Utilisation of Solar Energy for Electricity Generation at Universiti Teknologi PETRONAS:
A Performance Analysis of Stand-alone Photovoltaic System (SPVS)

by

Amran Bin Mohd Selva

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Nursyarizal Bin Mohd Nor)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Amran Bin Mohd Selva

ABSTRACT

Photovoltaic System is a vast topic that can be researched and studied on such as the improvement of performance of single components in PV system or the system designed itself. Yet in this research work, the scope has to be scaled down in appreciation to the given time. This research project would mainly concern about improving the PV system itself. Since, the field or simulated information on technical performance of Stand-alone Photovoltaic System (SPVS) of Universiti Teknologi PETRONAS (UTP) is still lacking in literature. In short, this study was made with an aim of analyzing performance of PV system at Universiti Teknologi PETRONAS (UTP). As such, the SPVS of UTP was simulated using a TRNSYS simulation model which was then validated by data measured from actual operating lab-scaled prototype of SPVS which was mounted at UTP's meteorology station. This study reports on performance results of the simulated system located at UTP based on the data recorded. The results tell us that if the system is designed in accordance to procedures stipulated at UTP's climatic data standards then it is capable of operating with a good mean performance ratio, PV array production factor and system efficiency. For the simulated location, loss of load probability of system was calculated based on the recorded data. If the system is under-designed, it was found that the system's performance ratio is reduced considerably, it is less reliable and its battery remains in low state of charge for long periods.

ACKNOWLEDGEMENT

In the name of Allah, Most Gracious, Most Merciful. All the praises are due to Allah, the Lord, The Cherisher of the Worlds. First and foremost, I would like to express my thanks and great gratitude to Him for guiding me to complete my final year project. Indeed, without His help and will, nothing will be accomplished.

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Last but not least, I would like to express my gratitude to all who have supported and helped me out all this while especially my friends Dimas Firmanda Al Reza and Ahmad Yusof Bin Razak to make this project possible.

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Nomenclature

AC	Alternate current
Ah	Ampere-hour
Cb	Battery capacity
DC	Direct current
DDOD	Daily depth of discharge
DF	De-rating factor
DOD	Depth of discharge
e	Open circuit voltage
Eday	Daily Energy
F	Fractional SOC of the last hour of previous month
g	Electrolyte coefficient
G	Global solar radiation
Gb	Beam radiation
Gd	Diffuse radiation
GEF	Global Environmental Facility
Go	Global solar radiation of value 1000W/m2
Gpoa	Global solar radiation on the plane of array
GT	Total irradiance
HVAC	Heating, ventilation and air conditioning
HVC	High voltage connection point for ON/OF controllers
HVD	High voltage disconnection point for ON/OFF controller
Ia	PV array current
Ib	Battery current
Icons	Current consumed by charge controller
IDC	DC current
IL	Module photocurrent
Io	Nominal PV array current
ID	Diode reverse saturation current
Isc	Short circuit current
kWh	kilo-watt-hour
LLP	Loss of load probability

LVD	Low voltage disconnection point
LVR	Low voltage reconnection point of ON/OFF controller
N	Number of data points
P	Power
PAC	AC power
Pl	Load power
PF	Production factor
PR	Performance ratio
PSH	Peak sunshine hours
PV	Photovoltaics
PWM	Pulse width modulation
q	Electron charge constant
Qa	PV array electrical charge
Qb	Electrical charge delivered by battery
Qd	Electrical charge demanded by load
Ql	Electrical charged delivered to load
Qp	PV array potential electrical charge
Qs	Electrical charge supplied by system
Quse	Useful electrical charge of the system
Quse,PV	Useful electrical charge directly supplied by PV array
Rd	Ratio of diffuse radiation on tilted surface to that on a horizontal surface
Rdir	Ratio of the load directly met by PV array to the total load demand
RE	Renewable energy
RMSE	Root mean square error
Rs	Series resistance
SOC	State of charge
SPVS	Stand-alone photovoltaic system
t	Time in hours
Tc	Module cell temperature
Vb	Battery voltage
Vb,nom	Nominal battery voltage
Vr	Regulation voltage
VAC	AC voltage

VRLA	Valve regulated lead acid
W	Watts
Wh	Watt-hour
Wp	Array's power at maximum power point at standard test conditions
Yaq	PV array charge normalized to rated current of the PV array
Yfq	Final useful charge normalized to rated current of the PV array
Yrq	Potential charge of the array normalized to rated current of the PV array

Greek Symbol

θ	Angle of incidence of beam radiation
θz	Solar zenith angle
γ	Empirical PV curve fitting parameter
ρg	Ground reflectance
β	Slope of surface
ηb	Battery charging efficiency
ηinv	Inverter efficiency
ηsys	System efficiency

Subscript

aq	Array charge
b	Battery
c	Charging
d	Discharging
day	Time from 0:00 -24:00
fq	Final charge
m	Monthly
rq	charge

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Renewable energy or also known as RE in abbreviation is readily available type of energy which has now seriously being looked into by many countries of the world especially by the developing countries as to substitute the non-renewable energy which is getting depleted as well as because of the energy security reason i.e. fluctuate price of fossil fuel in the market. In many countries, the utilisation of RE has lead to substantial economic and environmental gains. Many reasons can be expected why lately many countries are eagerly developing their technology in RE sector and for instance in business, exploiting renewable resources enhances profit margin and eliminate waste disposal cost. Besides, the potential of utilising RE allows progressive companies can generate electricity exports, seek regional markets and expand opportunities from lower manufacturing cost.

1.1.1 Renewable Energy for Global Scenario

Internationally, many European countries have driven their energy market into renewable energy sector as to reduce the total dependence in non-renewable energy especially in fossil fuel. As we know, the European Commission had published a White Paper in 1997 setting out a Community strategy for achieving a 12% share of renewables in the EU's energy mix [1]. The decision was of course being motivated by concerns about security of supply and environmental protection. The 12% target was adopted in a 2001 directive on the promotion of electricity from renewable energy sources, which also included a 22.1% target for electricity for the

EU-15[2]. The legislation was an important part of the EU's measures to deliver on commitments made under the Kyoto Protocol [3].

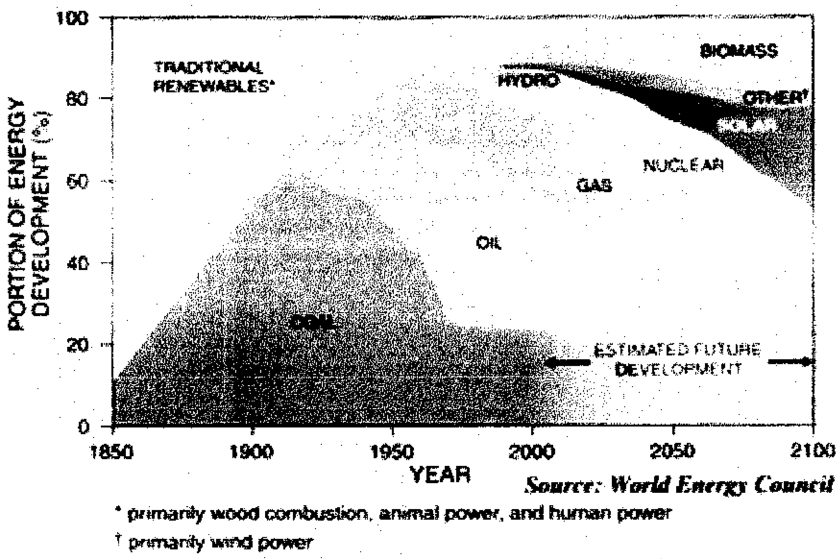

Figure 1-1: Future energy development

There were many European countries leaders who had signed up to a binding EU-wide target to source 20% of their energy needs from renewables, including biomass, hydro, wind and solar power, by 2020 [4]. In order to meet this objective EU leaders agreed a new directive on promoting renewable energies, which set individual targets for each member state. There are several actions which had been taken by them for example by setting out a Community Strategy and Action Plan for renewable energy, adopting Directive on the Promotion of Electricity from Renewable Energy Sources, issuing template for National Renewable Energy Action Plans (NREAPs) and the latest is setting up a target date for EU objective of sourcing 20% of energy from renewable sources [5].

On top of that, in term of overall global scenario of RE, there is a significant increase in interest amongst many countries of the world to allocate a huge portion of investment for their future energy development. This unexpected scenario is anticipated to be a good turning point to the RE sector. A divergence in percentage of solar and biomass sectors as future energy development towards the year of 2100 can be clearly seen in Figure 1-1 as to show that renewable energy has a good potential to substitute the non-renewable energy in the future to come.

1.1.2 Renewable Energy for Malaysia Scenario

In Malaysia, we are blessed with enormous renewable sources of energy, i.e. biomass, biogas, solar, wind and mini-hydro. The potential for Renewable Energy (RE) is enormous whereby these resources are not traded and mostly home-grown. Solar energy as for example is another type of RE resource which is naturally abundant and readily available, as Malaysia is geographically located close to the equator. In view of these potentials, the Malaysian Government has encouraged greater use of RE which is widely known as non-depleting and environmentally friendly energy sources. As to show its serious concern in developing RE sources in Malaysia, government has legislated several policies on RE like have been mentioned in Eighth and Ninth Malaysia Plans (8MP and 9MP), and the ten-year Third Outline Perspective Plan (OPP3) [6]. In these plans, the government has shown its keen desire to see the integration of RE as the "Fifth Fuel" in the national energy scenario supports these policies, and encourages rapid up-take for physical implementation of RE projects [7]. Apart from that, the core focus of the policies was to supplement our national energy mix to include contribution from RE and reducing the national dependence on depletable fossil fuel due to high energy consumption as clearly being shown in Figure 1-2 and 1-3.

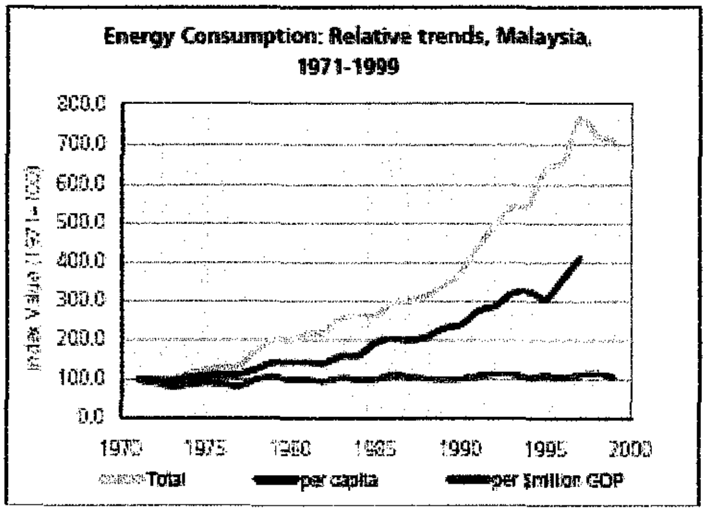

Figure 1-2: Energy consumption: Relative trends, Malaysia 1971-1999

Besides that, the government of Malaysia also has launched The Malaysian Government also launched several fiscal incentives in the form of Pioneer Status (PS) or Income Tax Allowance (ITA) and tax exemption on RE equipment to stimulate the emergence of RE activities and in particular to encourage the generation of RE using hydro, tidal and solar [8]. The first set of incentives begins to formally present in the national Budget for 2001 and it has been improved over the years [9].

For Malaysia, embarking on renewable energy provides many advantages which enable the country to remain strong and stable. Amongst these include an improved balance of trade, more competitive industries, foreign exchange savings, new export markets, employment opportunities, lower consumer prices and a better environment.

Renewable energy is a commodity just like any other type of energy. It has a major role in meeting energy demand and combating global warming. Currently, RE represents a prime opportunity to seek alternative energy options. Getting on board with RE today, secures our energy needs for the future.

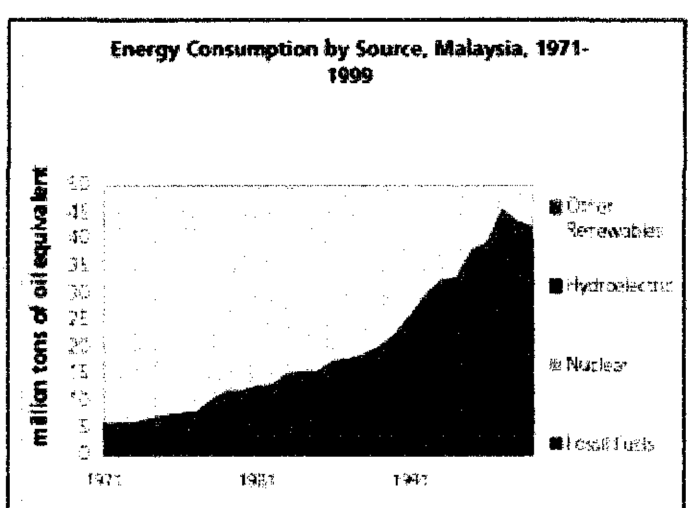

Figure 1-3: Energy consumption by source, Malaysia, 1971-1999

1.2 Problem Statement

The ability of non-renewable sources of energy to meet human energy requirements has never been questioned. However, the usage of this source has lead to its depletion besides it gives many harmful effects to humankinds as well as the environment. As we know, non-renewable energy sources are being depleted at a rapid rate these days. If this continues, the earth will be completely exhausted of all its natural energy reserves within a few years. Like in Malaysia, the oil source is expected to be totally depleted in the year of 2015 which would give severe impacts to the energy sector of the country since right now we are depending on fossil fuel in generating electricity.

Apart from that, utilization of non-renewable energy will harm the environment since it can cause severe pollution for instance when fossil fuels are burnt they will produce gas carbon dioxide (CO_2). Carbon dioxide is also known as a greenhouse gas because it traps heat from the sun, much like the glass in a greenhouse, preventing it from escaping out of the Earth's atmosphere into space. Greenhouse gases are found naturally in the atmosphere and they are essential for keeping the Earth warm. However, through the activities of humans, mainly as a result of burning fossil fuels, the amount of these gases in the atmosphere is increasing. As a result, global warming is occurring as the temperature of the Earth rises [10].

1.3 Objectives

The goal of the study was to analyze the performance of typical SPVS at Universiti Teknologi PETRONAS and it had the following specific objectives:

1. Simulate and carry out performance analysis of PV system sized according to meet typical load demand.
2. Simulate and examine the effect of under-designing SPVS.
3. Carry out performance analysis of actual SPVS with advanced PWM charging algorithm installed at UTP.

1.4 Scope of Study

The scope of study was however limited to SPVS being installed at UTP which has module nominal capacity of up to 10 W_p with systems' voltage of 12 V. Taking into consideration that a photovoltaic cell produces DC power, there is no need for an inverter to convert the DC power to AC, as in the most current PV systems. Besides, batteries provide DC power, and can be easily charged by a DC source. Many electrical appliances use DC power as well. Finally, since the SPVS is intended to provide power to a small area, and does not need to transmit power over large distances, transmission losses are not a concern. Thus, the study was limited to performance analysis of the system with purely DC load. The simulation was also limited to UTP's climatic data. Therefore the results can only be applicable to regions which share similar climatic data with UTP. In addition, the study was limited to VRLA type of batteries and silicon crystalline PV arrays.

1.5 Justification of the study

From technical point of view, it is imperative to analyze the performance SPVS because the results of the analysis form the basis of improving the system. Work on analyzing technical performance of installed SPVS in certain parts of the word had been carried out. For instance Jahn et al. (2000) evaluated SPVS of France. However, performance of PV systems is site-dependent implying that SPVS in different locations perform differently. The field or simulated information on technical performance of SPVS at UTP is lacking in literature. Less number system designed and installed according to UTP's receive radiation set standard had been evaluated to verify its conformance to the expected performance. There was a need to get a technical insight on how the installed SPVS at UTP perform and the results would form a base data from which system improvements can be build on. To achieve this, it was justifiable to carry out an investigation on the performance of SPVS designed and managed according to UTP's climatic data specifications. In addition, it had been known from literature that PWM charge controller are better than ON/OFF controllers. This meant that there is a room of improvement of the systems if the PWM controllers are used hence the PWM controllers were chosen as the working controller in the simulations of this study.

Additionally, there are a number of reasons why it was worthwhile to investigate the performance of SPVS at UTP. Firstly, the findings of the investigation will add valuable information on improvement of system's reliability at UTP. The improved reliability of the system will stimulate the university management itself to confidently invest in PV technology. Consequently technology dissemination will be enhanced. In addition, it would be useful for the established lighting systems which are grid connected to invest in solar technology either as backup power. This will increase electricity production base thereby smoothening electricity supply.

Secondly, the recommendations drawn from the findings of this study will be helpful for system designers as they will be guided on what factors are essential for good performance of the system. On the other hand it will help PV system inspectors to only approve the system which can render good performance. Further, the findings can be used to train users on how they can manage their systems to yield best performance. The findings can also be used to teach students who study the subject of solar energy technology. Thirdly, the study results will be instrumental in the revision of code of practice and specifications of UTP which specify the guideline on how a battery based PV system should be designed for the system to continue working for a particular period without problems. Fourthly, the simulation model used in this study can be used to access the performance of any SPVS at any place at UTP provided the weather data and other input data are available which, during preliminary evaluation of the system can reduce the travel time and cost to site.

CHAPTER 2
LITERATURE RIVIEW

2.1 Introduction

Solar energy is used to generate electricity and to provide heat for buildings and water. This is done in two main ways: the phòtovoltaic process and the solar thermal electric process.

2.1.1 Solar Thermal Energy

Solar thermal energy is a technology for harnessing solar energy for thermal energy (heat). Solar thermal energy is a form of energy in which the sun is used to produce heat which can be utilized in a variety of ways. People have been using solar thermal energy for thousands of years for a variety of tasks, and modern technology has considerably expanded the applications for the sun's thermal energy. This should not be confused with solar power, in which the sun's light is used to produce electrical energy.

Some of the applications for solar thermal energy are very ancient. For example, solar drying is a technique which uses heat from the sun in food preservation. In this application, food products are laid out on rocks, and the sun's warmth is used to dry them. Evaporation ponds such as those used to concentrate salt also utilize solar thermal energy, and desalination plants can also apply this energy.

2.1.2 Photovolataic (PV)

Solar electricity is created by using Photovoltaic (PV) technology by converting solar energy into solar electricity from sunlight. Photovoltaic systems use sunlight to power ordinary electrical equipment, for example, household appliances, computers and lighting. The photovoltaic (PV) process converts free solar energy - the most abundant energy source on the planet - directly into solar power. Note that this is not the familiar "passive" or solar electricity thermal technology used for space heating and hot water production.

A PV cell consists of two or more thin layers of semi-conducting material, most commonly silicon. When the silicon is exposed to light, electrical charges are generated and this can be conducted away by metal contacts as direct current (DC). The electrical output from a single cell is small, so multiple cells are connected together and encapsulated (usually behind glass) to form a module (sometimes referred to as a "panel"). The PV module is the principle building block of a PV system and any number of modules can be connected together to give the desired electrical output [11].

PV equipment has no moving parts and as a result requires minimal maintenance. It generates solar electricity without producing emissions of greenhouse or any other gases, and its operation is virtually silent.

2.2 Types of PV Cell

2.2.1 Monocrystalline Silicon Cells

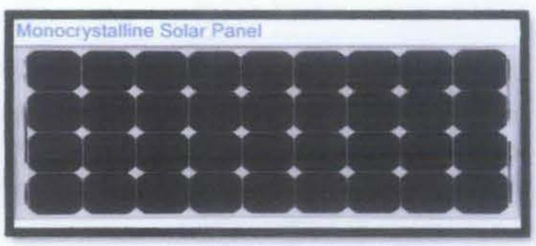

Figure 2-1: Monocrystalline silicon cell

Monocrystalline silicon cell is made by using cells saw-cut from a single cylindrical crystal of silicon, this is the most efficient of the photovoltaic (PV) technologies. The principle advantage of monocrystalline cells are their high efficiencies, typically around 15%, although the manufacturing process required to produce monocrystalline silicon is complicated, resulting in slightly higher costs than other technologies [12]. Figure 2-1 above shows the monocrystalline silicon cell.

2.2.2 Polycrystalline Silicon Cells

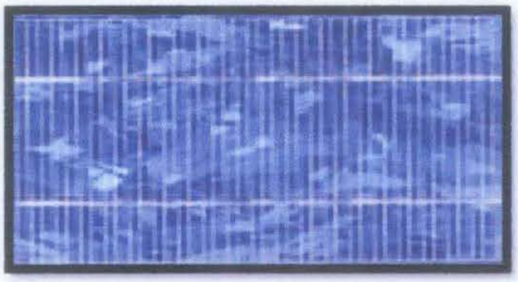

Figure 2-2: Polycrystalline Silicon cell

Policrystalline silicon cell as shown as in Figure 2-2 above is made from cells cut from an ingot of melted and recrystallised silicon. In the manufacturing process, molten silicon is cast into ingots of polycrystalline silicon; these ingots are then saw-cut into very thin wafers and assembled into complete cells. Polycrystalline cells are cheaper to produce than monocrystalline ones, due to the simpler manufacturing process. However, they tend to be slightly less efficient, with average efficiencies of around 12%, creating a granular texture [13].

2.2.3 Amorphous Silicon Cell

Figure 2-3: Amorphous silicon cell

Amorphous silicon cells as shown as in Figure 2-3 above are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon is also known as a "thin film" PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible, which makes it ideal for curved surfaces and "fold-away" modules [14]. Amorphous cells are, however, less efficient than crystalline based cells, with typical efficiencies of around 6%, but they are easier and therefore cheaper to produce [15]. Their low cost makes them ideally suited for many applications where high efficiency is not required and low cost is important.

2.2.4 Thin Films

Figure 2-4: Thin film

The current thin film PV materials have uniform nearly black appearance, indistinguishable visually from amorphous silicon modules. They also have lower efficiency compared to mono and poly silicon. Thin film cells are deposited in thin, consecutive layers of atoms, molecules or ions. They use much less material, which make the cell's active area is approximately 1 to 10μm thick [16]. Thin film has one distinguish advantage over other types is that it can be deposited on flexible substrate materials [17]. This implies its high adaption ability to the various residential surfaces. Figure 2-4 above shows the image of a thin film.

2.2.5 Dye-Sensitized Solar Cells (DSSC)

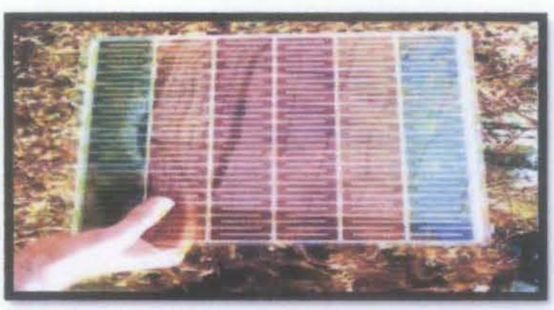

Figure 2-5: Dye-synthesized solar cell

DSSC cells as shown as in Figure 2-5 are another class of low cost thin film solar cells that are in development. They use low cost materials and are relatively easy to produce in bulk. They are a very promising category of solar cells due to their potential price and performance ratio for them to compete with traditional fossil fuels. Currently, there is mass market production of DSSC but they are not as widespread.

2.3 System Configuration

The simplest PV system configuration is a PV array connected to a load. Other components can be added to produce increasingly complex and sophisticated systems. A large number of combinations are possible for PV systems. The optimal configuration for an application depends on load usage, load type, insolation, auxiliary power sources and many other factors.

2.3.1 Stand-Alone Systems

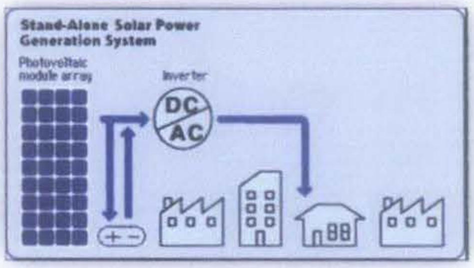

Figure 2-6: Stand-alone system

A stand-alone PV system as shown as in Figure 2-6 above is a type of PV system that operates autonomously and supplies power to electrical loads independently of the electric utility. Stand-alone PV systems are most popular for meeting small to intermediate size electrical loads and are extensively used in remote, 0ff-grid areas, or where extending the utility service is cost prohibitive or impossible. Stand-alone systems may be designed to power DC and/or AC electrical loads and typically store energy in batteries.

A stand-alone system may use a PV array as the only power source or may include one or more additional power sources such as engine generator or wind turbine. However, stand-alone systems do not interact with the utility grid.

Stand-alone PV systems are sized and designed to power a specific electrical load using the solar radiation source at a given location. Since the size and cost of any stand-alone system is related to the magnitude and duration of the electrical load and the solar resource, energy efficiency is critical. For these reasons, a thorough load analysis is the first step required in the design and installation of any stand-alone system.

2.3.2 Utility-Interactive Systems

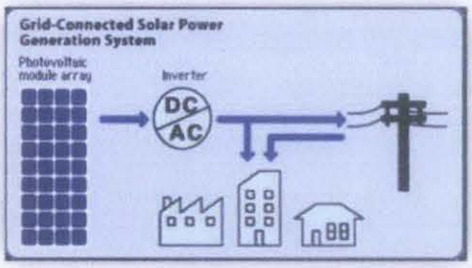

Figure 2-7: Utility-interactive system

A utility-interactive system as shown in Figure 2-7 above is a PV system that operates in parallel with and is connected to the electric utility grid. These systems are sometimes called "grid-connected" or simply "interactive" systems. These systems are the simplest and least expensive PV systems that produce AC power because they require the fewest components and do not use batteries. The primary component in a utility –interactive system is the inverter, which directly interfaces to the array and the electric utility network and converts DC output from an array to AC power that is synchronous with the utility grid. Utility-interactive systems are modular, so large systems can be designed as several smaller systems with individual inverters and then connected together.

Utility-interactive systems make a bidirectional interface with the utility at the distribution panel or electrical service entrance. When the PV system does not produce enough power to meet system loads, additional power is imported from the utility. If there is an excess of PV power, the excess power is fed back to the grid.

2.3.3 Bimodal Systems

A bimodal system is a PV system that can operate in both utility-interactive or stand-alone mode, and uses battery storage. Bimodal systems are sometimes referred to as battery-based interactive systems. The key component in a bimodal system is the inverter which draws DC power from the battery system instead of the arrays. In this case, the array simply acts as a charging source for the battery system.

Bimodal systems operate in a manner similar to UPSs and have many components similar to those found in UPSs. Under normal circumstances, bimodal systems operate in interactive mode, serving the on-site loads or sending excess power to the utility grid while keeping the battery fully charged. However, if the grid becomes de-energized, control circuitry disconnects from the utility and operates the inverter to supply AC power from the battery bank.

If the system must be taken off-line for service or maintenance, a manual transfer switch or bypass circuit can isolate the array, battery and inverter from the remainder of the system and directly connect the loads to utility supply.

Bimodal systems are typically used to back up critical loads but can also be used to manage the energy supply for different times of the day in order to reduce electricity bills.

2.3.4 Hybrid Systems

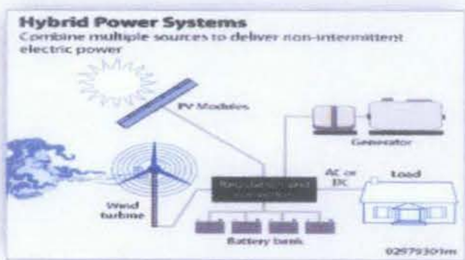

Figure 2-8: Hybrid system

A hybrid system as can be seen in Figure 2-8 above is a system that includes an energy source other than an array and the utility. Common energy sources used in hybrid systems include engine generators, wind turbines, or micro hydroelectric turbines. Hybrid systems offer several advantages over PV only or generator systems, including greater system reliability and flexibility in meeting variable loads.

Hybrid systems are perhaps the most complex of all PV systems in terms of equipment, system design and installation. However, they offer the greatest flexibility with regard to configurations and control strategies. The contribution from each source can be optimized for the application while minimizing the initial and operating costs.

2.4 Component of the PV System

PV systems include equipment to conduct, control, convert, distribute, store and utilize the energy produced by an array. The specific components required depend on the functional and operational requirements of the systems.

2.4.1 Module and Array

The primary components common to all PV systems is the PV array. An array consists of individual PV modules that are electrically connected to produce a desired power output. Modules as shown as in Figure 2-9 and arrays produce DC power, which can be used to charge batteries, directly power DC loads, or be converted to AC power by inverters to power AC loads and be interfaced with the electric utility grid.

Figure 2-9: Solar modules

The voltage of PV modules varies somewhat with temperature and the current varies widely with solar radiation, so power output is rarely constant. PV systems usually require means to store or condition power so that it can be used efficiently by loads.

2.4.2 Battery

Figure 2-10: Battery bank

A Battery converts electrical energy into chemical energy when charging and vice versa when discharging. Battery used in PV systems varies greatly in size, cost, and performance. Although a number of battery types can be used, lead-acid batteries are most common. Other types, including nickel-cadmium, nickel metal hydride, and other advanced battery technologies, can also work well in PV systems but are considerably more expensive.

Most PV systems require more battery capacity than can be supplied by a single battery. A battery bank as shown as in Figure 2-10 is a group of batteries connected together with series and parallel connections to provide a specific voltage, and capacity. Batteries in a PV system is charged by the array and discharged by loads.

In addition to energy storage, battery provides short surge currents for loads with special starting requirements, which PV modules as current-limited power sources cannot provide. Most importantly, batteries establish a relatively stable system operating voltage at which the array and loads both operate. A stable system voltage allows electrical loads or inverters to operate at their rated voltages, avoiding damage from high voltages or reduced performance from low voltages. A battery system also establishes the operating voltage of the array, which can be optimized to deliver maximum power.

Battery is characterized by their chemistry, nominal voltage and energy storage capacity in ampere-hours and kilowatt-hours. They can also be evaluated in terms of their specific energy (kWh/kg), specific power (kW/kg) or cost ($/kWh), when comparing various battery types and other forms of energy storage.

2.4.3 Inverter

Figure 2-11: Inverter

An inverter as can be seen in Figure 2-11 is a device that converts DC power to AC power. In PV systems, inverter converts DC power from battery systems or arrays to utility-grade AC power for AC loads or export to the utility grid. Inverter is characterized by power source, power ratings, input and output voltages, waveform, power quality and power conversion efficiency. Inverter used in PV systems is further classified as either battery-based or utility-interactive.

2.4.4 Charge Controller

Figure 2-12: Charge controller

Nearly every PV system that uses a battery requires a charge controller. A charge controller as shown as in Figure 2-12 is a device that regulates battery charge by controlling the charging voltage and/or current from a DC power source, such as a PV array. Charge controller protects the battery from overcharge and over discharge, improving system performance and prolonging battery life.

Charge controller regulates battery charging by terminating or limiting the charging current when the battery reaches a full state of charge. Charge controller may also protect batteries from extreme discharges by disconnecting electrical loads when the battery reaches a low state of charge. Charge controller is characterized by their method of charge regulation, voltage and current ratings, and other features and functions.

Chapter 3

Theory and Calculation

This chapter elucidates on the formulations of mathematical expressions which were used in this study. It starts by giving the detail procedure of system sizing. It later provides the derivation of mathematical formulae which were used to calculate the *PR*, *PF*, ηsys and *LLP*. It finally gives a brief description of the simulation software used in the study.

3.1 Sizing of standalone PV system

Sizing of SPVS can be approached in different ways but all approaches have at least three common steps and these are load estimation; battery sizing; and PV array sizing. The procedure given by Solar Energy International (2007) is to sequentially estimate the electric load, size the battery, size the PV array, specify charge controller, specify DC/AC inverter, and perform system wire sizing. The approach given in Australian Standards (2002) follows 7 steps given in their order of occurrence as load determination; selection of battery capacity, first approximation of tilt angle; determining insolation of the location; first approximation of array size optimizing array tilt angle and optimizing array size. On the other hand, Chapman (1987) approaches the PV system sizing by firstly defining site-specific and application-specific parameters then determining battery storage and finally determining the array size.

The following sub-sections will give a detail SPVS sizing basing on approach for load estimation, battery sizing and array sizing while using approach by Solar Energy International (2007) for charge regulator sizing.

Step 1: Load estimation

The daily load estimation is accomplished if the electrical devices, their power rating, number of operated hours in a day are known. If P is the power rating of electrical device in Watts (W), N is the number of electrical devices of type i and t is the daily number of hours for which a particular device operates then the total daily load (E_{day}) in Wh is estimated by equation (3.1). Equation (3.2) is then used to calculate the daily load (Q_{day}) demand in terms of electrical charge in Ah.

$$E_{day} = \sum_i P_i N t \tag{3.1}$$

$$Q_{day} = \frac{E_{day}}{V_{b,nom}} \tag{3.2}$$

Where $V_{b,nom}$ is the system's nominal battery voltage.

After the daily load is estimated, the actual hours of the day at which the electrical load is expected to be operated should be established in order to know the loading profile to which the system will be subjected to.

Step 2: PV array sizing

First it is assumed that during solar window1 load demand is directly met by PV array output and from the loading profile established in Step 1, the load demand expected to be directly met by PV array is known. The required generated power from PV array (Q_a) is then calculated by

$$Q_a = Q_{day}\left(R_{dir} + \frac{(1-R_{dir})}{\eta_b}\right) \tag{3.3}$$

where R_{dir} is the ratio of the load directly met by PV array to the total load demand and η_b is the battery charging efficiency. If DF is the PV's de-rating factor and PSH is location's peak sunshine hours then equation (3.4) is used to calculate the expected maximum power output of the array

$$W_p = \frac{Q_a \times V_{b,nom}}{DF \times PSH} \tag{3.4}$$

Step 3: Battery sizing

The battery is used to supply electrical energy during night and cloudy days. In cloudy days there is little if any battery charging. Therefore, depending on location, any SPVS must be designed with battery capacity to meet at least 2 days of autonomy. Therefore, if the desired depth of discharge is *DOD* and the desired days of autonomy are *n* then the battery is subjected to daily depth of discharge (*DDOD*) equal to *DOD* divided by *n*. From the daily load charge demand and *DDOD,* the expected battery capacity (C_b) is calculated by equation (3.5)

$$C_b = \frac{Q_{day}(1-R_{dir})}{DDOD} \tag{3.5}$$

Step 4: Sizing of charge controller

Since the controller is specified by the operating current, then maximum current from the PV array which is expected to pass through the controller must be determined. This is calculated by equation (3.6)

$$I_{controller} = 1.25 I_{sc} N_p \tag{3.6}$$

where I_{sc} is the short circuit current of PV module, *Np* is the number of modules connected in parallel and 1.25 is the factor of safety recommended by Solar Energy International (2007).

Step 5: Inverter sizing

The inverter is usually specified by the continuous and surge powers. Therefore in order to specify the right inverter, the total power of AC load ($P_{AC,tot}$) is used as the continuous power while the surge power is roughly estimated as 3 times the continuous power ($3P_{AC,tot}$) suggested by Solar Energy International (2007) as a safe estimate. In addition, it is necessary to calculate the continuous DC current that will be supplied at the DC input of the inverter. This is calculated by dividing $P_{AC,tot}$ by nominal battery voltage (equation 3.7).

$$I_{DC} = \frac{P_{AC,tot}}{V_{b,nom}} \tag{3.7}$$

Since in the project, the inverter was not being used. Thus, the calculation for Step 5 can be ignored.

3.2 Performance analysis of SPVS

Performance analyses of SPVS are often done using energy balance parameters while their energy reliabilities are measured through loss of load probability (Markvart, 2000) .The calculation of *PR*, *PF* and η_{sys} of the PV system based on energy parameters are given in Commission of the European Communities (1997a; 1997b) and International Standard IEC 61724 (1998). Munoz et al. (2006) further proposed and recommended use of charge parameters in performance analyses of SPVS without maximum power point tracker. These performance indicators based on charge parameters can be calculated from measured or simulated global solar radiation on plane of array (G_{poa}), array output current (I_a), current drawn from the battery (I_b), battery voltage (V_b) and load power demand (P_l) as detailed in section 3.2.1 and 3.2.2.

3.2.1 Derivation of PR, PF, and η_{sys}

In charge parameter method, *PR* is defined as the ratio of useful output charge to the charge the PV array can potentially produce at its nominal rating while *PF* is the ratio of actual array output to the charge PV array can potentially produce at its nominal rating and η_{sys} is the ratio of useful output charge to actual array output charge. Equations (3.8) to (3.10) give the mathematical definitions of the *PR*, *PF* and η_{sys} evaluated over a day's period

$$PR = \frac{Y_{fq}}{Y_{rq}} \tag{3.8}$$

$$PF = \frac{Y_{aq}}{Y_{rq}} \tag{3.9}$$

$$\eta_{sys} = \frac{Y_{fq}}{Y_{aq}} \tag{3.10}$$

where Y_{rq}, $Y_{aq}$and Y_{fq} are respectively array potential yield, array yield and final yield all normalised to array's nominal current (I_o). See equation 3.11, 3.12 and 3.13. These normalised yields enable systems of different sizes and at different location to be successfully compared.

$$Y_{rq} = \frac{Q_p}{I_o} \tag{3.11}$$

$$Y_{aq} = \frac{Q_a}{I_o} \tag{3.12}$$

$$Y_{fq} = \frac{Q_{use,PV}}{I_o} \tag{3.13}$$

where Q_p is potential array charge at nominal rating, Q_a is array output charge, $Q_{use,PV}$ is useful charge output, and I_o is the nominal PV array current.

Since nominal rating of PV array are normally at standard temperature conditions where global solar radiation on the plane of array is G_{poa}, then Q_p can be found by multiplying *Io* with the location's *PSH* where *PSH* can be evaluated from the quotient of integral of G_{poa} and radiation at STC (*Go)* (equation 3.14) while Q_a is found by integrating I_a over the day's period as given in equation (3.15).

$$Q_p = I_o \times PHS = I_o \times \frac{\int_{day} G_{poa} dt}{G_o} \tag{3.14}$$

$$Q_a = \int_{day} I_a dt \tag{3.15}$$

In the SPVS, if the charge controller consumes I_{cons} current then the daily charge ($Q_{b,in}$) fed into the battery can be calculated by equation (3.16) and the daily charge ($Q_{b,out}$) drawn from the battery can be found by integrating I_b (equation 3.17). The net charge supplied to the battery $Q_{b,net}$ is given as the difference between $Q_{b,in}$ and $Q_{b,out}$ (equation 3.18)

$$Q_{b,in} = \int_{day} (I_a - I_{cons}) dt \tag{3.16}$$

$$Q_{b,out} = \int_{day} I_b dt \tag{3.17}$$

$$Q_{b.net} = Q_{b,in} - Q_{b,out} \tag{3.18}$$

Since electrical power is voltage multiplied by current, then the daily charge demanded by the load (Q_1) can be calculated from the load's power (P_l) and battery voltage as given in equation (3.19).

$$Q_1 = \int_{day} \frac{P_l}{V_b} dt \tag{3.19}$$

For the system's operation in a day, charge directly used by the load plus the net charge supplied to battery are regarded as useful charge. Therefore useful charge (Q_{use}) can be calculated by equation (3.20) where η_b is the battery charging efficiency. The daily charge supplied by system (Q_s) is given by equation (3.21) where the absolute value of $Q_{b,net}$ is the magnitude of charge supplied from the previous storage.

$$Q_{use} = \begin{cases} Q_1 + \eta_b Q_{b,net} & for\ Q_{b,net} \geq 0 \\ Q_1 & for\ Q_{b,net} < 0 \end{cases} \quad (3.20)$$

$$Q_s = \begin{cases} Q_a - Q_{b,net} & for\ Q_{b,net} \leq 0 \\ Q_a & for\ Q_{b,net} > 0 \end{cases} \quad (3.21)$$

Therefore the daily useful charge directly supplied by PV array ($Q_{use,PV}$) is given by equation (3.22) where $\frac{Q_a}{Q_s}$ is the measures of how much PV array contributes to total useful charge in a day.

$$Q_{use,PV} = \frac{Q_a}{Q_s} \times Q_{use} \quad (3.22)$$

Using equations (3.15) through (3.21), Q_{use}, PV can be expressed in terms of I_a, I_b, V_b and P_l as given in equation (3.23).

$$Q_{use,PV} = \begin{cases} \dfrac{\int_{day} I_a dt \int_{day} \frac{P_l}{V_b} dt}{\int_{day} (I_{cons} + I_b) dt} & for\ (I_a - I_{cons} - I_b) < 0 \\ \int_{day} \left(\frac{P_l}{V_b} + \eta_b (I_a - I_{cons} - I_b) \right) dt & for\ (I_a - I_{cons} - I_b) \geq 0 \end{cases} \quad (3.23)$$

Therefore PR, PF and η_{sys} can be given in terms of measured or simulated global solar radiation on G_{poa}, array output current (I_a), current drawn from the battery (I_b), battery voltage (V_b) and load power demand (P_l) as follows:

$$PR = \begin{cases} \dfrac{G_o \int_{day} I_a dt \int_{day} \frac{P_l}{V_b} dt}{\int_{day} I_o G_{poa} dt \int_{day} (I_{cons} + I_b) dt} & for\ (I_a - I_{cons} - I_b) < 0 \\ \dfrac{G_o \int_{day} \left(\frac{P_l}{V_b} + \eta_b (I_a - I_{cons} - I_b) \right) dt}{\int_{day} I_a G_{poa} dt} & for\ (I_a - I_{cons} - I_b) \geq 0 \end{cases} \quad (3.24)$$

$$PF = \frac{G_o \int_{day} I_a dt}{\int_{day} I_a G_{poa} dt} \quad (3.25)$$

$$\eta_{sys} = \begin{cases} \dfrac{\int_{day} I_a dt \int_{day} \frac{P_l}{V_b} dt}{\int_{day}(I_{cons}+I_b)dt \int_{day} I_a dt} & for\ (I_a - I_{cons} - I_b) < 0 \\ \dfrac{\int_{day}\left(\frac{P_l}{V_b}+\eta_{b(I_a-I_{cons}-I_b)}\right)dt}{\int_{day} I_a dt} & for\ (I_a - I_{cons} - I_b) \geq 0 \end{cases} \tag{3.26}$$

3.2.2 Loss of Load Probability

The loss of load probability (*LLP*) is defined as the ratio between the energy not supplied to the users and the energy demand and is usually through an energy balance over long periods. In analysis of SPVS, monthly *LLP* values are more appropriate, since the lack of energy in standalone PV systems is more probable in certain periods of the year, with lower solar radiation (or high consumption) (Diaz et al., 2007). The monthly *LLP* can be calculated using equation (3.27).

$$LLP_m = \frac{\int_{month} Energy_{deficit}}{\int_{month} Energy_{demand}} \tag{3.27}$$

The monthly energy deficit is calculated as the difference of monthly charge demanded ($Q_{d,m}$) and the monthly charge available for supply ($Q_{a,m}$). Equations (3.28) and (3.29) respectively calculate monthly charge available for supply and monthly charge demand.

$$Q_{a,m} = n_b \times \int_{month} I_a dt \tag{3.28}$$

$$Q_{d,m} = \frac{1}{\eta_{inv}} \times \int_{month} \frac{P_l}{V_b} dt \tag{3.29}$$

where η_b is battery charging efficiency, η_{inv} is the inverter efficiency. If *n* is the number of days since the system was installed, then at *n*=0, the battery capacity is

C_{bi}. To take into consideration ageing of battery, assume that its capacity declines at the rate of D% per day. Then the battery capacity (C_{bn}) after n days is given by equation (3.30). Using equations (3.28) and (3.30), the monthly charge which the system can supply is written as equation (3.31).

$$C_{b_n} = \left(1 - \frac{D}{100}\right)^n C_{bi} \tag{3.30}$$

$$Q_{s,m} = f \times C_{b_n} + \eta_b \times \int_{month} I_a dt - Q_{min} \tag{3.31}$$

where f is the fractional SOC of the last hour of previous month, Q_{min} is the minimum charge to which the battery can be discharged to and is defined in equation (3.32), C_{br} and DOD are rated battery capacity and depth of discharge respectively.

$$Q_{min} = (1 - DOD)C_{br} \tag{3.32}$$

But energy deficit is the positive difference of charge demanded and charge supplied, therefore using equations (3.29), (3.31) and (3.32) then equation (3.27) can be re-written

$$\text{as} LLP_m = \frac{\frac{1}{\eta_{inv}} \times \int_{month} \frac{P_l}{V_b} dt - \left(f \times C_{b_n} + \eta_b \times \int_{month} I_a dt - Q_{min}\right)}{\frac{1}{\eta_{inv}} \times \int_{month} \frac{P_l}{V_b} dt} = \begin{cases} 0 & for\ numerator < 0 \\ (0.1] & for\ numerator \geq 0 \end{cases}$$

(3.33)

3.3 Simulation of SPVS

There are numerous commercially available simulation programs which are used to simulate SPVS. This section introduces TRNSYS 16 simulation program which can be used to simulate SPVS. TRNSYS 16 is in fact a transient systems simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS 16 library includes many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. The modular nature of TRNSYS 16 gives the program tremendous flexibility, and facilitates the addition to the program of mathematical models not included in the standard TRNSYS 16 library. TRNSYS 16 is well suited to detailed analyses of any system whose behaviour is dependent on the passage of time.

TRNSYS 16 has become reference software for researchers and engineers around the world who specifically doing research related to solar energy. Main applications of TRNSYS 16 include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells. In addition, it also has a flexible visual user interface (called simulation studio) where a project can easily be set up and design by simply connecting components graphically [18].

Each type of component is described by a mathematical model in the TRNSYS 16 simulation engine and has a set of matching Performa's in the simulation studio. On top of that, the user can specify the values and units of parameters and constants inputs in dialogue the box [19]. The simulation studio also consist of an output manager from where the user can control which variables are integrated, printed and/or plotted, and a log/error manager that allows the user to study in detail what happen during a simulation [20].

CHAPTER 4
METHODOLOGY

In this chapter, it will tell about the methodology which was followed to meet the objectives of the study. The study was divided into experimental and simulation parts and each part followed its own method. Sections 4.1 and 4.2 report the methods which were used in the experiment and simulations respectively.

4.1 Experimental methods

The experiment comprised of a small lab-scaled prototype which consists of PV array, charge controller, battery, DC load and Fluke Hydra Series data logger (Figures 4-1 and 4-2) and was designed to collect data which was later used to analyze its performance and to validate simulation model.

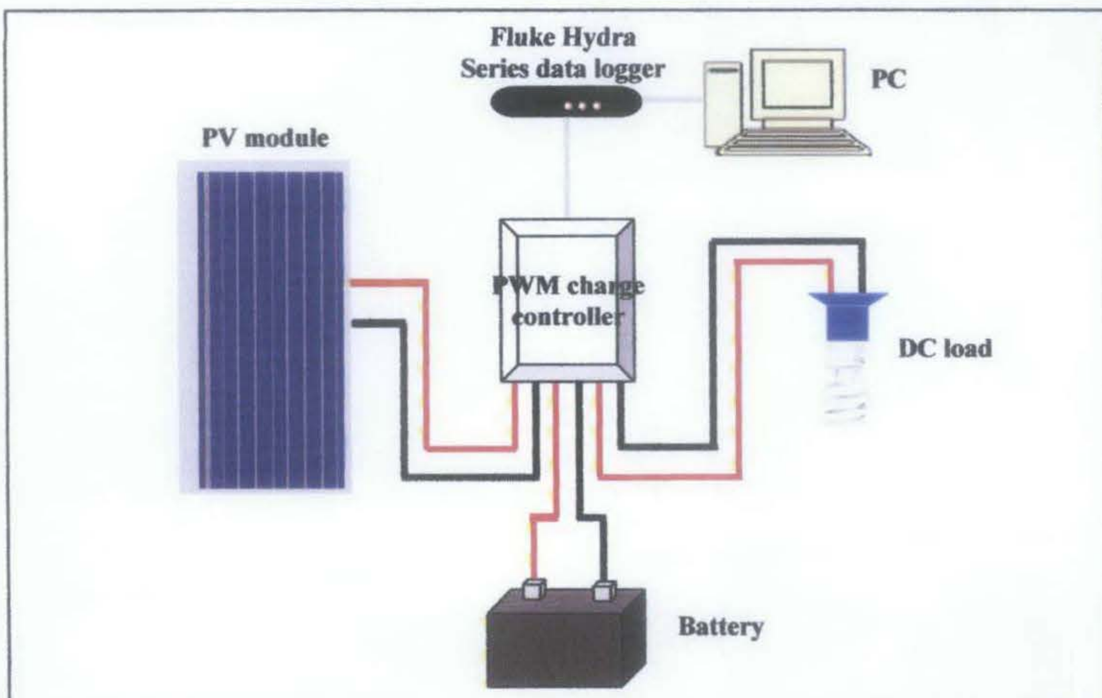

Figure 4-1: Schematic of apparatus for experimental SPVS

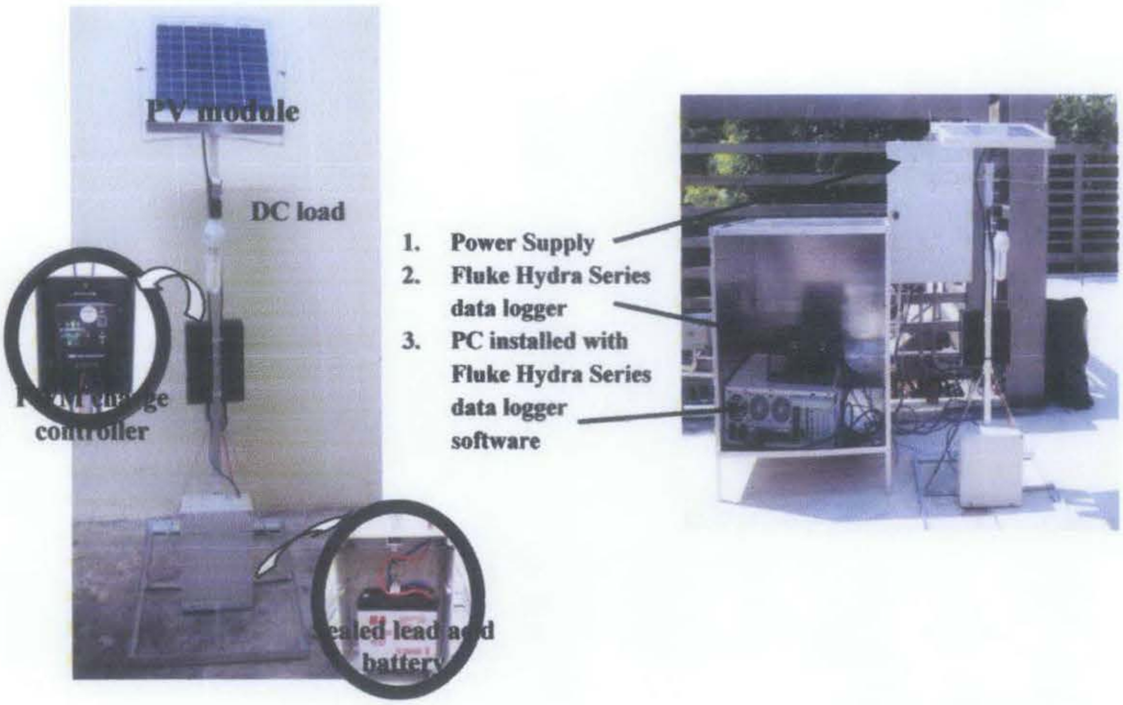

Figure 4-2: Captured photos of apparatus of the experiment (a) Outdoor 10 W_P PV module (b) System components

The experimental SPVS was installed at Universiti Teknologi PETRONAS which is located at latitude 4.38 °N, longitude 100.97 °E and altitude 36 m. A more installation conditions of the experiment are given in Table 4-1.

Table 4-1: Installation condition of the experimental SPVS

Location	Universiti Teknologi PETRONAS, Malaysia
Latitude	4.38°N
Longitude	100.97°E
Altitude	36 m
PV array tilt angle	5°
Direction of PV array	South
Room condition of installed indoor components	Room temperature

The system was sized following the procedure given in section 3.1. The daily load was 18W, the calculated PV array size was 10 W and calculated battery size at 2 days of autonomy was 7.2 Ah. The actual size of PV module used was 10 W_P of polycrystalline silicon type manufactured by SC ORIGIN. Table 4-2 gives general specification of the module used and detailed data sheet can be found in Appendix 4-1.

Table 4-2: Specification of PV module

Manufacturer	SC ORIGIN
Model	ET-M53610
Type	Polycrystalline silicon
Characteristic at standard test conditions (STC)	
Open circuit voltage	21.96V
Short circuit current	0.63A
Voltage at maximum power point	17.82V
Current at maximum power point	0.57A

STC: 1000 W/m2, spectrum of 1.5 air mass and cell temperature of 25°C.

A battery of nominal capacity 7.2 Ah was used. The nominal capacity was rated at 12 h. The nominal battery voltage was 12 V. The type of the battery was **Sealed Valve Regulated Lead Acid Battery** (VRLA) manufactured by MSB. Table 4-3 contains the specifications of the battery type used and detailed data sheet is given in Appendix 4-3.

Table 4-3: Specification of battery used in the experiment

Manufacturer	**MSB**
Model	MSI 12-7.2
Boost/ Equalize voltage	14.5-15.0 V
Float voltage	13.5-15.8V
Maximum charging current	2.16A

The charge controller size that met the minimum specifications calculated using methods in section 3.1.4 was selected. The charge controller used was of PWM charging type manufactured by Solar Power Mart. Its charging algorithm has 4 stages Figure 4-3) namely bulk charging, PWM absorption, float and equalization stages. During bulk charging, the controller allows full PV array current to be delivered to the battery for charging and it starts tapering the current when the battery voltage nears pre-set regulation voltage (V_r). At PWM absorption stage, charging continues at a constant voltage equal to V_r while current to the battery is sent in pulses of widths which vary with the state of charge of the battery. For the type of the battery used in this study, V_r was set to 14.5V. The controller was set to initialize battery equalization at 10 minutes interval and temperature compensation was set at -30mV/$_o$C deviation from 25$_o$C. The float voltage was set to 13.6V. The battery discharge and charge control was achieved through charge controller by setting the load disconnects voltage at 11.1V and load re-connect at 12.6V. The specification of charge regulator is given in Table 4-4 detailed data sheet is given in Appendix 4-2.

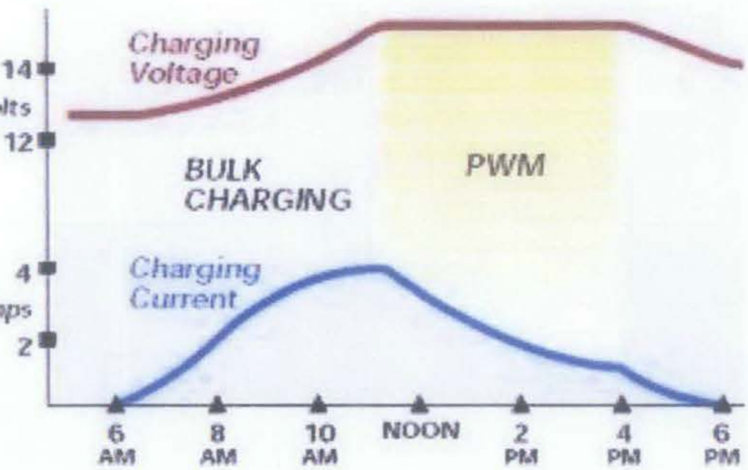

Figure 4-3: Solar charging stages for PWM charging (Source: Solar Power Mart, 2011)

Table 4-4: Specification of charge controller

Manufacturer	Solar Power Mart
Model	GAMMA
Rated solar input	10A
Rated load	10A
25% current overload	1 minute
Load disconnect	11.1V
Load re-connect	12.6V
Equalization voltage (10 minutes)	14.6V
Boost voltage (10 minutes)	14.4V
Float voltage	13.6V
Temperature compensation (mV/°C)	-30mV
Temperature	-35°C to +55°C

The experimental data was acquired through Fluke Hydra 2625A data logger and 2620A Data Acquisition Unit with 20 input channels which is integrated in the GAMMA charge controller and the measured data was logged into the computer at 5 minute interval using Fluke Hydra Logger software. The data logger measured variables of voltage and current of PV module, battery and load on during charging and discharging. The data were then automatically being recorded in Microsoft Excel file. The global horizontal radiation data ware obtained from the data measured by pyranometer which is mounted at solar tower (Figure 4-2) within the same premises where the PV system was installed. Figure 4-5 shows real time plotting of Global Radiation received at UTP in ComGraph32 software user interface. Besides, the ambient data used in this study were collected from UTP whether station (Figure 4-6) with the time interval of every 30 minutes using specific data logger. Table 4-5 gives the instrument's name and the type of data which it measured.

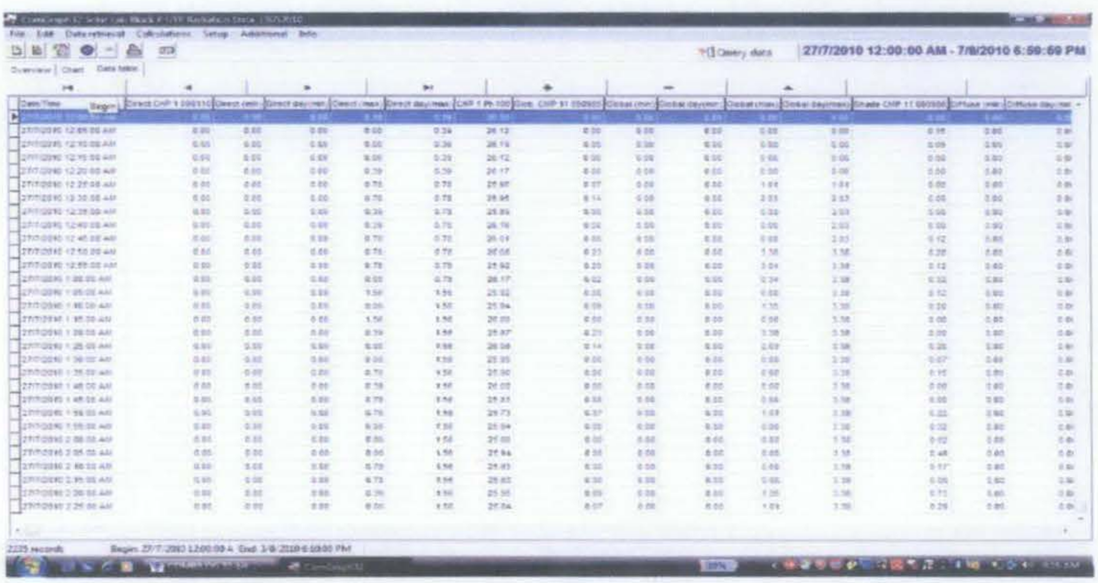

Figure 4-4: ComGraph32's user interface showing the collected radiation at UTP.

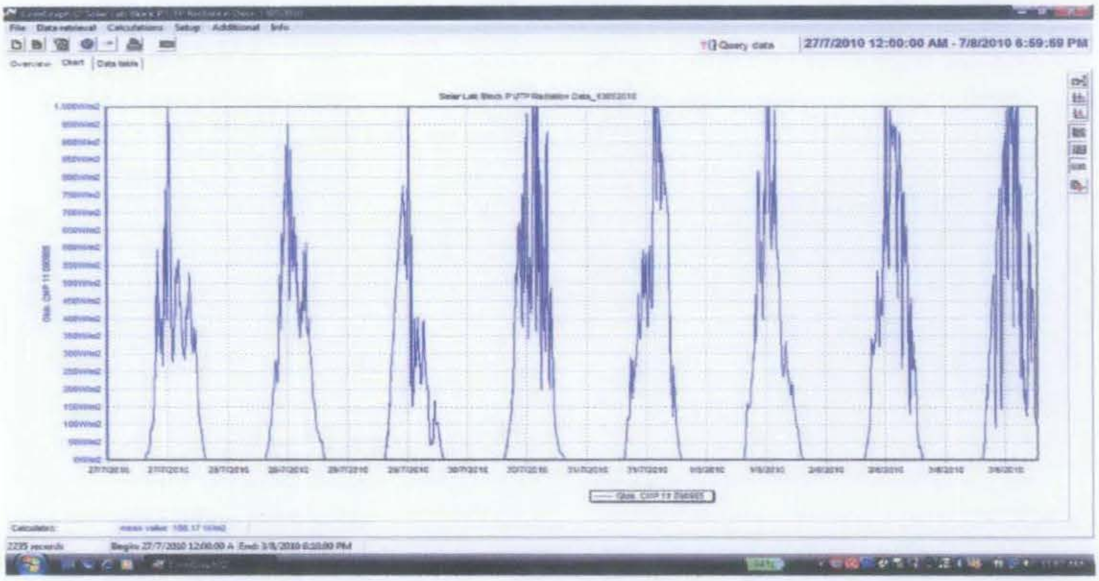

Figure 4-5: ComGraph32's user interface showing real time plotting of global radiation at UTP.

Table 4-5: Measuring instrument and the data it measured

Instrument	Data measured
Fluke Hydra Series Data logger	Array voltage, array current, battery terminal voltage battery terminal current, load voltage and current, ambient temperature
Pyranometer	Global horizontal radiation, direct horizontal radiation and diffuse horizontal radiation

Figure 4-6: Photo of UTP weather station

4.2 Simulation Methods

Transient System Simulation Program version 16 (TRNSYS 16) was used to simulate the SPVS operating at Universiti Teknologi PETRONAS (UTP), Tronoh, Malaysia. Geographically, UTP is located at 4.38°N 100.97°E and elevation of 36 metres. Results from experimental SPVS discussed in section 4.1 were used to validate the simulation model. System sizing procedure given in sections 3.1.1 through 3.1.6 was used to size the lab-scaled SPVS prototype used in this experiment which operates DC load of 12V, 18W lamp. It was assumed that a daily load profile is constant throughout the month and Figure 4-6 depicts the daily load profile which is considered randomly to represent the actual lighting load at UTP. In order to meet this load demand the calculated solar array size was found to be 10 W_P, the battery capacity with 2 days of autonomy was calculated as 7.2 Ah, a charge controller of 10 A minimum current rating was found to suffice. Therefore, in the simulations of SPVS of UTP, a 10 W_P SC ORIGIN ET-M53610 solar module, a 7.2 Ah MSB MSl 12-7.2 battery and 10 A GAMMA charge controller were used.

Table 4-6: Daily load profile used in this system

No.	Item	Rated Power, P	Quantity	Operation hours	Wh/day
1	Lamp	18 W	1	12	216

In order to simulate the SPVS, a TRNSYS 16 simulation model shown in Figure 4-7 was used. It comprised of a connected weather data reader, solar array, charge controller, battery and output printer components. The system was simulated at an hourly interval for the period of one month. At every time step, each component sent data to and/or received data from its connected components. Weather data reader sent global radiation on tilted surface; ambient temperature and slope of tilted surface to solar array through link 1 and sent global radiation on tilted surface to the output printer via link 2. Solar array sent array current and voltages to charge controller and output printer via links 3 and 4 respectively. The battery's fractional SOC; voltage; charge cut-off voltage; discharge cut-off voltage; power corresponding to charge; and discharge cut-off voltages, maximum power for charge and discharge were sent to charge controller through link 6 and battery voltage was sent to the output printer through link 9. The load profile component sent the load power to charge controller & inverter component via link 7. The charge controller sent power (array power or load power) to the battery through link 8 and sent load current and load power to output printer through link 10. The output printer logged to an external text file the data values of global radiation on tilted surface; array currents and voltages; battery voltage, load current and load power. The logged data were then used for further analysis in MATLAB.

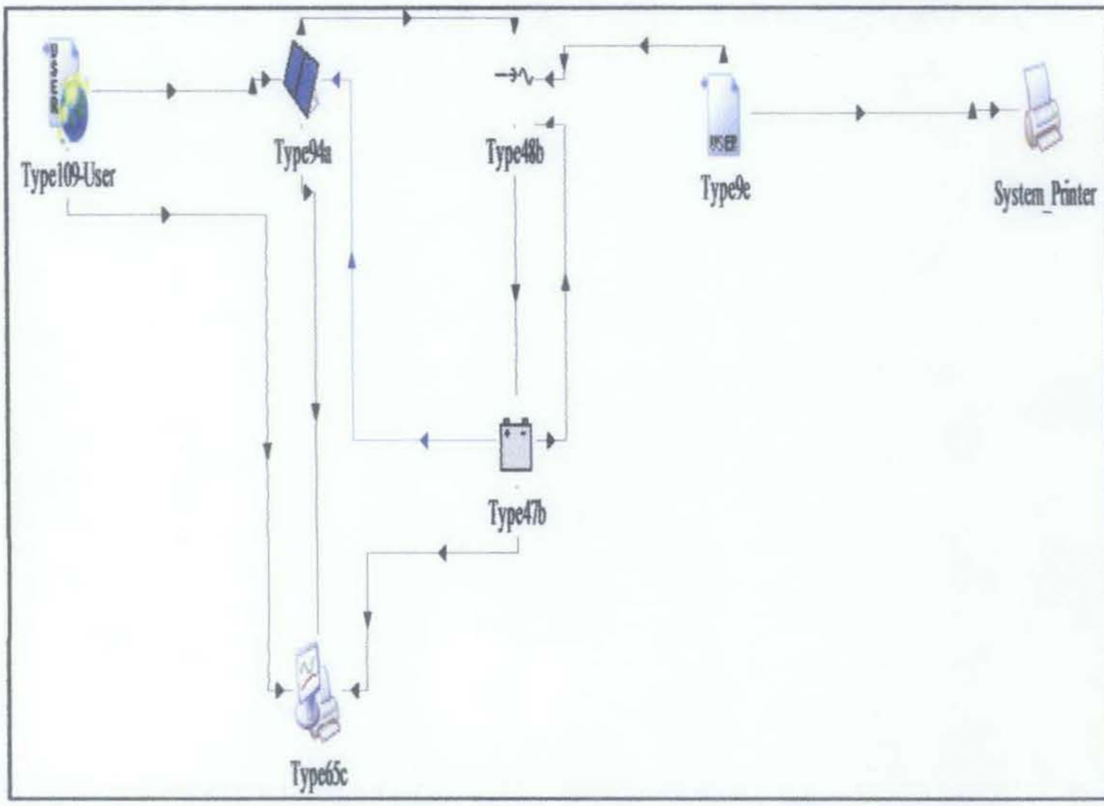

Figure 4-7: TRNSYS 16 16 simulation project for SPVS.

4.3 Flow chart

The project activities flow is shown as below:

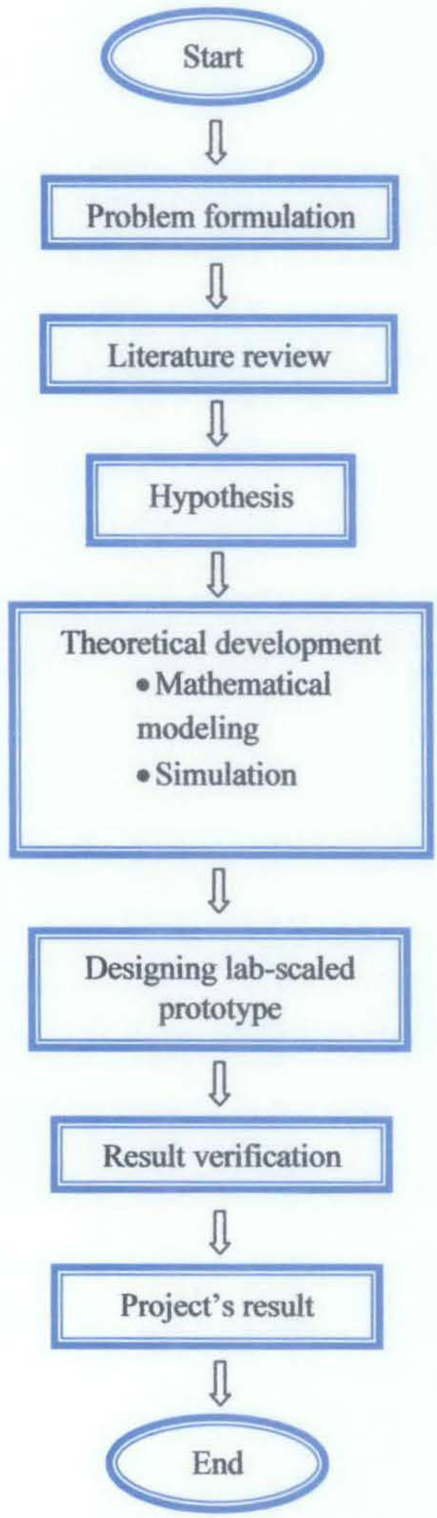

Figure 4-8: Flow chart of the project

4.4 Gantt chart

Please see Appendix 4-4 and 4-5 for the Gantt chart which summarizes all the project activities which were covered within these two semesters.

CHAPTER 5
RESULTS AND DISCUSSIONS

This chapter provides the results for both experiment and simulation. It begins by presenting the analyzed experimental results of SPVS and its discussion. The second half of the chapter reports on the simulation results and its comparison with the experimental result. After that a discussion of the reported results is given.

5.1 Experimental results and discussion

A. Converting Solar Irradiance sub-hourly data to hourly data

All parameters in the measurement system were recorded in 5 minutes time intervals. Most of the weather stations provide hourly data, so in this research the data were converted to hourly data by taking hourly averages. Figure 5-1 shows Solar Irradiance measurement results during the 3-7 July 2010 periods in 5 minutes time intervals and Figure 5-2 is the equivalent hourly converted versions.

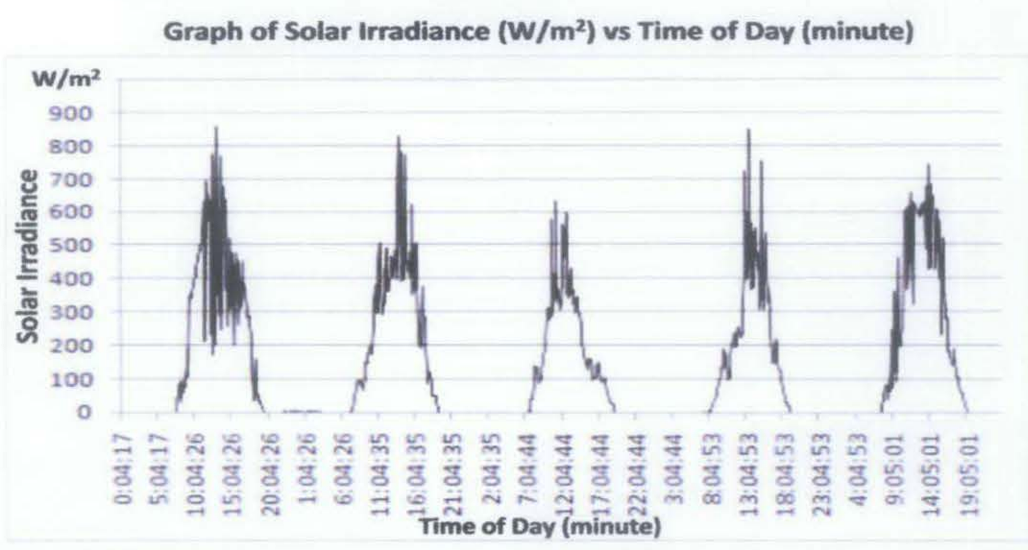

Figure 5-1: Measured Solar Irradiance 3-7 July 2010 (5 min time step)

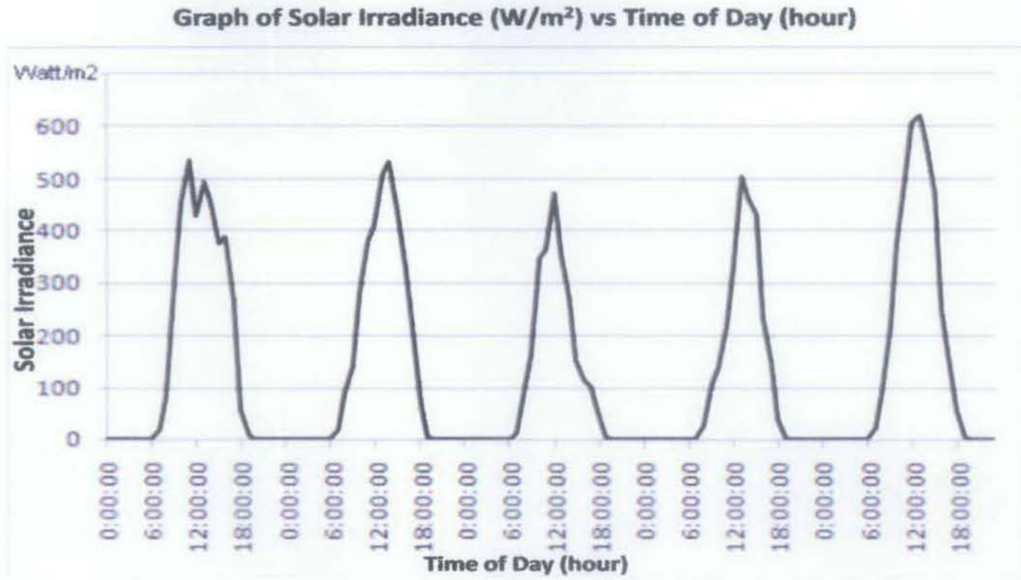

Figure 5-2: Measured Solar Irradiance 3-7 July 2010 (hourly average)

The measurement indicated that during 3-7 July 2010 period the maximum irradiance on site was about 850 Watt/m2. After averaging the data, the curves become smoother with maximum irradiance at about 610 Watt/m2. This results show that there is discrepancies between the data in different time steps.

B. Energy Input and Output of Solar power System

Figure 5-3 shows the monitored results of the power-in and out of the battery storage system and Figure 5-4 shows hourly data. Power-in from the PV panels is indicated in positive values and the power out due to the loading indicated by negative values. The load was about 18 Watt in the 12 hour duration during the night. Therefore the total lighting equivalent load for each day was approximately 216 Wh per day.

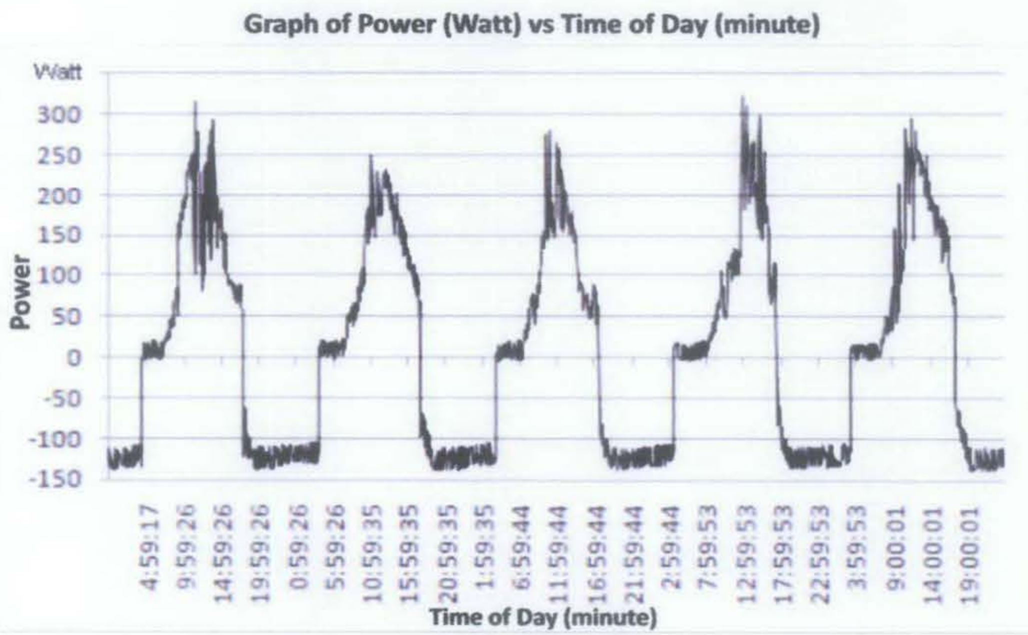

Figure 5-3: Power input and output to/from battery (5 minutes time step)

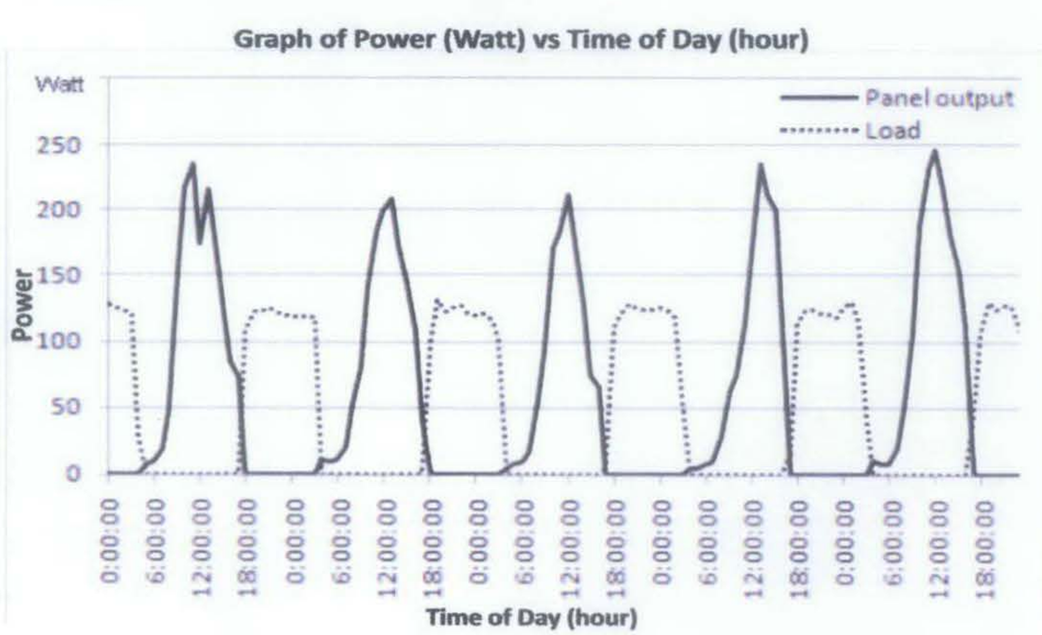

Figure 5-4: Power input and output to/from battery (hourly average)

It can be observed from the data presented in Figure 5-4 that the designed system works well and was not interrupted during the observation period. Power input and output is separated into two hourly data, called solar panel output and load data as input for TRNSYS 16 simulation. The negative load value is converted to positive value because in TRNSYS 16 simulation, load data is considered as positive value.

C. Battery Voltage during charge and discharge

The state of charge of the batteries can be observed by monitoring their voltage. The level change of the battery voltage during charging and discharging can be observed in more detail in Figure 5-5. The controller maintained the battery voltage to not exceed 14.5 Volts to avoid overcharging. During discharging, the battery level drops linearly due to the constant loading. In the afternoon, after charging process, the battery level drops to about 13.2 Volts.

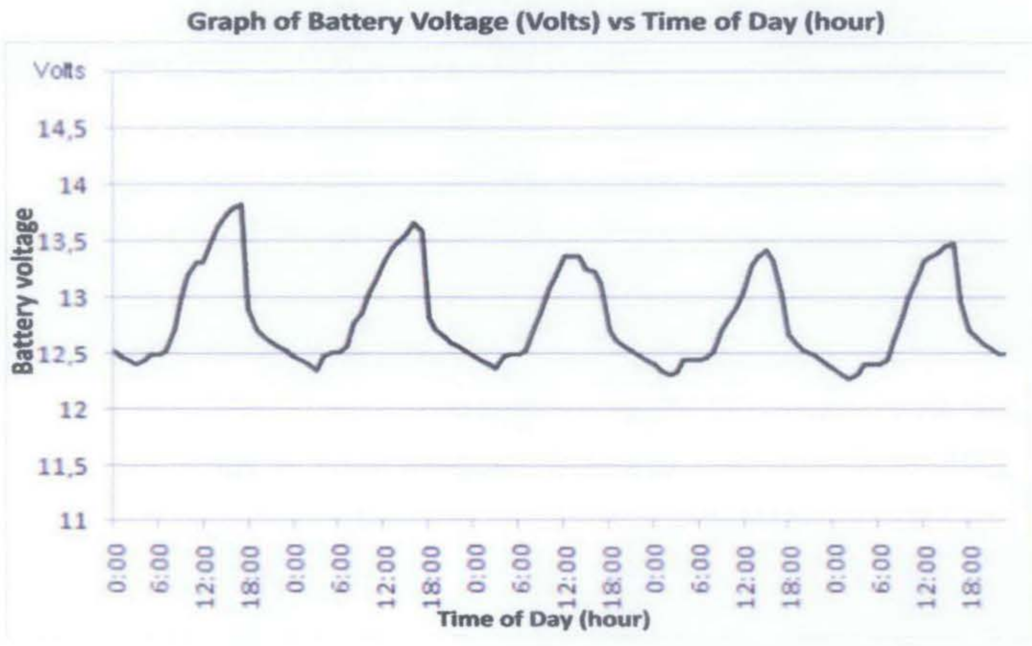

Figure 5-5: Battery voltage 3-7 July 2010 (hourly average)

5.2 Simulation results and discussion

A. Comparison between Measurement and Simulation Results

Before using experimental data in TRNSYS 16, the 5 minutes interval data was converted to hourly data by taking the average for every hour, then a comparison between simulated and measured results were carried out. Residual error was calculated using Root Mean Square Error (RMSE) and Mean Bias Error (MBE) equations 5.1 and 5.2 as follows:

$$RMSE = \left[\frac{\{\Sigma Y_C - Y_O\}^2}{n}\right]^{\frac{1}{2}} \tag{5.1}$$

$$MBE = \frac{\Sigma(Y_C - Y_O)}{n} \tag{5.2}$$

Figure 5-6 shows the solar panel energy output comparison between the measured and simulated results. Calculation results shows, for Solar Panel output RMSE is about 3.352 Watt and MBE is about 1.08 Watt, while simulation results in Fig.13 shows better and closer results to experimental value. The results show that the simulation error is bigger in low irradiance days and on the contrary the simulation error in higher irradiance days is smaller.

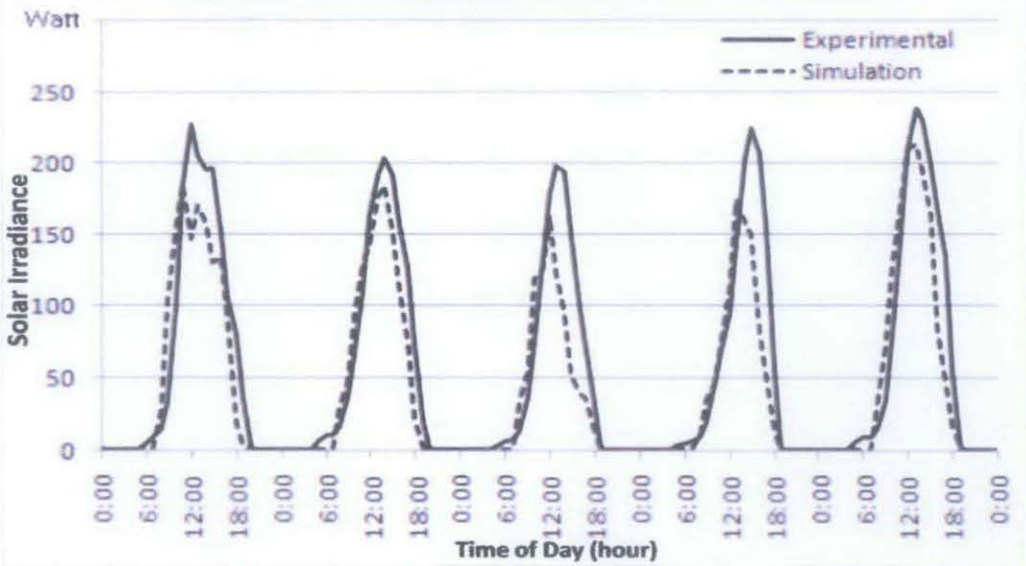

Figure 5-6: Comparison between measured and simulated battery voltage

Figure 5-7 shows battery voltage changing during the charging and discharging period, comparing between the measured and simulated results. It can be seen from the simulation results that similar results were obtained. The energy output of the panels in simulation results show lower values compared to the measured results. MBE for battery voltage is about -0.08 Volts and RSME is about 0.42 Volts. This value is relatively high errors. The model should be further analyzed to minimize error.

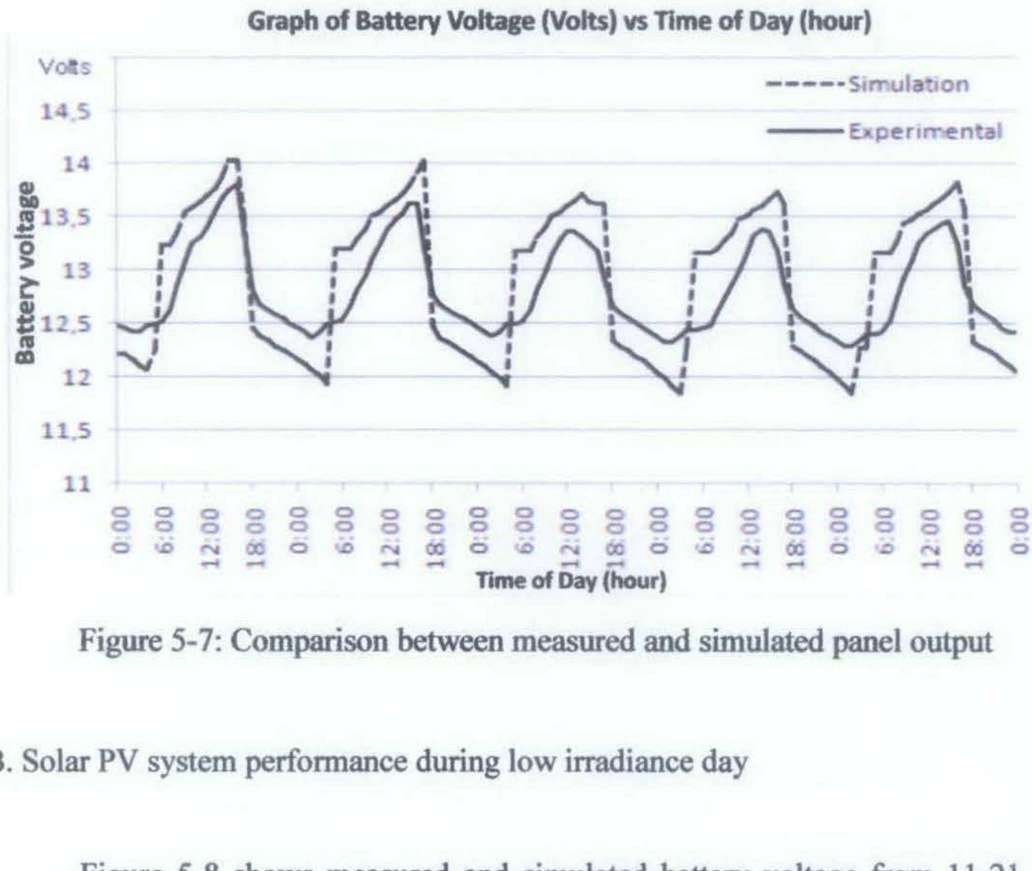

Figure 5-7: Comparison between measured and simulated panel output

B. Solar PV system performance during low irradiance day

Figure 5-8 shows measured and simulated battery voltage from 11-21 July 2010 monitoring period. Low irradiation day was occurred in 12 July 2010 with PSH value only about 1.6 hours. Thus, during monitoring period the low irradiation day only occurred once which was on 12 July.

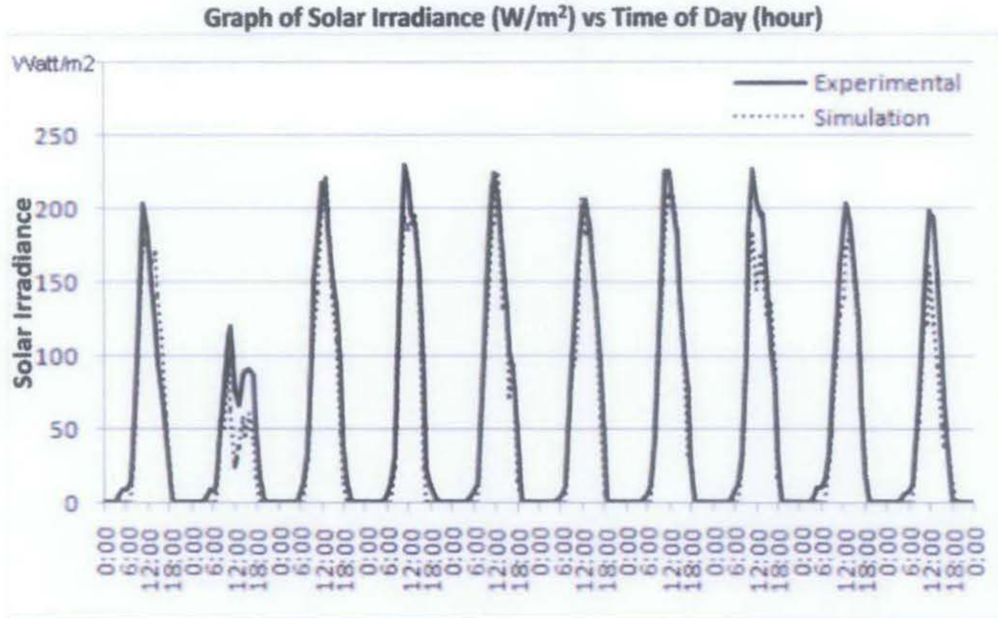

Figure 5-8: Measured and simulated battery voltage 11-21 July 2010

Figure 5-9 shows measured and simulated panel output from 11-21 July 2010 monitoring period. In low irradiation day, after loading time at the night, the battery voltage drop to 11.8Volts. The next five days, the after loading battery voltage increasing and almost reach initial voltage before low irradiation day, but the battery voltage dropped again on the sixth day due to low irradiation. However, the PV systems still work well continuously during monitoring period.

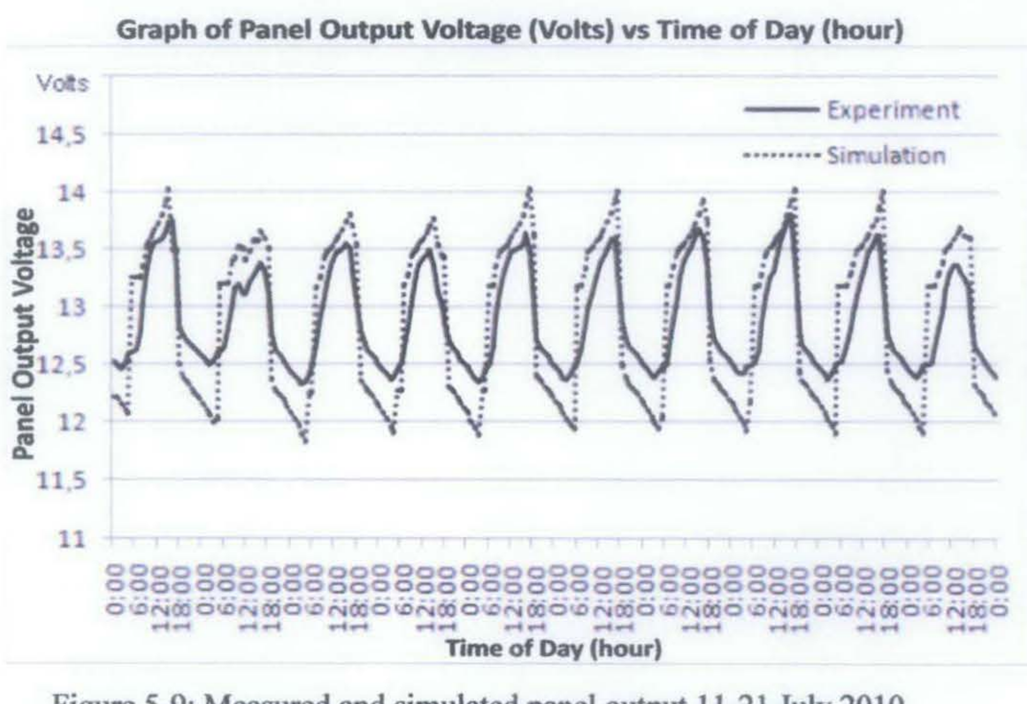

Figure 5-9: Measured and simulated panel output 11-21 July 2010

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

This chapter will draw the inferences emanated from results of this study. It has two sections in which the first one gives list of conclusions drawn from the results of the study and the second section is the list of recommendations for this project.

6.1 Conclusions

This study aimed at analyzing performance of standalone PV system (SPVS) at Universiti Teknologi PETRONAS (UTP) and the following conclusions are drawn from the results got out of the study.

- SPVS at UTP, can operate with an daily mean performance ratio of 0.65 and the difference of location of the two places will not give significant impact on the performance ratio since the geographical area of UTP is not considered big simulated had no impact
- The array's production factor does not vary with difference in solar radiation from place to place. For the solar array used in this study, its production factor was found to be 0.85. Operating the solar array at points lower than its maximum power point is found to be the main cause of the loss in production factor.
- Battery is the main components that lower system efficiency. With the type of battery used in this study, a system efficiency of about 78% can be attained.
- The loss of load probability, a measure of reliability, varies considerably with differences of solar radiation received on every single day. A *LLP* of 0.07 was found

to be the best. Its battery life is longer than the system where load is given priority over battery charging.

• The number of autonomy days designated during design stage can hardly be met in practice.

• Simulation and experimental work have been carried out for a SPVS. As the lighting loads occur during the night, the experiment equivalent lighting load was implemented for about ten hours during the night. Measurement result shows that the system works well with the designed load of about 200Wh during the night.

• TRNSYS 16 16 simulation result shows that the TRNSYS 16 16 model can be used for a standalone PV system simulation but some components like the PV panel and the battery storage system need to be improved to get better results. The trend between the measured and simulated results is similar but there are some differences in value, this difference might have come from the measurement error or from errors within the TRNSYS 16 16 component.

6.2 Recommendations

From the outcomes of the study, the author suggests that the following recommendations would help to improve PV system in UTP and also to this research.

• Since the study only involve a few day data taken, so the accuracy of the performance ratio is not very high and good. Supposedly, a long data sample should be taken, at least a period of one year to have more accurate analysis.

• Since the study only utilized purely DC load, author would like to recommend that the study on the same subject after this will utilize purely AC load or combination of both which would produce a practical result.

• Establishment of easily accessed database of solar radiation covering area at UTP as much as practical so that the research can be easily conducted.

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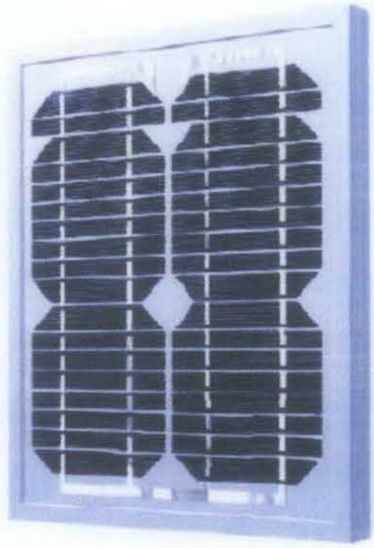
APPENDICES

Datasheet of solar PV module

Solar Panel – Mono-crystalline (SC0010) with 10 Wp

Inspired by the sun



EFFICIENCY

- Low voltage-temperature coefficient ensures high-temperature operation
- Exceptional low light performance combined with high sensitivity to light enables excellent energy delivery
- Up to 17.37% solar cell efficiency
- Up to 14.62% module efficiency

MATERIALS

- Highest quality, high-transmission tempered glass provides enhanced stiffness and impact resistance
- Advanced EVA encapsulation system with triple-layer back sheet meets the most stringent safety requirements for high-voltage operation
- A sturdy, anodized aluminum frame allows modules to be easily roof-mounted with a variety of standard mounting systems
- Ultra reliable bypass diodes prevent damage through overheating due to shaded or defective cells

BENEFITS

- Manufactured in an ISO 9001:2000 certified plant
- High efficiency, high safety, high reliability
- Output power tolerance of +/-5%
- 25 year limited warranty on power output, 5 year limited warranty on materials and workmanship
- Generate more energy per square meter
- Equipped weatherproof junction box, flawless operation in wet weather and marine applications
- Resilient to harsh weather conditions
- Optimal panel performance
- Long term product performance

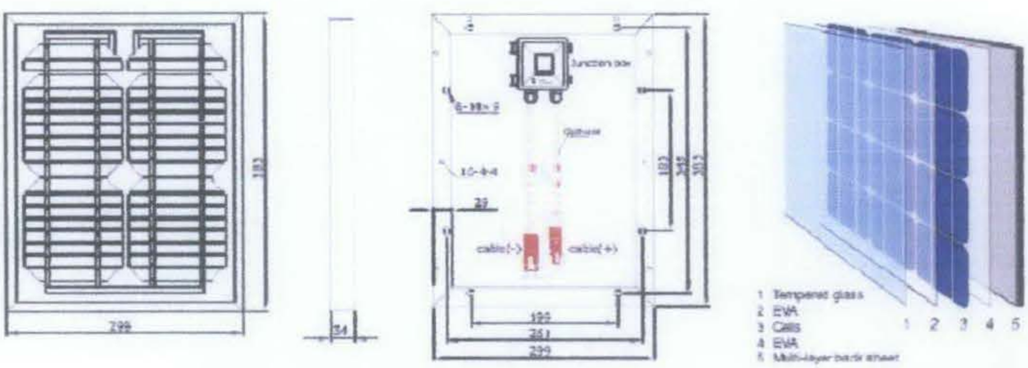
www.scorigin.com

SPECIFICATIONS

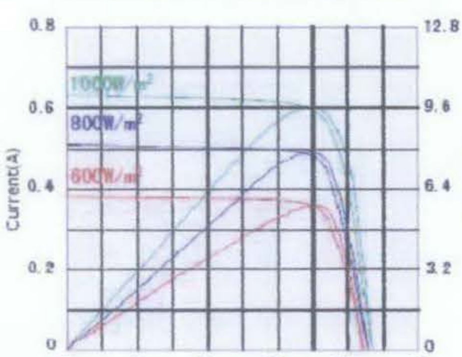
Model type	ET-M53610
Peak power(Pmax)	10W
Weight	1.7kg (3.7lbs)
Dimensions	383×299×34mm 15.1×11.8×1.3inch
Maximum power voltage (Vmp)	17.82V
Maximum power current (Imp)	0.57A
Open circuit voltage (Voc)	21.96V
Short circuit current (Isc)	0.63A
Maximum system voltage	DC 1000V
Temp. Coeff. of Isc (TK Isc)	0.06%/℃
Temp. Coeff. of Voc (TK Voc)	-0.397%/℃
Temp. Coeff. of Pmax (TK Pmax)	-0.549%/℃
Normal Operating Cell Temperature	44.4±2℃

Note: the specifications are obtained under the Standard Test Conditions (STCs): 1000 W/m² solar irradiance, 1.5 Air Mass, and cell temperature of 25 ℃.

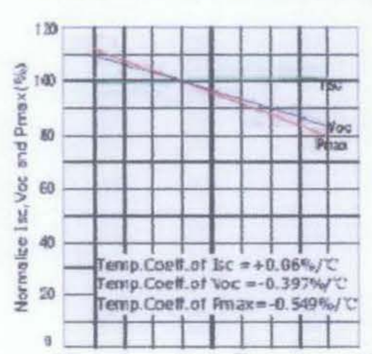
PHYSICAL CHARACTERISTICS Unit: mm(inch)



Electrical Performance cell temperature: 25℃



Temperatur dependence of Isc, Voc and Pmax



Datasheet of solar charge controller

USER MANUAL

GAMMA 10A
SOLAR CHARGE CONTROLLER

RATINGS (12V)

GAMMA 10A, 12V, 10Amp

NOTES: For use with solar panels only

TECHNICAL INFORMATION

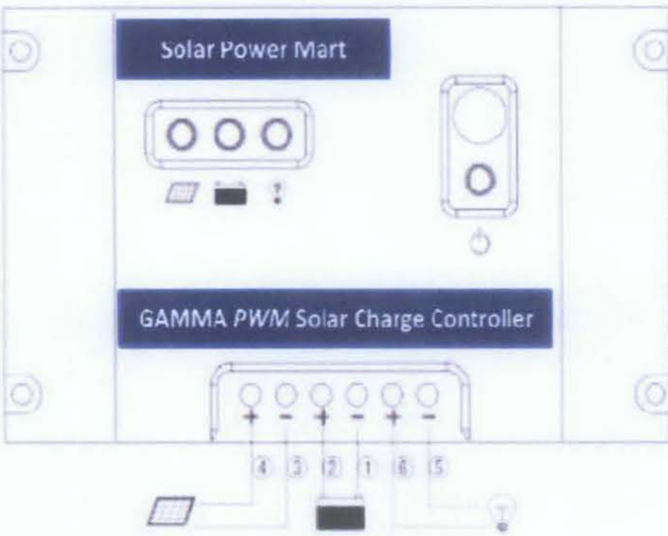
12Volt

Rated solar input	10A
Rated load	10A
25% Current overload	1 min.
Load disconnect	11.1V
Load re-connect	12.6V
Equalization voltage (10 minutes)	14.6V
Boost voltage (10 minutes)	14.4V
Float voltage	13.6V
Temp Comp. (mV/°C)	-30mV
Temperature	-35°C to +55°C

QUICK START INSTRUCTIONS

Please review the entire manual to ensure best performance and hassle-free services.

1. Mount the controller to a vertical surface.
2. Allow space above and below the controller for air ventilation.
3. Make sure the PV and load currents do not exceed the ratings of the controller being installed.
4. It is recommended that the connections be made in the order of 1 to 6 (see schematic below).



- Use with 12V batteries only
- Use with 12V systems only

5. Connect the **BATTERY** first.

   CAUTION: Naked wires do not get in touch with the controller metal case

6. Connect the **SOLAR** (PV array) next. The green LED indicator will light on if sunlight is present.
7. Connect the **LIGHT/ LOAD** at final stage. If the red LED indicator lights on, the battery capacity is low and should be charged before completing the system installation.
8. Press the **BUTTON** as **6.** or **7.** to verify if system is connected.

LIGHTING CONTROL OPTIONS 

9. Press the power switch for 5 seconds, and select the desired LIGHTING CONTROL option. The LED is on, which confirmed you have selected the right one.
10. The controller requires 10 minutes of continuous transition values before it starts to work. These constraints avoid false transitions due to lightning or dark storm clouds.
11. The controller requires 10 minutes relay before it begins operational.
12. Brief description as followings:

Number 0	Dusk-toDawn, light is on all night
Number 1	Light turns on at dusk for 1 hour
Number 2	Light turns on at dusk for 2 hour
Number 3	Light turns on at dusk for 3 hour
Number 4	Light turns on at dusk for 4 hour
Number 5	Light turns on at dusk for 5 hour
Number 6	Light turns on at dusk for 6 hour
Number 7	Light turns on at dusk for 7 hour
Number 0.	Light turns on at dusk for 8 hour
Number 1.	Light turns on at dusk for 9 hour
Number 2.	Light turns on at dusk for 10 hour
Number 3.	Light turns on at dusk for 11 hour
Number 4.	Light turns on at dusk for 12 hour
Number 5.	Light turns on at dusk for 13 hour
Number 6.	Light remains off, ON/OFF mode
Number 7.	Test mode, light is on after it detects no light, light is off after it detects light

TROUBLESHOOTING

1. Charging LED indicator is off when it is daytime

a. The green Charging LED should be on if its day time.
b. Check that the proper battery type has been selected.
c. Check that all wire connections in the system are correct and tight. Check the polarity (+ and -) of the connections.
d. Measure the PV array open-circuit voltage and confirm it is within normal limit. If the voltage is low or zero, check the connections at the PV array itself. Disconnect the PV from the controller when working on the PV array.
e. Measure the PV voltage and the battery voltage at the controller terminals. If voltage at the terminals is the same (within a few tenths of volts) the PV array is charging the battery. If the PV voltage is close to the open circuit voltage of the panels and the battery voltage is low, the controller is not charging the batteries and may be damaged.

2. Charging LED indicator is blinking

a. First check the operating conditions to confirm that the voltage is higher than specifications. Consider the temperature compensation of the controller's PWM setpoint. For example, at 0°C the controller will regulate at about 15 volts
b. Check that all wire connections in the system are correct and tight.

3. Load LED indicator is blinking, flashing, or turned red (load is not operating properly)

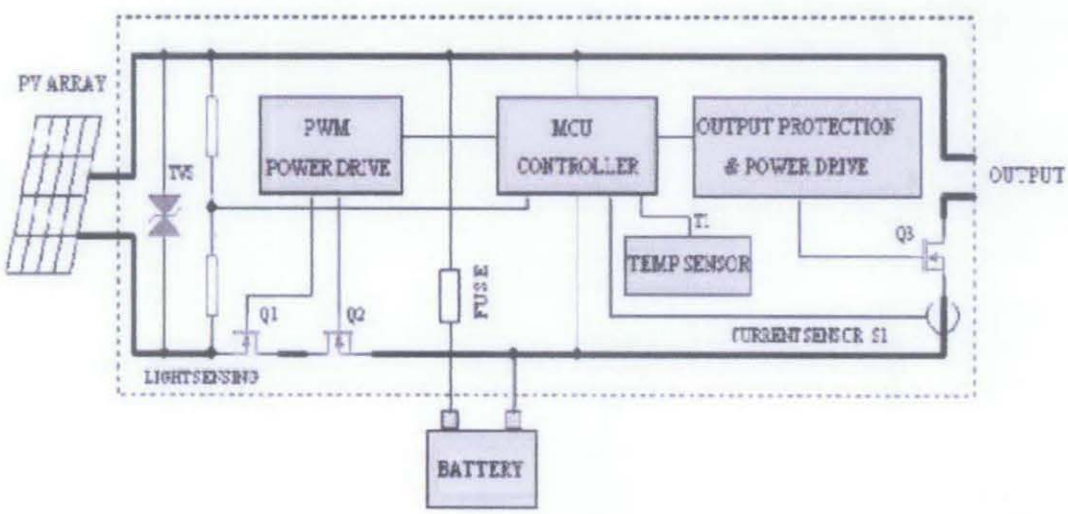
a. Check that the load is turned on. Check that no system fuses are defective.
b. Check connections to the load, and other controller and battery connections. Make sure voltage drops in the system wires are not too high.
c. If the LED indicator is blinking and no output, check if the load is short-circuit. Disconnect the load, and press the switch button, the controller will return to work after 30 seconds.
d. If the LED indicator is flashing and no output, check if the load is over the rated power. Reduce the load, and press the switch button, the controller will return to work after 30 seconds.

INSPECTION AND MAINTENANCE

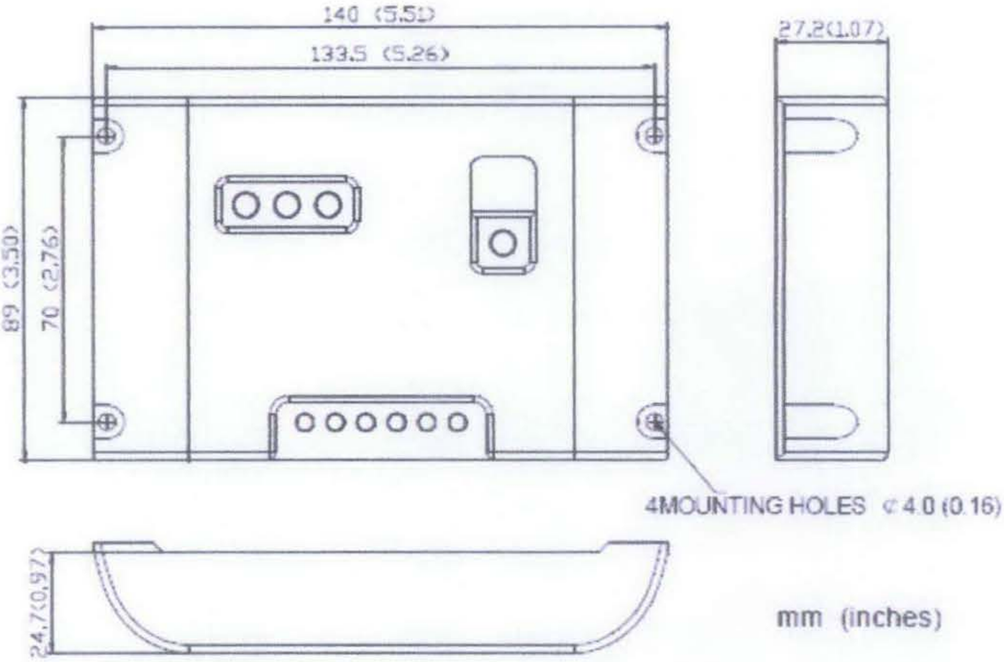
The following inspections and maintenance tasks are recommended at least once per year for optimum controller performance.

1. Confirm that the correct battery type has been selected.
2. Confirm that the current levels of the solar array and load do not exceed the controller ratings.
3. Tighten all the terminals. Inspect for loose, broken, or burnt wire connections. Be certain no loose strands of wire are touching other terminals.
4. Press the TEST button (number: 6 or 7) to verify if the lights are working.
5. Check that the controller is securely mounted in a clean environment. Inspect for dirt, insects, and corrosion.
6. Check the air flow around the controller is not blocked.
7. Protect from sun and rain. Confirm that water is not collecting under the cover.
8. Check that the controller functions and LED indicators are correct for the system conditions at that time.
9. Make sure the PV array is clean and clear of debris and snow. Confirm the array is oriented correctly for the installation location.

SYSTEM MAIN CIRCUIT DIAGRAM



MECHANICAL


140 (5.51)
133.5 (5.26)
27.2(1.07)
89 (3.50)
70 (2.76)
4MOUNTING HOLES ⌀ 4.0 (0.16)
24.7(0.97)
mm (inches)

Datasheet of solar battery

Introduction

Our batteries are manufactured under the guidelines of ISO 9002. Each battery undergoes a series of rigid manufacturing and quality control before the battery leaves the factory.

Features

-Maintenance-free operation/ Seal construction
Our batteries have been classified as "Non-spillable." During the expected services life of our batteries, there is no need to check the specific gravity of the electrolyte, or add water. The unique construction and sealing technique guarantee that no electrolyte leakage can occur from the terminals or case of any battery. These ensure the battery can operate safety in vertical or horizontal position.

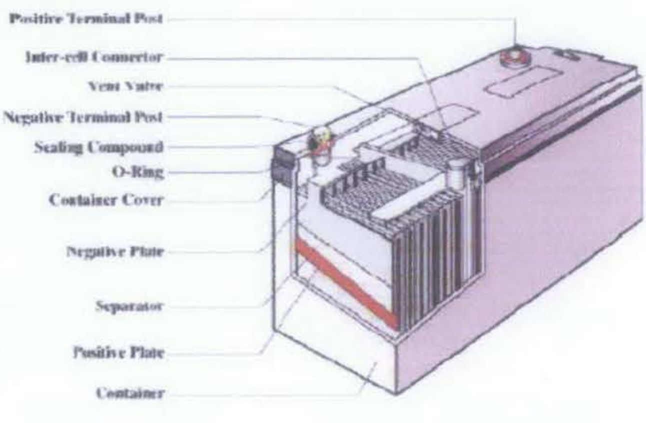
- Wide operating temperature range:
Our battery will operate from -30C to (-22F) to 60C when it is fully charged.

-Long service life: Thick calcium grids extend service life.

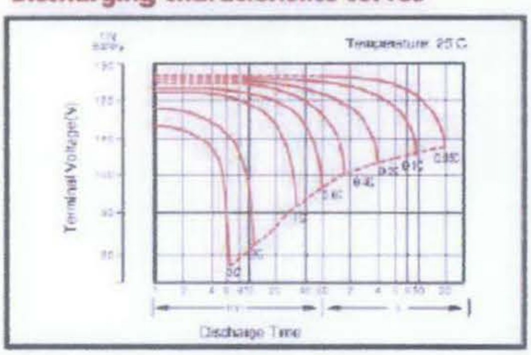
- Low internal resistance and high discharge rate: Our SLA battery has low internal resistance when it is fully charged, therefore has a high discharge rate.

-Working safely: Our battery equipped with a safe, low pressure venting system. Which operates at 1 psi to 6 psi, designed to release excess gas and reseal automatically in the event that gas pressure to a level above the normal rate. Thus, there is no excessive buildup of gas in the batteries.

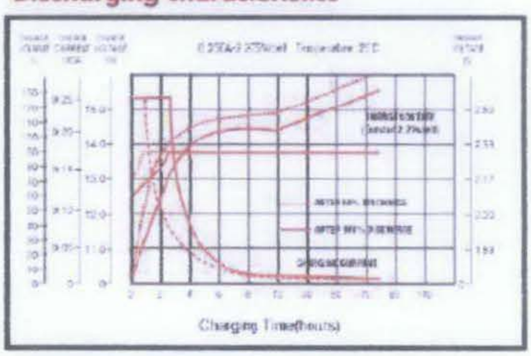
Battery Construction



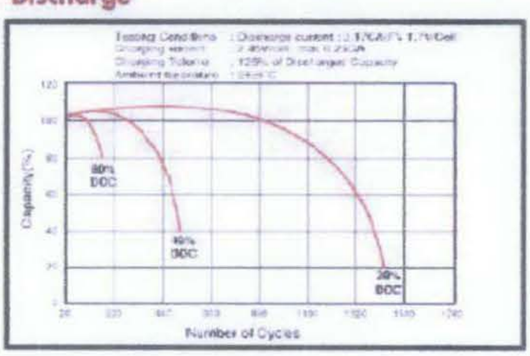
Discharging characteristics curves



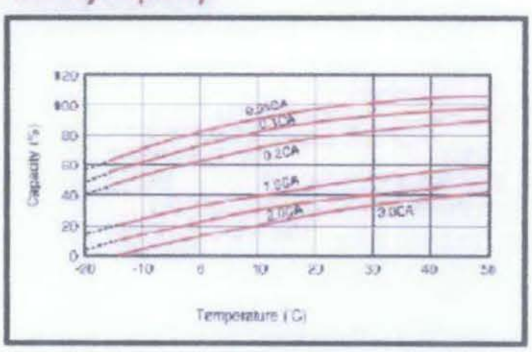
Discharging characteristics



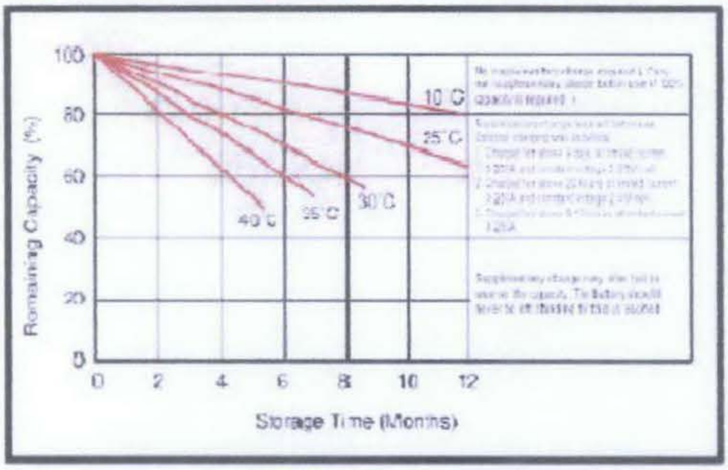
Cycle Service Life in Relation to Depth of Discharge



Temperature effects in relation to battery capacity



Self discharging characteristics and complementary charge methods



Appendix 4-4

Gantt chart for first semester Final Year Project (FYP 1)

No.	Details/Week	1	2	3	4	5	6		7	8	9	10	11	12	13	14	SW
1	Selection of the project topic							MIS-SEMESTER BREAK									
2	Research on SEGS																
3	Submission of Preliminary Report																
4	Learn on PV technology																
5	Collecting Data																
6	Submission of Progress Report																
7	Seminar																
8	Simulation/Designing work																
9	Submission of Interim Report (Draft)																
10	Submission of Final Report																
11	Oral Presentation																

Process

Appendix 4-5

Gantt chart for second semester Final Year Project (FYP 2)

No.	Details/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	SW
1	Simulation of designed system																
2	Building up the lab-scaled prototype																
3	Validation and Analysis																
4	Submission of Progress Report								MIS-SEMESTER BREAK								
5	Submission of Draft Report																
6	Submission of Technical Paper																
7	Submission of Dissertation (soft bound)																
9	Oral Presentation																
10	Submission of Project Dissertation (Hard Bound)																

Process