts. Traditionally, fuel costs are escalated at a separate and slightly higher rate than other costs. Typical annual inflation rates for remote power systems used in this analysis are 5-10 % for fuel and 3-8% for non-fuel expenses.

6.7. Cost annuity

The cost annuity converts all net cash flows without inclusion of income in the calculation; it can only be used for evaluating the relative favorability of investment projects on the basis of costs per annum or per unit production [2].

$$Ak = \frac{LCC}{Pa} \quad \textbf{(6-9)}$$

$$(\$/kWh) = \frac{Ak}{\text{Total yearly kWh produced}} \quad \textbf{(6-10)}$$

Where Ak is the cost annuity, Pa is the cumulative present worth factor.

6.8. Net present value (NPV)

The NPV of an investment project at time t=0 is the sum of the present values of all cash inflows and outflows linked to the investment [2].

NPV=PW (income) – LCC **(6-11)**

Where PW (income) = annual revenue of energy sold x Pa

A project is profitable when NPV>0 and the greater the NPV the more profitable. Negative NPV indicates that minimum interest rate will not be met [2]

6.9. Sensitivity analysis

Sensitivity analysis is a simple technique to assess the effects of adverse changes on a project. It involves changing the value of one or more selected variables and calculating the resulting change in the cost annuity (NIS/kWh).

In this work the scenarios of sensitivity analysis are:

1- Increase the fuel inflation rate and discount rate by 50%

2- Decrease in PV module price by 50 %.

3-Increase in diesel fuel price by 50 %.

4- Combination of factor 2 and 3.

CHAPTER SEVEN

SOFTWARE DEVELOPMENT

7. Software development

Matlab had been used in programming of the software in this study due to simplicity when dealing with matrix of data.

7.1. Approach to optimization

Hourly simulation is used to find the least cost combination of different sized systems that meet the electrical load demands. For each hour the software compares the electrical load and the energy supply in that hour, the software decides for each hour when to operate the diesel generator and wither to charge or discharge the battery.

- **Energy Flow**

The following operating strategy is employed

- The use of electric power generated by the photovoltaic arrays has priority in satisfying electricity demand over that provided by the batteries or by the electric diesel generator.

- If the total electric power generated by the photovoltaic array is higher than the load demand, the additional electric power wi1l be charged the batteries.

- After charging the battery, the electric power exceeds is disposed (dump energy).

- If the total electric power generated by the photovoltaic arrays is less than the load, electric power will be discharged from the batteries to supply the demand because once the batteries are bought, their major cost would have been committed and their use is given priority.

- If batteries cannot supply the load, then electric power has to be drawn from the electric power generator. Diesel generator can charge the batteries and continue in operation until the batteries reach full charge, this can help to reduce the start and stop times of diesel generator and to operate diesel generator efficiently.

7.2. Steps of optimization

Methods mentioned in Chapter 5 for sizing the system components (PV, battery storage and other components) gave an approximation for the components size. Simulation depends these results as reference values and runs with varying PV contribution and the battery bank size .By this variation many parameter or outputs varies .For example dump energy is an indication for energy produced by the PV array without use ,operating hours of diesel generator ,fuel consumption and kg of CO_2 produced are inputs for economical equations to calculate, for a proposed design, the cost of generating electricity ($/kWh) .Selecting the most economical design is achieved by minimum cost of energy generated.

7.3. Software inputs, outputs

Inputs:

Load demand (typical daily load curve)

PV contribution

Autonomy days

Hourly solar radiation over a year

Hourly temperature over a year

Component cost and economical factors

Outputs:

Diesel generator operating hours

Diesel generator fuel consumption

PV rated power (kW)

Battery storage capacity

Dump energy

State of charge

CO_2 produced

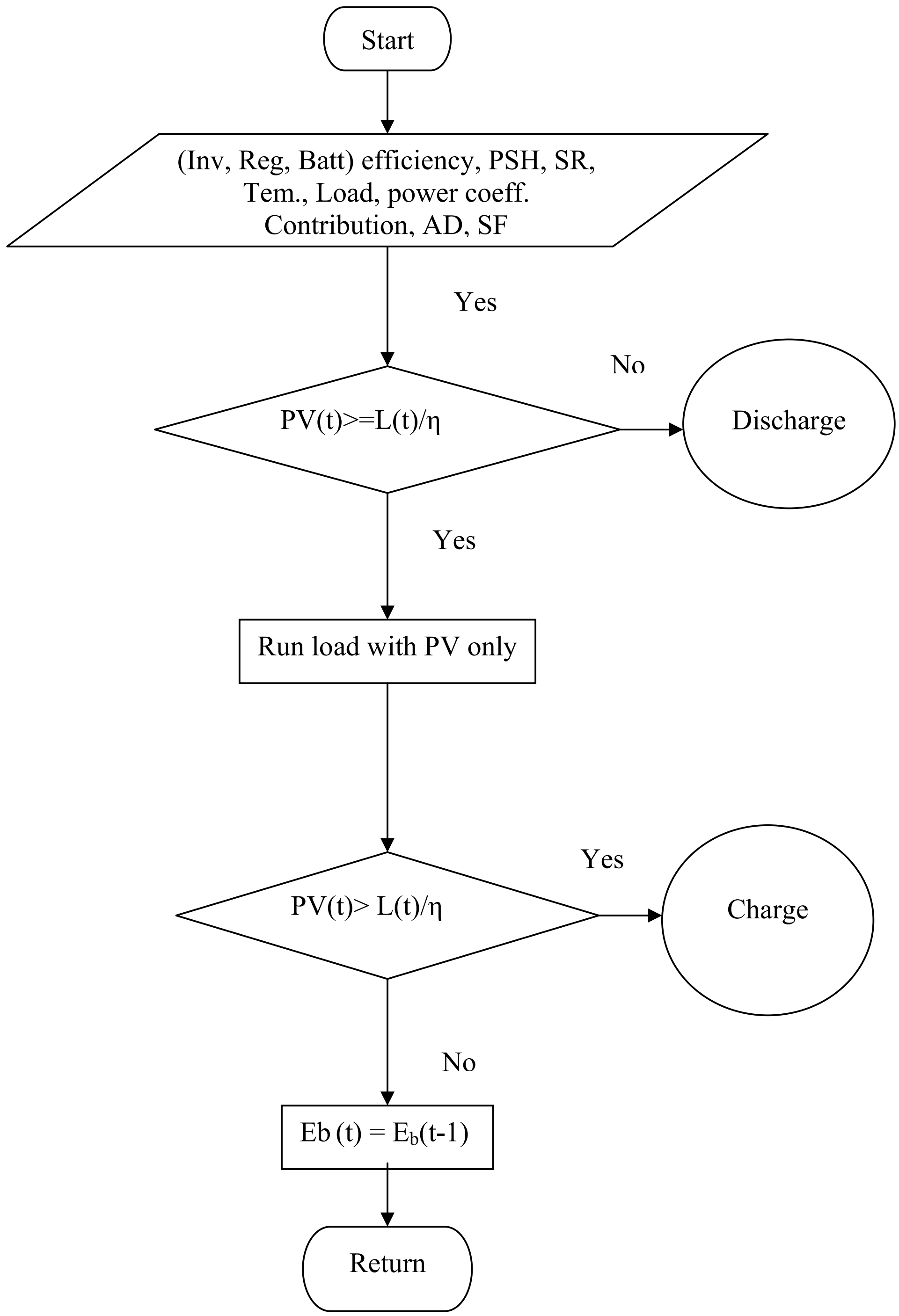
Operating load of diesel performance

Cost annuity ($/kWh)

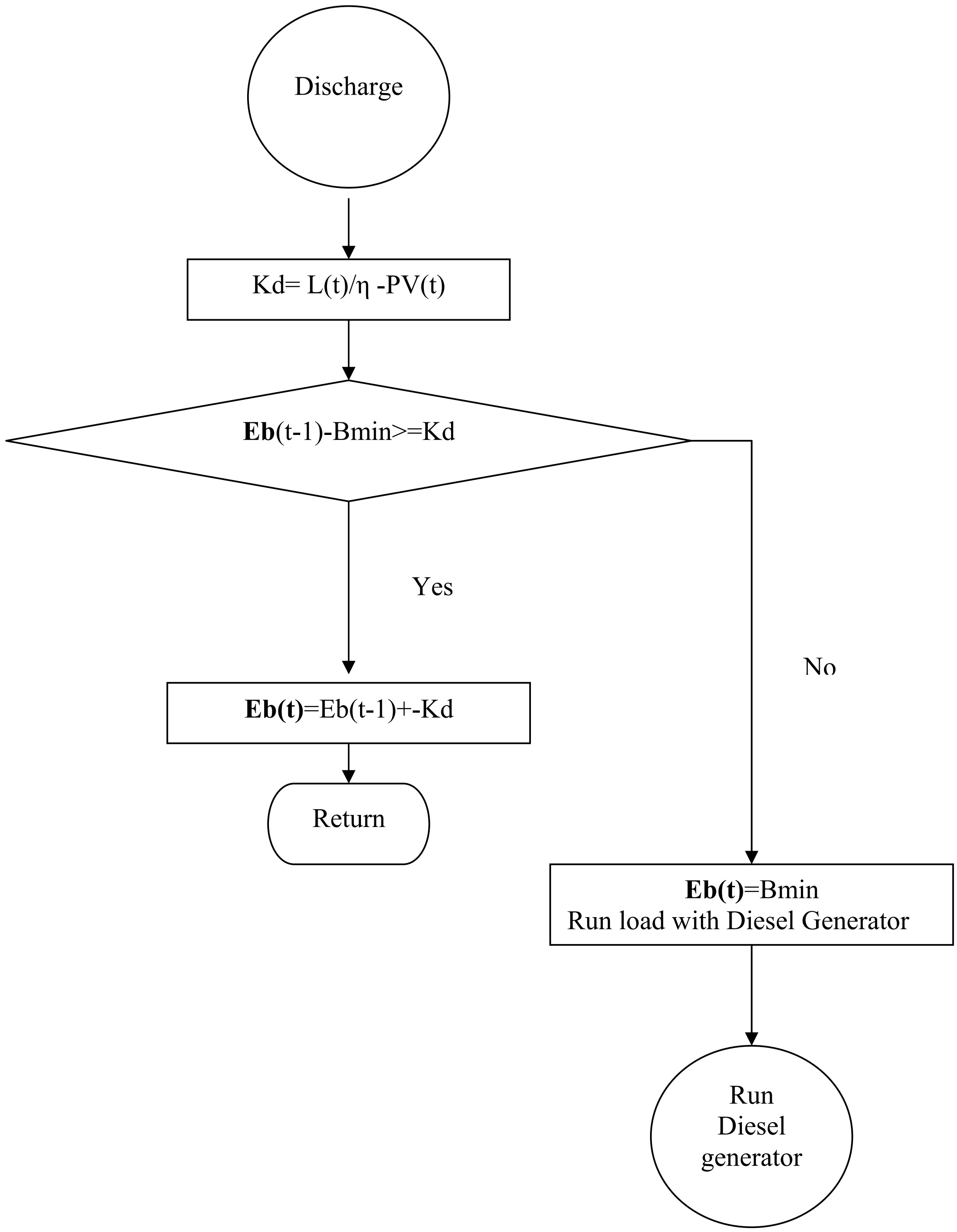
Graphs

7.4. Software flow chart

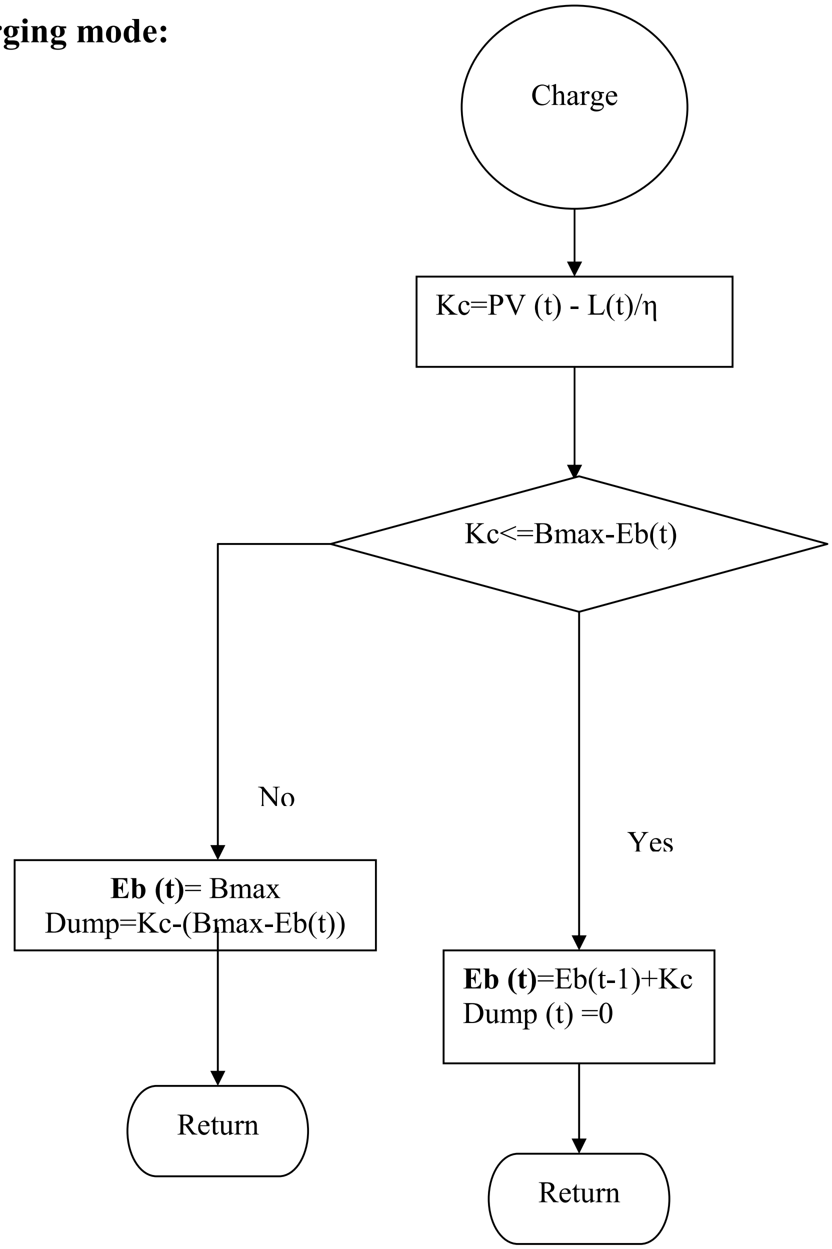
Main part



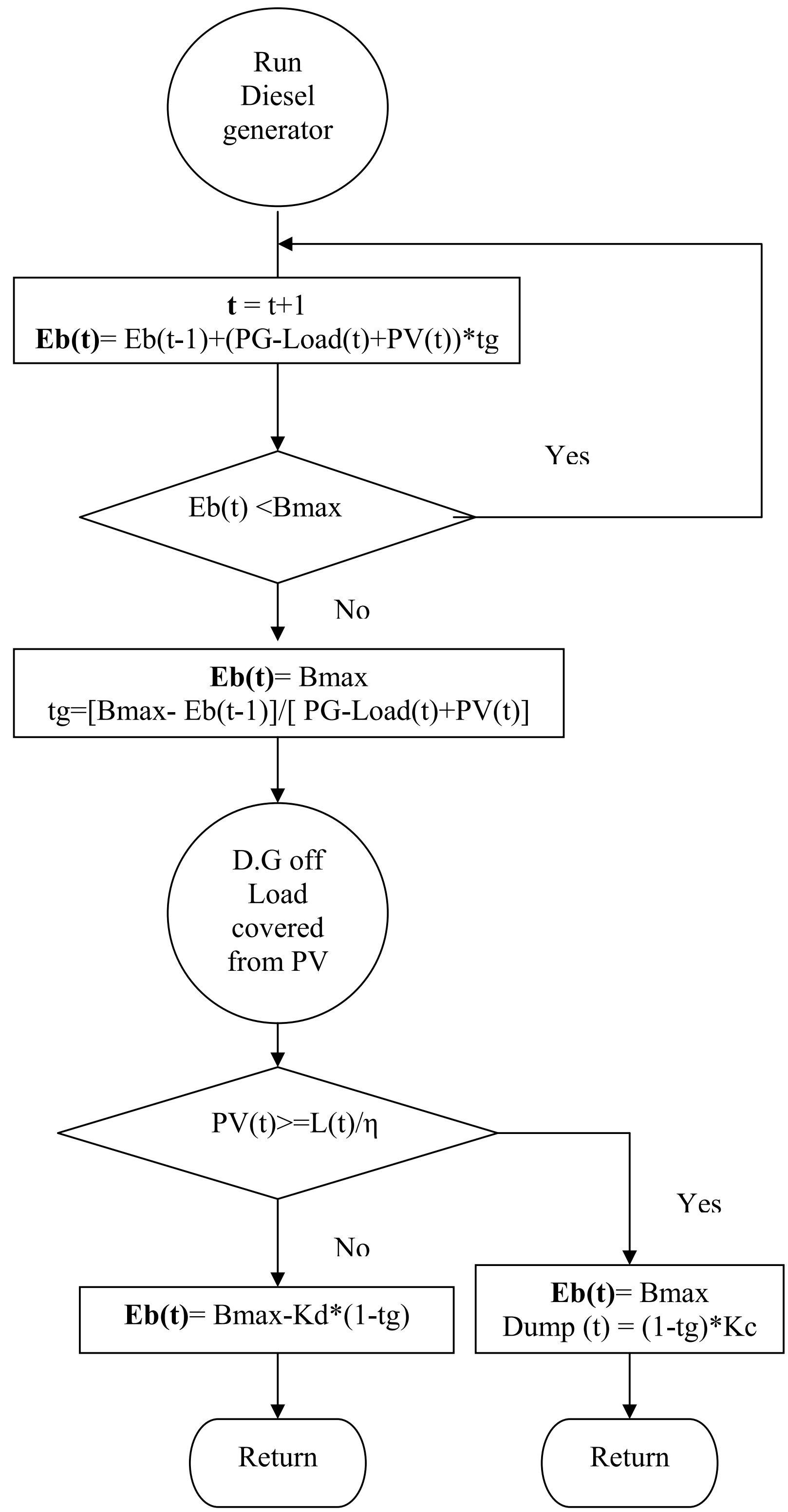
Discharging mode:



Charging mode:



Running Diesel generator mode:



CHAPTER EIGHT

DESIGN EXAMPLE

8. Design example

The objective of this chapter is to illustrate an optimum energy system design, where the energy components are sized to meet loads over 24 hours. The battery storage bank is maintained at appreciable level of charge and the overall life cycle cost of the system is minimized.

8.1. Inputs

Figure 8.1 illustrates typical daily load of small village in Palestine. Total daily energy 100 kWh, maximum power peak load is 8 kW and minimum is 2 kW.

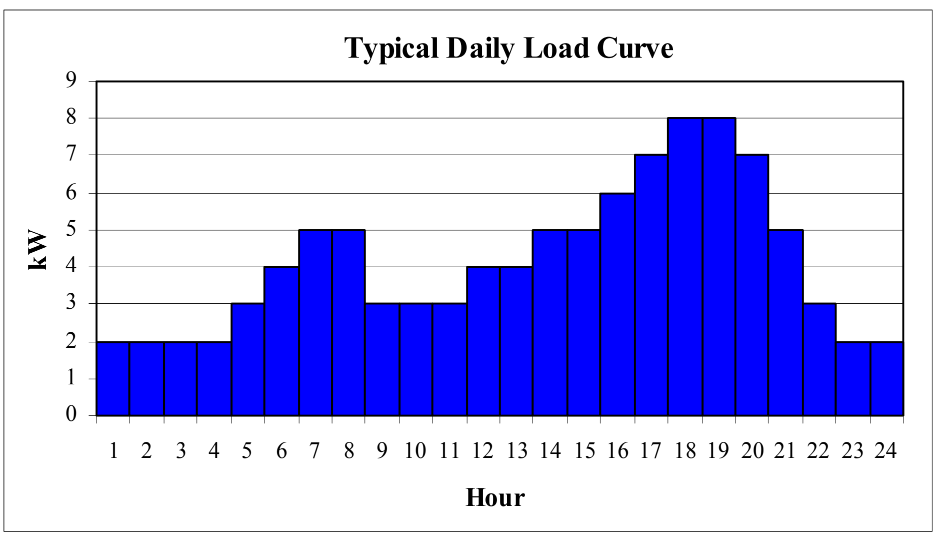


Figure (8.1): typical daily load curve

Table (8.1): The diesel generator data

Power output (kW)	10
Cost ($)	10000
Fuel cost ($/liter)	1
Oil change cost ($ each 250 hours)	5
Oil filter replacement cost ($ each 500 hours)	10
Air filter replacement cost ($ each 3000 hours)	35
Fuel filter replacement cost ($ each 750 hours)	5
Overhaul cost ($) each 6000 hours	1500
Diesel life time hours	24000
Technician cost ($/year)	1200
Diesel generator salvage value ($)	750

Table (8.2): The PV –battery system data

PV cost ($/kW)	5000
PV installation cost ($/kW)	400
Inverter cost ($)	12000
Regulator cost ($)	10000
Rectifier cost ($)	2500
Inverter efficiency (%)	0.92
Regulator efficiency (%)	0.95
Rectifier efficiency (%)	0.97
Battery efficiency (%)	0.85
Battery cost ($/kWh)	200
PV life (years)	24
Battery Life (years)	12

Table (8.3): The economical factors.

Interest rate (%)	8
General inflation rate (%)	4
Fuel inflation rate (%)	5
life cycle period (year)	24

8.2. Outputs

The following results vary with variation of PV contribution and autonomy day.

8.2.1. General outputs.

Table (8.4): Price of energy (NIS/kWh)

	PV Contribution (%)				
AD	20	40	60	80	100
0.25	2.379	2.133	2.149	2.263	2.409
0.5	2.554	2.311	2.234	2.039	2.089
0.75	2.574	2.375	2.177	2.013	**2.008**
1	2.684	2.443	2.212	2.060	2.050
1.25	2.753	2.516	2.297	2.136	2.141
1.5	2.844	2.610	2.411	2.227	2.243

Where AD is the daily autonomy, PV contribution is the percentage of energy covered by PV.

The lowest price is **2** NIS/kWh at PV contribution 1 and 0.75 autonomy day.

Table (8.5): the LCC of system (NIS)

	PV Contribution (%)				
AD	20	40	60	80	100
0.25	1396563	1252285	1261603	1328765	1414668
0.5	1499244	1357053	1311644	1196911	1226395
0.75	1511319	1394646	1278339	1181764	**1179169**
1	1575976	1434075	1298696	1209472	1203677
1.25	1616566	1476999	1348363	1254281	1256988
1.5	1669891	1532652	1415755	1307685	1316862

The lowest value of LCC is **1179169** NIS at PV contribution 100 and autonomy day 0.75.

Table (8.6): NPV of Hybrid System.

	PV Contribution (%)				
AD	20	40	60	80	100
0.25	71262	215540	206222	139060	53157
0.5	-31419	110772	156181	270914	241430
0.75	-43495	73179	189486	286061	**288656**
1	-108151	33750	169129	258353	264148
1.25	-148741	-9174	119462	213544	210837
1.5	-202066	-64827	52070	160140	150963

* the price of sold unit of energy (2.5 NIS/kWh)

The greatest NPV **288656** NIS at PV contribution 100% and autonomy day 0.75.

Table (8.7): Total Yearly operating hours of diesel generator.

	PV Contribution (%)				
AD	20	40	60	80	100
0.25	3494	2628	2269	2107	2023
0.5	3672	2815	2250	1489	1198
0.75	3512	2750	1988	1236	**885**
1	3549	2692	1862	1140	771
1.25	3495	2647	1843	1105	766
1.5	3489	2650	1889	1099	784

The yearly operated hours of diesel generator decrease with increasing the PV contribution.

Table (8.8): yearly fuel consumption of diesel generator in liter.

	PV Contribution (%)				
AD	20	40	60	80	100
0.25	11535	8678	7490	6955	6679
0.5	12123	9292	7430	4917	3955
0.75	11596	9079	6563	4082	**2922**
1	11716	8888	6149	3764	2547
1.25	11539	8741	6084	3647	2527
1.5	11520	8750	6238	3629	2589

The yearly fuel consumption of diesel generator decrease with increasing the PV contribution.

Table (8.9): Yearly CO_2 produced from diesel generator in kg.

	PV Contribution (%)				
AD	20	40	60	80	100
0.25	28837	21695	18724	17388	16697
0.5	30308	23231	18574	12293	9888
0.75	28989	22697	16408	10205	**7304**
1	29289	22221	15371	9409	6368
1.25	28848	21851	15210	9118	6318
1.5	28799	21874	15595	9072	6471

The yearly CO_2 produced of diesel generator decreased with increasing PV contribution.

- Variation of diesel generator size, we select scenario of minimum cost (PV contribution =100%, AD=0.75) and vary diesel generator size. Table 8.10 shows the evaluation results.

Table (8.10): Variation of diesel generator size

Diesel Size	**10.0**	**14.0**	**18.0**
NIS/kWh	2.10	2.17	2.22
LCC	1233216	1272632	1304703
operated hours per year	885	675	543
Fuel consumption (Liter/Year)	2922	3122	3226
CO_2(kg/Year)	7304	7804	8065

Results show with increase Diesel generator size, diesel operating hours decrease but fuel consumption increase.

8.2.2. Performance evaluation of system at PV contribution of 100 % and autonomy of 0.75.

The size of system components are shown in Table 8.11.

Table (8.11): Design data for (PV contribution 100%, AD = 0.75)

PV Panel size (kW)	24
Battery size (kWh)	120
Dump kWh yearly	8317
D.G operating Hours	885
Yearly fuel consumption	2922
D.G Capacity (kW)	10
NIS/kWh	2.01
CO_2 (Kg/year)	7304

- Dump energy: is the energy generated from PV and lost without use in supplying load or charging battery.

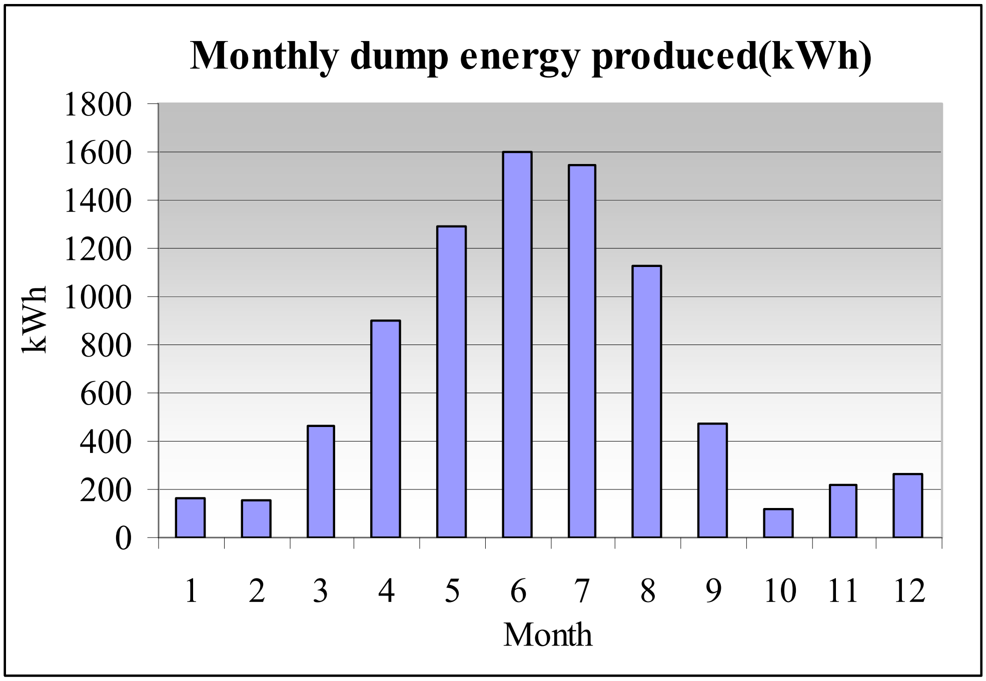


Figure (8.2): Monthly dump energy produced.

Dump energy increased in summer, because the excess energy from PV is increased with higher solar radiation.

- Battery state of charge (SOC).

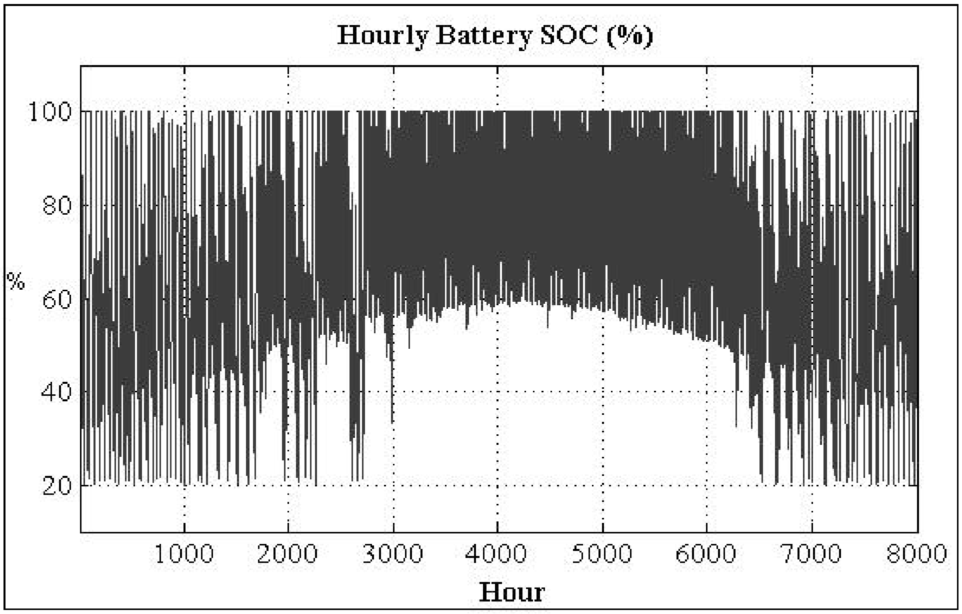


Figure (8.3): Hourly battery SOC during the year.

SOC reaches minimum in winter; DOD Reaches maximum.

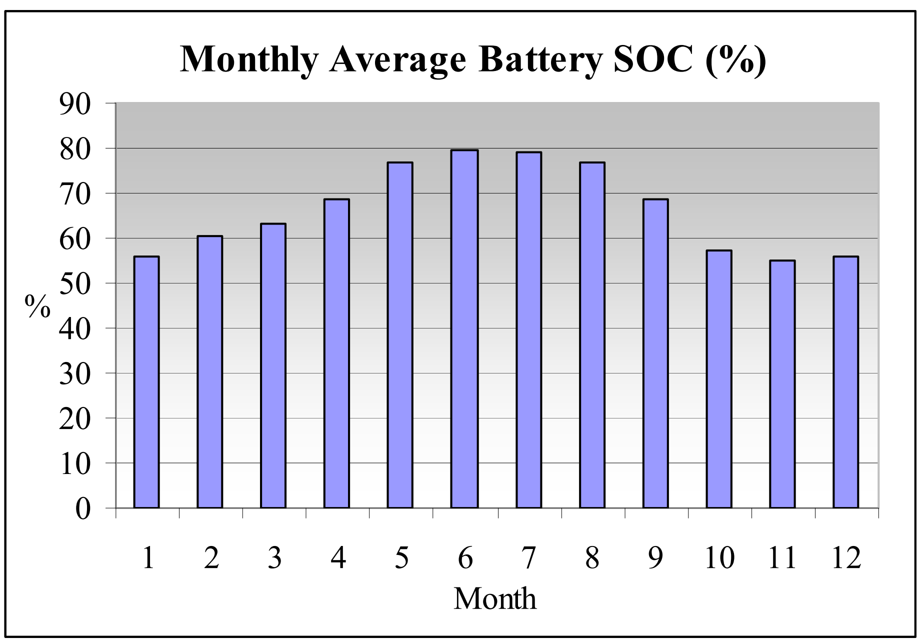


Figure (8.4): Monthly state of charge for the battery block.

Monthly average SOC worst case occurs in November (low solar radiation) while best case occurred at June (high solar radiation).

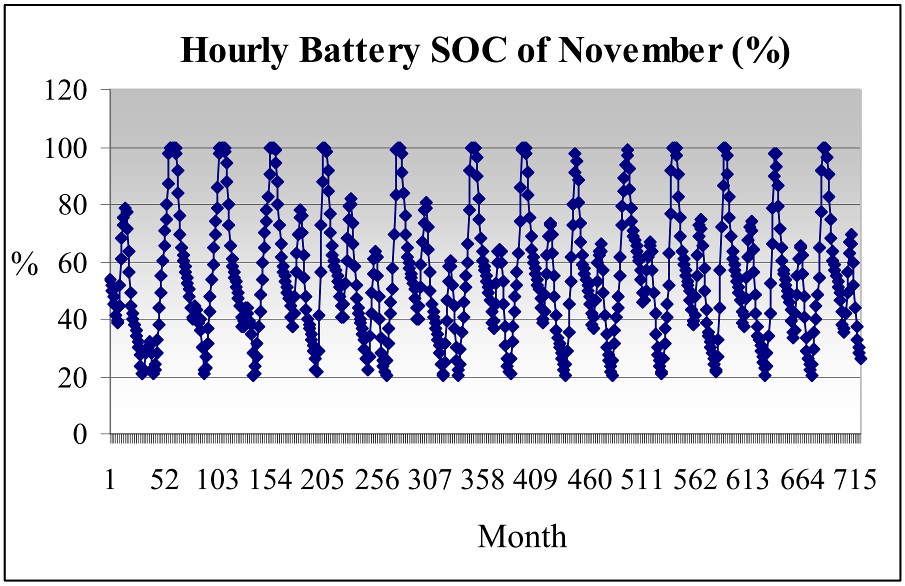


Figure (8.5): Hourly battery SOC during November (worst case)

In worst case month the minimum SOC reaches 20% and the maximum SOC is 100 %.

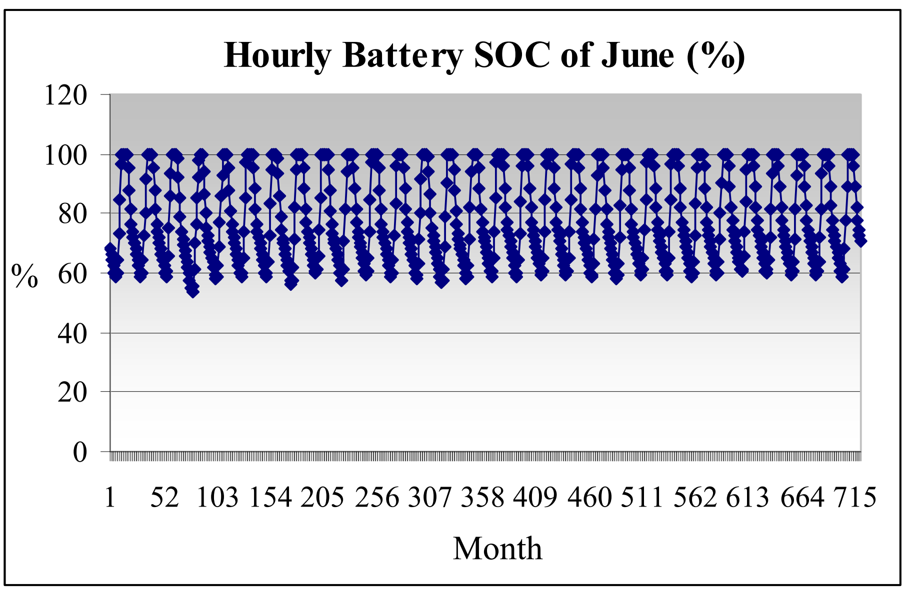


Figure (8.6): Hourly battery SOC during June (Best case).

Battery operates between 100 % and 60% state of charge which is mean the battery reaches to 60 % of maximum capacity then charged again.

-Diesel generator

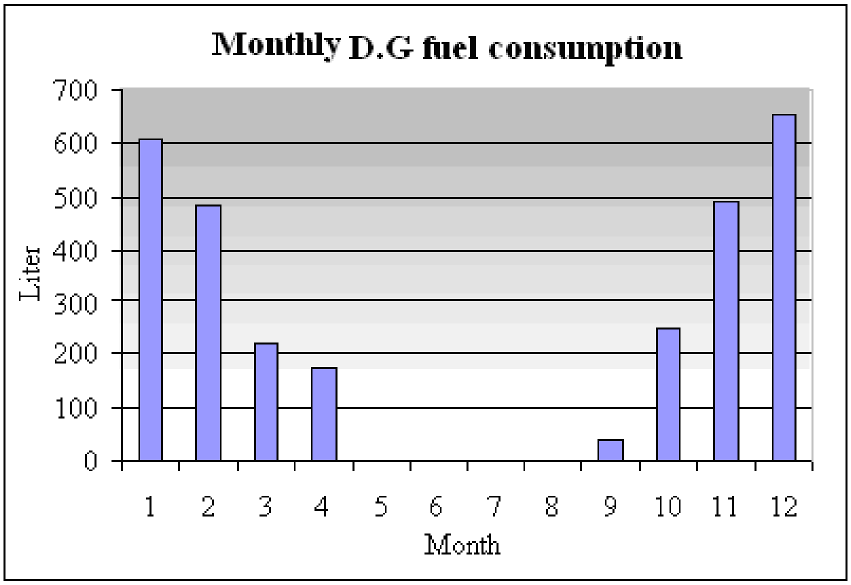


Figure (8.7): Monthly Fuel consumption of diesel generator.

Diesel generator consume more energy in months with low solar radiation, diesel generator do not operates in May, June, July and august.

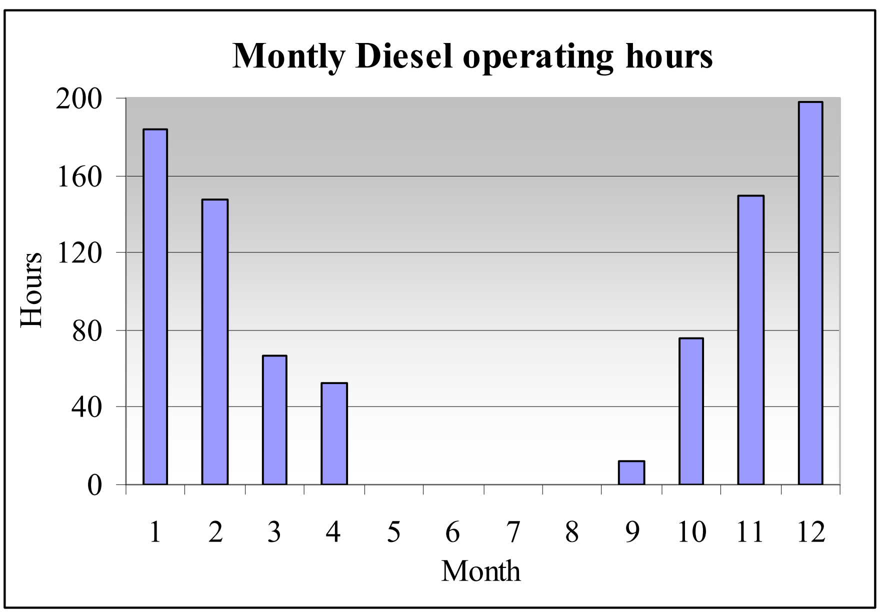


Figure (8.8): Monthly diesel generator operating hours.

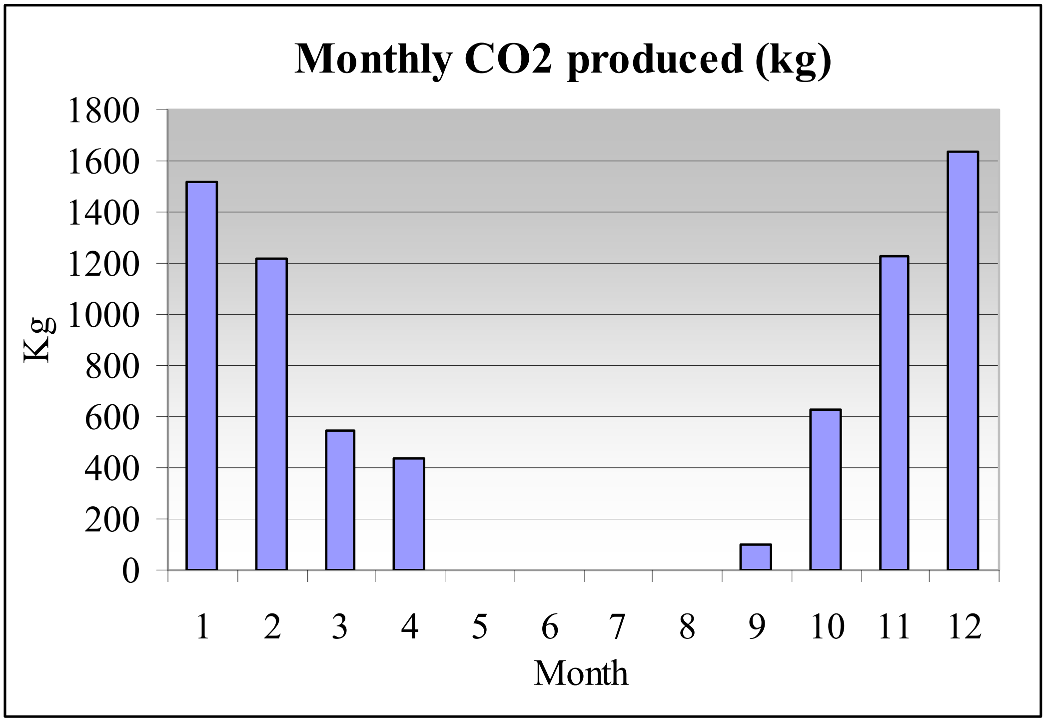


Figure (8.9): Monthly CO_2 produced**.**

The amount of CO_2 is proportional to amount of fuel consumption, the higher value of CO_2 produced in December, while in June and July no CO_2 is produced because diesel generator not operates.

8.3. Output energy from PV-diesel hybrid system

The total energy produced from the system is 53260 kWh where 68 % of this energy is used and 16 % of it is not used (dump energy) and 16 % is the amount of losses, the losses in the system comes from system components losses. Inverter efficiency = 92%, regulator efficiency =95, rectifier efficiency = 97, and battery charging efficiency 85%.

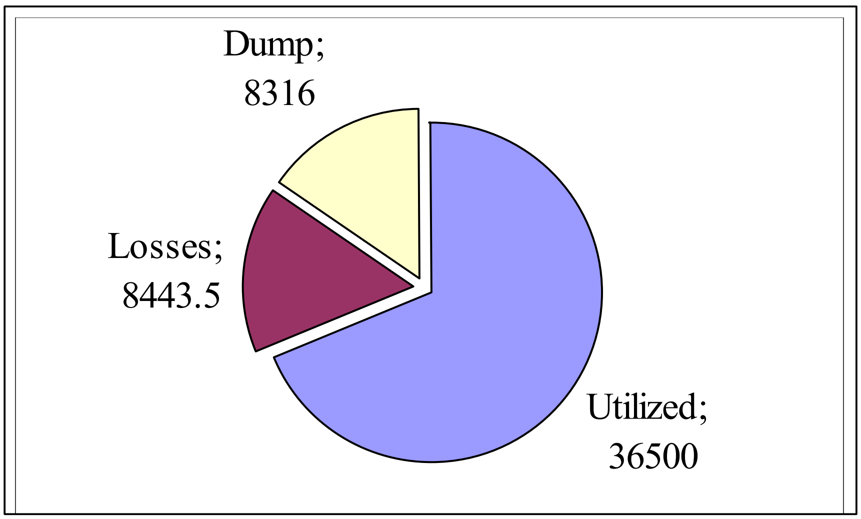


Figure (8.10): Yearly output energy from hybrid system (kWh)

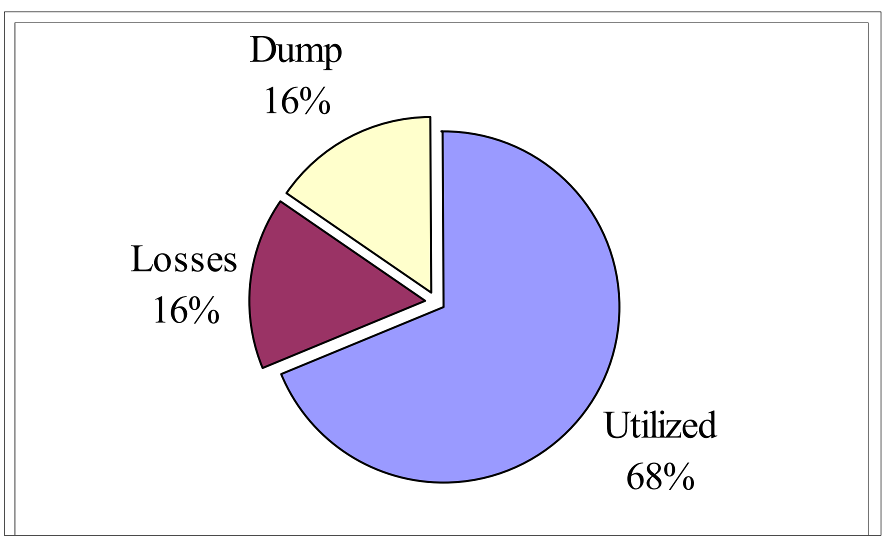


Figure (8.11): Yearly output energy from hybrid system (%)

Energy generated from each part: PV generates 83 % of total energy produced and the remaining 17 % is generated by the diesel generator.

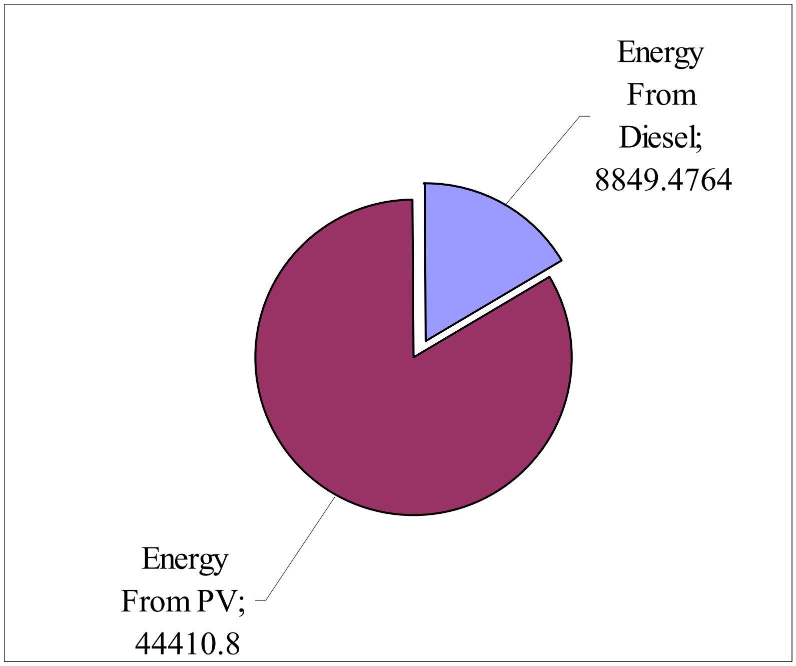


Figure (8.12): Yearly output energy from PV and D.G (kWh)

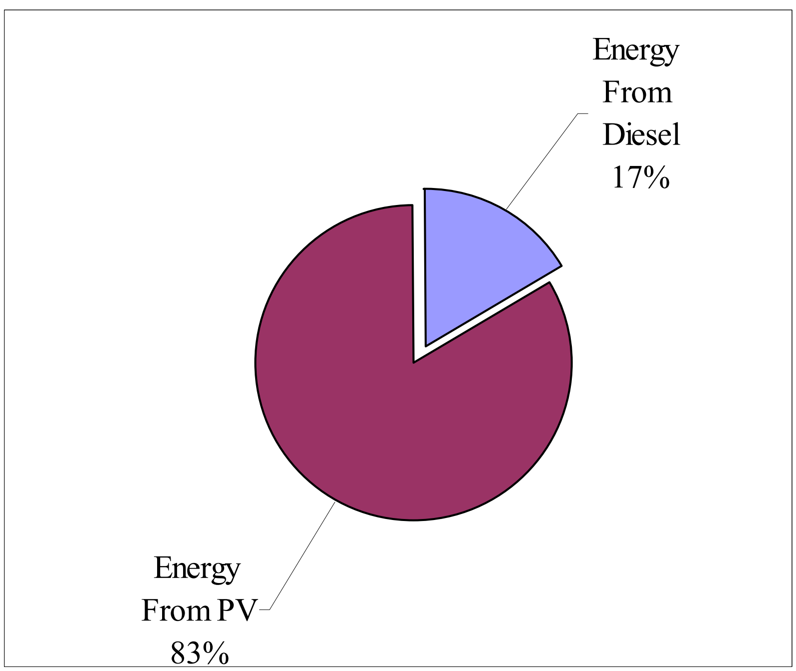


Figure (8.13): Yearly output energy from PV and D.G (%)

8.4. Hybrid system life cycle cost.

LCC of hybrid system= LCC of PV-battery + LCC of Diesel generator

The diesel generator represents 30 % of the total LCC representing only the covering of 17 % of the energy demand. This is an indication for the price of energy produced by the diesel generator which is of higher cost than the energy produced by the PV.

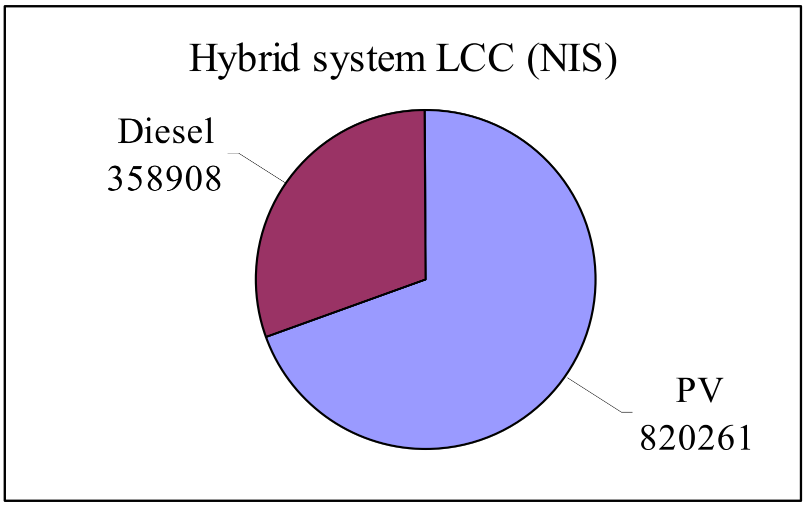


Figure (8.14): Total LCC cost of PV -diesel hybrid system (NIS).

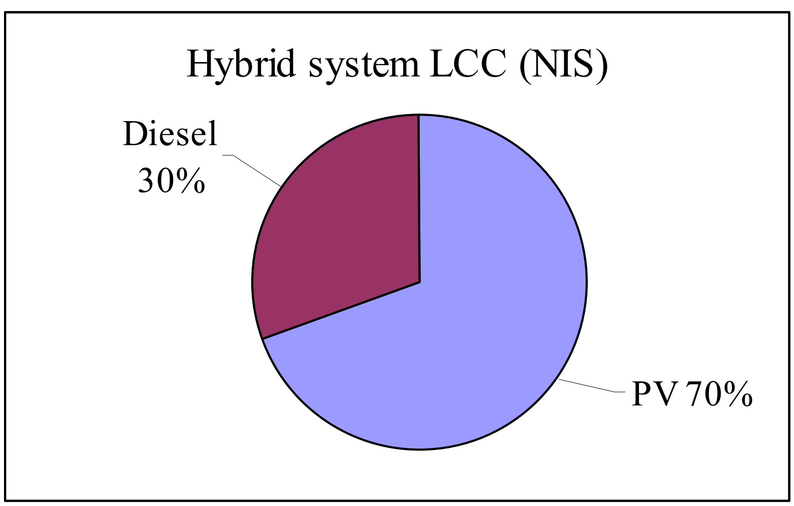


Figure (8.15): Total LCC cost of PV -diesel generator (Hybrid system) (%).

- Life cycle cost of PV part:

PV panel cost represent the high present of total LCC of PV –Battery system (63%) ,battery 20 % and the others represent 17%.

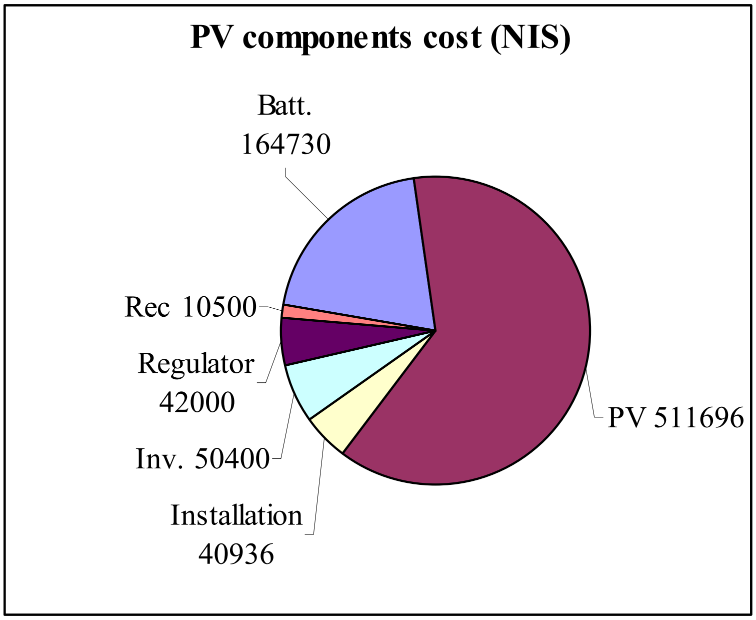


Figure (8.16): Total LCC cost of PV system. (NIS)

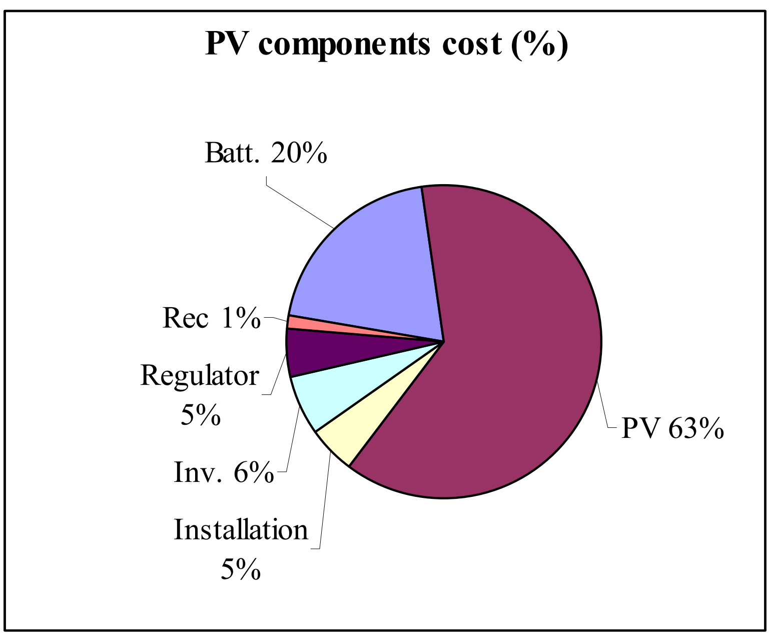


Figure (8.17): Total LCC cost of PV system. (%)

- life cycle cost of diesel generator part: Fuel cost represents the highest percent of total LCC of diesel generator system (61%) and initial plus maintenance costs represent only 39 %.

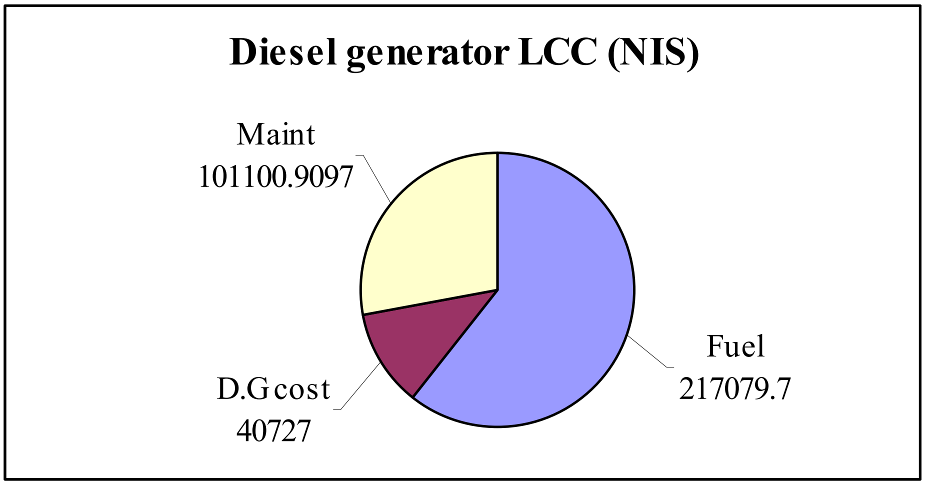


Figure (8.18): Total LCC cost of diesel generator system (NIS).

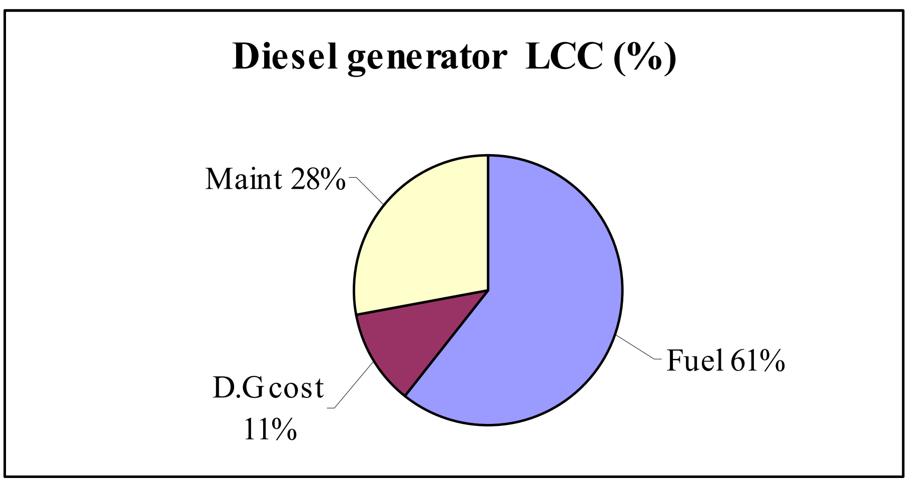


Figure (8.19): total LCC cost of diesel generator system (%).

8.5. Sensitivity analysis

Sensitivity analysis is carried out to verify the effects on the cost of energy (NIS/kWh) produced with the following scenarios.

1- Increase the fuel inflation rate and discount rate by 50%.

Table 8.12: Sensitivity analysis, scenario 1

NIS/kWh					
	PV Contribution (%)				
AD	20	40	60	80	100
0.25	3.34	3.10	3.20	3.43	3.71
0.5	3.58	3.35	3.32	3.15	3.30
0.75	3.61	3.44	3.27	3.11	3.22
1	3.76	3.53	3.31	3.18	3.28
1.25	3.86	3.63	3.43	3.29	3.40
1.5	3.99	3.77	3.59	3.42	3.54

From table 8.12 the price of energy generated from the system is increased with Increase the fuel inflation rate and discount rate.

2- Decrease in PV module price by 50 %.

Table 8.13: Sensitivity analysis, scenario 2

NIS/kWh					
	PV Contribution (%)				
AD	20	40	60	80	100
0.25	2.29	1.96	1.89	1.91	1.97
0.5	2.47	2.14	1.97	1.69	1.65
0.75	2.49	2.20	1.92	1.66	1.57
1	2.60	2.27	1.95	1.71	1.61
1.25	2.67	2.34	2.04	1.79	1.71
1.5	2.76	2.44	2.15	1.88	1.81

This can happen if the PV panels are funded by 50% of their cost. The lowest price of energy is decreased and it reaches 1.57 NIS.

3-Increase price of diesel fuel by 50 %.

Table (8.14): Sensitivity analysis, scenario 3

NIS/kWh					
	PV Contribution (%)				
AD	20	40	60	80	100
0.25	3.11	2.68	2.62	2.70	2.83
0.5	3.32	2.90	2.70	2.35	2.34
0.75	3.31	2.95	2.59	2.27	2.19
1	3.43	3.00	2.60	2.30	2.21
1.25	3.48	3.07	2.68	2.37	2.30
1.5	3.57	3.16	2.81	2.46	2.41

Table 8.14 the lowest price is **2.19** NIS/kWh at 100% PV contribution and 0.75 autonomy day it is increased by 9.5 % of original value 2 NIS/kWh.

4- Combination of factor 2 and 3.

Table (8.15): Sensitivity analysis, scenario 4

NIS/kWh					
	PV Contribution (%)				
AD	20	40	60	80	100
0.25	3.02	2.51	2.36	2.35	2.40
0.5	3.23	2.72	2.44	2.00	1.90
0.75	3.22	2.78	2.33	1.92	1.76
1	3.34	2.83	2.34	1.95	1.78
1.25	3.40	2.89	2.42	2.02	1.87
1.5	3.49	2.99	2.54	2.11	1.97

Combination of 2 and 3 results the lowest price of energy generated occurs with high contribution and low diesel generator operation.

8.6. Comparisons of energy supply options (PV only system, diesel generator, hybrid PV-Diesel).

Options of supplying rural areas with electrical energy are

Option 1: PV-Standalone system

Table (8.16): PV-Standalone power system expenses.

Maintenance cost ($/year)	500
PV panel cost ($/kW)	5000
Installation cost ($/kW)	400
Battery cost ($/kWh)	200
Inverter Cost $	12000
Regulator cost $	10000
System life year	24
Price of kWh sold (NIS)	2.5

Table (8.17): PV-Standalone system scenarios.

PV Cont.(%)	100	100	100	100
Solar radiation (kWh/m^2-day) considered in sizing PV	5.4	5.4	4	2.8
Days of autonomy	2	2.5	2.5	3
PV (kW)	24	24	33	47
Battery (kWh)	341	426	426	512
NIS/kWh	1.95	2.15	2.48	3.22
LCC (NIS)	1147376	1264517	1457938	1894816
NPV (NIS)	320449	203308	9887	-426991

The negative NPV indicates that minimum interest rate will not be met and so the project is not profitable.

PV contribution at 100 % is calculated at 5.4 kWh/m^2-day, but in Palestine the worst month average solar radiation reaches 2.8 kWh/m^2-day, sizing the PV panels at this low solar radiation value resulting high LCC of the system.

Option 2: diesel generator system

Tow similar diesel generators supply the load for 24 hours each one operates 12 hour per day.

Table (8.18): Diesel generator system information.

Annual maintenance ($)	7125
LCC Maintenance ($)	114605
Annual Fuel cost ($)	12348
LCC Fuel cost ($)	218457
Replacement period for each (years)	5
Daily operating hours for each	12
Yearly fuel consumption (liter)	12348
Initial cost for each	10000
Salvage value for each ($)	750
Total LCC (NIS)	1678563
NIS/kWh	2.858
Price of kWh sold (NIS)	2.5
NPV (NIS)	-210738

The negative NPV indicates that minimum interest rate will not be met and so the project is not profitable.

Option 3: Hybrid power system (PV contribution 100%, AD=0.75)

Table (8.19): PV-Diesel Hybrid system information.

Total LCC (NIS)	1179169
NIS/kWh	2
Price of kWh sold (NIS)	2.5
NPV (NIS)	288656

We select scenario for PV – power system of PV rated power 47 kW and days of autonomy 3 days, to cover the load for 24 hours/day along the year, two diesel generators operate on duty for 24 hour/day and PV-diesel hybrid system with PV contribution (100%) and 0.75 days of autonomy. the table below summarizes the results.

Table (8.20): Evaluation results of three energy supply systems.

	PV-Stand alone	Diesel only	PV-diesel hybrid
Total LCC(NIS)	1879027	1678563	1179169
NIS/kWh (cost)	3.22	2.858	2
Price of (kWh) sold (NIS)	2.5	2.5	2.5
NPV (NIS)	-426991	-210738	288656

It is evident that single energy source PV or Diesel system does not provide an economical year-long dependable energy supply; therefore we select the hybrid system which is economical and available for 24 h/day along the year.

CHAPTER NINE

CONCLUSIONS AND FUTURE WORK

9. Conclusions and future work

9.1. Conclusions:

Based on the illustrated simulation results, the following conclusions can be made:

- The PV-diesel hybrid power system is an applicable and relatively an economical one for covering of electrical power requirements in rural isolated areas. Considering a PV contribution 100% and autonomy of 0.75 days for the battery size we achieved the optimum design scenario in this case the cost of 1 kWh is 2 NIS.

- It is not economical or practical to provide all energy with PV modules because the solar radiation in the main three winter months is low. Large number of PV modules would be in this case required to meet load requirements for 24h/day. This issue will increase the initial investment cost and will increase the waste or dumped energy in summer where the solar radiation is high. The price of kWh produced from such PV system designed on the basis of winter months solar radiation would be 3.2 NIS.

- Diesel generator is another option to supply the load in the rural areas however; we will use tow diesel generators in order to secure the energy supply for 24 hours/day. This option will increase the maintenance and operational costs .in addition, the production of CO_2 would be increased by 23.5 ton/year since the total CO_2 amount produced by the hybrid system would be only 7.3 ton/year. The energy cost of the diesel power system would be 2.85 NIS/kWh.

- It is evident that single energy source (PV, Diesel) does not provide an economical year-long dependable energy supply; therefore we select the hybrid system which is economical and available for 24 h/day along the year.

- PV contribution of 100% is an indication that the diesel generator operates as a backup source. Which is very acceptable because of the high diesel fuel cost amounting to 1 $ /liter.

- The total losses of hybrid system with PV contribution (100%) and 0.75 days of autonomy is 16 % .This number consists of the total losses in the converter, inverter and the battery .The dumped energy which is high in summer can be used for irrigation and other uses which will decrease the waste and accordingly will increase the system efficiency.

9.2. Future work

It is recommended that future work be focused on the professional implementation of the algorithm and in-depth evaluation of the software results. In addition future work should concentrate on evaluating many more case scenarios with the goal of gaining a general understanding how operating decisions, real control implementation , sizing and costs.

Another option to be considered is to replace diesel generator with a wind turbine, as wind energy is clean, and can be utilized in such sites where the annual average wind speed exceeds 5 m/s.

LIST OF REFERENCES

List of References

[1] Wichert,B. (1997)" *PV-Deisel hybrid energy systems for remote area power generation –A review of current practice and future developments*": **Renewable and Sustainable Energy reviews**.3 (209-228).

[2] Mahmoud ,Marwan M.(2006)"*Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems diesel generators and electric grid*": **Renewable and Sustainable Energy reviews** 10 (128-138).

[3] Energy Research center (ERC). (2005). Metrological measurements in west bank /Nablus, An-Najah National University.

[4] Quaschning Volker. (2005). **Understanding Renewable energy systems, earthscan publishing** .UK.London.

[5] www.scolar.org.uk/html/pdf/stu-pdf/advanced.pdf

[6] http://www.infinitepower.org/pdf/No18%2096-815B.pdf

[7] Software package PVSYST V4.0 developed by Center for the Study of Energy Problems, university of Geneva

[8] Messenger Roger.A. (1998).**Photovoltaic system engineering**, 2nd edition, CRC published.

[9] http://socrates.berkeley.edu/~kammen/C226/Berkeley-C226 PVTechComp-Pres.pdf

[10] Whitaker C.M. et al. (1991) "*Effects of irradiance and other factors on PV temperature coefficients*": **IEEE**. (608-613).

[11]http://www.who.int/entity/water_sanitation_health/hygiene/om/linking chap5.pdf

[12] Nayar C.V. et al. (1993)."*Novel Wind/Diesel /Battery Hybrid Energy System*": **Solar energy**, 51 (65-78).

[13] http://www.allworlddieselgen.com/faq.htm

[14] Sonntag. (2002). **Fundamentals of Thermodynamics**, 6th Edition, New York; Wiley.

[15] Mahmoud Marwan M. (2004) "*On the storage batteries used in solar electric Power Systems and development of an algorithm for determining their ampere-hour capacity"*: **Electric Power Systems Research**.71 (85-89).

[16] Chedid .R (1998), "*A decision support Technique for the design of hybrid solar–wind power systems*": **IEEE** Transaction on Energy conversion, 13 (76-82).

[17] Bin Ai et al. (2003)"*Computer aided design for PV/Wind Hybrid system*": **3rd world conference on photovoltaic Energy conversion**, Osaka, Japan.

جامعة النجاح الوطنية
كلية الدراسات العليا

" تصميم وتقييم الأداء لأنظمة الطاقة الكهربائية الهجينة الشاملة للخلايا الشمسية ومولدات الديزل بواسطة الحاسوب "

إعداد
معين علي أحمد عمر

إشراف
أ.د.مروان محمود
د.عماد بريك

قدمت هذه الأطروحة إستكمالاً لمتطلبات درجة الماجستير في هندسة الطاقة النظيفة وترشيد الإستهلاك بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس،فلسطين.

2007

" تصميم وتقييم الأداء لأنظمة الطاقة الكهربائية الهجينة الشاملة للخلايا الشمسية ومولدات الديزل بواسطة الحاسوب "

إعداد

معين علي أحمد عمر

إشراف

أ.د.مروان محمود

د.عماد بريك

الملخص

البحث الذي تم إعداده يشتمل على تحليل ودراسة أنظمة الطاقة الكهربائيـــة الهجينـــة وإمكانيـــة تطبيقها في الأماكن والتجمعات السكانية المعزولة البعيدة عن الشبكة الكهربائية في فلسطين .
لقد تم دراسة كل جزء من أجزاء النظام (الخلايا الشمسية،مولدات الديزل وبطاريات التخزين) ودراسة الوضع المثالي لتشغيلها حسب الحمل الكهربائي وبأقل تلكفة وأعلى كفاءة.

كما تم تمثيل هذه الأجزاء رياضياً وإعداد برنامج محاكاة محوسب يمثل النظام كوحدة متكاملة. يتضمن البحث أيضا دراسة الجدوى الاقتصادية للعديد من السيناريوهات المفترضة طيلة فتـــرة تشغيل النظام وإختيار النظام الأقل تكلفة ،كما تم مقارنة الأنظمة الكهربائية الهجينة مع الأنظمـــة الأخرى التي يمكن إستعمالها في المناطق المعزولة مثل أنظمة مولدات الديزل والخلايا الشمسية المستقلة .

لقد أظهرت نتائج هذا البحث أن أنظمة الطاقة الكهربائية الهجينة هي الأعلى كفاءة والأفضل من الناحية الاقتصادية من الأنظمة المستقلة .

يمكن لهذا البحث والبرنامج المحوسب الذي تم إعداده أن يكون أداة مساعدة في تصميم مثل هذه الأنظمة والحصول على النظام الأمثل منها.