EXPERIMENTAL STUDY OF COMPARATIVE PERFORMANCE BETWEEN THREE TYPES OF PHOTOVOLTAIC MODULES IN STATIC AND DYNAMIC INSTALLATIONS UNDER PENANG CLIMATIC CONDITION

By

MUHAMAD AZHAR BIN GHAZALI

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TABLE OF CONTENTS

CHAPTER 2: LITERATURE REVIEW

PART 2 – EMPIRICAL AND ANALYTICAL STUDIES

CHAPTER 3: RESEARCH METHOOLOGY AND DESIGN

CHAPTER 4: RESULTS AND DISCUSSIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

AC	- Alternations Current.
APEC	- Asia-Pacific Economic Cooperation
APERC	- Asia Pacific Energy Research Centre
a-Si	- Amorphous Silicon
BiPV	- Building Integrated Photovoltaic
CdTe	- Cadmium Telluride
CIS	- Copper Indium Selenide
CLEAR	- Comfortable Low Energy Architecture
DANIDA	- Danish International Development Agency
DC	- Direct Current
GaAs	- Gallium Arsenide
GBI	- Green Building Index
GEF	- Global Environment Facility
GMT	- Greenwich Mean Time
HSA	- Horizontal Shadow Angle
IEA	- International Energy Agency
LEEE	- Laboratory of Energy, Ecology and Economy
LGBC	- Laser Grooved Buried Contact
MBiPV	- Malaysia's Building Integrated Photovoltaic
MMD	- Malaysia Meteorological Department
m-Si	- Monocrystalline Silicon
Mtoe	- Million Tonnes of Oil Equivalent
NSPRI	- National Solar Power Research Institute

PC	- Personal Computer
PLC	- Programmable Logic Controller
PR	- Performance Ratio
p-Si	- Polycrystalline Silicon
PV	- Photovoltaic
PVPS	- Photovoltaic Power System Programme
RH	- Relative Humidity
STC	- Standard Test Condition
TISO	- Ticino Solare
UNDP	- United Nation Development Program
UNEP	- United Nation Environment Program
UV	- Ultra Violet
VSA	- Vertical Shadow Angle

LIST OF SYMBOLS

CO_2	- Carbon Dioxide
W	- Power (W)
I	- Current (A)
V	- Voltage (V)
δ	- Solar Declination Angle
ω	- Hour Angle
φ	- Geographical Latitude
α	- Angle between the sun's direction and the horizon is the elevation
ψ	- Azimuth
β	- Sun altitude angle
$ŋ_p$	- Power output efficiency (%)
P_{mea}	- Average power output (W) measured on site in the given period.
P_{max}	- Maximum power output (W) of panel.
ŋ	- Conversion Efficiency
$ŋ_{eve}$	- Average module efficiency (%)
$P_{eve \cdot mea}$	- Average power output (W) measured on site in the given period.
H	- Average incident radiation (W/m2) on site in the given period.
PV_A	- Surface area (m^2)
T	- Module Temperature
$P_{eve \cdot mea}$	- Average power output (W) measured on site in the given period.
P_{max}	- Maximum power output (W) of panel.
H	- Average incident radiation (W/m2) on site in the given period.
G_{STC}	- Irradiance at STC (W/m^2) = $1000W/m^2$

KAJIAN EKSPERIMEN PERBEZAAN PRESTASI ANTARA TIGA JENIS MODUL PHOTOVOLTAIC PADA PEMASANGAN STATIK DAN DINAMIK DI KEADAAN IKLIM PULAU PINANG

ABSTRAK

Tujuan utama kajian ini adalah untuk meningkatkan kecekapan teknologi photovoltaic dan untuk memastikan ia sesuai dalam keadaan iklim Malaysia sebagai menyahut seruan dibawah Program *Malaysia Building Integrated Photovoltaic* (MBiPV), program kerjasama antara Kerajaan Malaysia dan *United Nation Development Program (*UNDP). Dengan mengaplikasikan sistem pengesanan solar, kecekapan modul photovoltaic dijangka dapat ditingkatkan di dalam keadaan iklim Malaysia. Kajian ini memberi tumpuan kepada tiga jenis panel solar yang biasa terdapat di pasaran Malaysia dan membandingkannya dari segi prestasi diantara pemasangan dinamik (*time/date single axis*) dan pemasangan statik. Sistem dinamik dalam eksperimen ini direkabentuk untuk menyokong tiga jenis panel PV dan membenarkan ia bergerak dengan darjah kebebasan tunggal (mendatar) mengikut pergerakan orientasi matahati (terbit hingga terbenam) iaitu dari timur ke barat. Pergerakan panel PV adalah tegak dan lurus ke arah kedudukan matahari supaya sinaran suria boleh dioptimumkan dari pagi sehingga petang. Sementara itu, sistem pemasangan static pula ditetapkan pada kedukukan 0^o melintang. Kajian ini mendapati bahawa modul *poly-crystalline* dan *mono-crystalline* telah menunjukkan prestasi yang lebih baik dalam sistem dinamik. Manakala modul amorphous mempunyai kecekapan yang tinggi dengan pemasangan yang static. Dengan

mengaplikasikan sistem penjejakan solar, ia yang tidak hanya meningkatkan prestasi yang panel PV yang dipasang tetapi ia juga dapat disepadukan kepada rekabentuk bangunan sebagai sebahagian daripada *building integrated photovoltaic* (BIPV). Ini dapat dilaksanakan sebagai sebahagian daripada fungsi khusus bahagian luar bagunan (misalnya, teduhan bagi tempat letak kereta, mengurangkan haba langsung dari matahari di atas bumbung, mengurangkan cahaya matahari secara langsung untuk pencahayaan semula jadi).

EXPERIMENTAL STUDY OF COMPARATIVE PERFORMANCE BETWEEN THREE TYPES OF PHOTOVOLTAIC MODULES IN STATIC AND DYNAMIC INSTALLATIONS UNDER PENANG CLIMATIC CONDITION

ABSTRACT

This study response to the Malaysia's Building Integrated Photovoltaic (MBiPV) Program, a collaboration program between Malaysian Government and United Nation Development Program (UNDP) to find ways to increase the efficiencies of photovoltaic technologies and to ensure it is applicable in Malaysian climate condition. With the solar tracking system, the efficiency of photovoltaic module is expected to increase under Malaysian climate condition. This study focuses on the three common types of solar panels available in the Malaysian market and compares the performance between dynamic (single axis time/date tracking) and static photovoltaic installation's system according to each type of photovoltaic panels. The dynamic system in this experiment was designed to support the three types of PV panels which allowed it to move with single degree of freedom (horizontally) according to the sun's orientation (sunrise to sunset) from east to west. The movement of PV panels allowed it to set perpendicularly toward the sun insolation (incoming solar radiation) so that solar rays can be optimized from morning until evening. While in static system, each type of photovoltaic panels was set 0^o horizontally. The study found that poly-crystalline and mono-crystalline photovoltaic panel has shown better performance in dynamic system. However,

amorphous solar module performed significantly better with static system installation compared to dynamic system under Malaysian climate condition. Thus, it will influence on building envelope as future possibilities in designing green building. In built environment, by replacing the conventional type of solar installation with solar tracking installation, it's not only increase the performance of the PV panels installed but also, it can be integrate to the overall building design as part of Building Integrated Photovoltaic (BiPV) to perform specific function to the building envelope (e.g., provide shades on top of parking lot, minimize direct heat from sun at roof top, minimize direct sunlight for natural lighting).

PART 1 – RESEARCH AND THEORETICAL STUDIES

CHAPTER 1: INTRODUCTION

1.1 Research Background

Concerning about the depleting of fossil fuel and the alarming of global warming's effect, Malaysia has developed various policy and strategies to promote and continuously encourage the development of renewable energy. Under *The Ninth Malaysian Plan 2006 – 2010*, focuses have been given on renewable energy and energy efficiency as an action to develop a sustainable energy sector. In *National Energy Policy*, renewable energy resources will be develop to ensure the provision of adequate, secure and cost-effective energy supplies to the country. Meanwhile, in *The Five-Fuel Policy*, renewable energy became one of the components in the fuel mix for power generation after oil, coal, gas and hydro. Malaysian Government also launched the *National Green Technology Policy* as an effort to provide path toward sustainable development and one of the four pillars that this policy built on is to attain energy independence and promote efficient use.

In recent event, Malaysian Government has established a fund to provide soft loan to companies that supply and utilize green technology. In May 2009, Green Building Inde*x* (GBI) was launched to promote sustainable and energy efficiency in built environment. This rating system was developed specifically for the Malaysian-tropical climate, environmental and developmental context.

Pusat Tenaga Malaysia now known as the Green Tech Office has been campaigning for the use of solar electricity with the help of the Danish Government via its implementation arm program known as Danish International Development Agency (DANIDA). With the launch of Malaysia's Building Integrated Photovoltaic (MBiPV) Program by the Government and United Nations Development Program (UNDP), urges us to find ways to increase the efficiencies of the photovoltaic technologies and to ensure it is applicable to the Malaysian climate. *Suria 1000* Program is a pioneer project under MBiPV with support from UNDP, Global Environment Facility (GEF), Suruhanjaya Tenaga and private sector to promote building integrated photovoltaic (BiPV) installation at residential and commercial buildings.

1.2 Problem Statement

In tropical countries, most of this energy consumption is for the functioning of lighting, electrical appliances, and for air-conditioning. According to Asia Pacific Energy Research Centre (APERC), (2006) about 40 percent of Malaysia's total energy demand in commercial sector required is for space cooling. This was supported by an energy audit done by DANIDA and ECO-Energy Systems, a 987m^2 single storey office consumed about 232,050 kWh giving it an energy index of 235 kWh/m^2/year and the breakdown was 64 percent for air-conditioning, 12 percent for lighting and 24 percent for general equipment. Meanwhile, in typical Malaysian terraced house of about 180m^2, the refrigerator is usually the largest consumer of electricity while the air conditioning will increasingly become more important as living standards rise (Chan, 2004). A large number of fossil fuel energy had been use in order to make each and every building serve their purpose. With the rising of energy cost and the increasing of electrical consumption, it can lead to environmental and social instability.

Solar energy has been acknowledged as a free and infinite source of energy. Solar energy provides an alternative energy source where there is no pollution of the environment and decreases the rate of depletion of energy reserves (Sharan, 2008). The energy supply from the sun is truly enormous: on average, the earth's surface receives about 1.2 x 10^{17} W of solar power. This means that in less than one hour enough energy is supplied to the earth to satisfy the entire energy demand of the human population over the whole year (Markvart, 1994).

In 1839, Edmund Becquerel observed that 'electrical current arose from certain light-induced chemical reactions' and from that moment start the solar cells technology and soon became photovoltaic technology (Markvart, 1994). With the introduction of Photovoltaic (PV) technology that can harvest solar heat and convert it into electricity for daily usage has become one of the most promising renewable energy technologies. According to Prasad & Snow (2005), photovoltaic are solid-state devices that simply make electricity out of sunlight, silently and with little to no maintenance, no pollution and no significant depletion of material resources.

Solar energy is undeniably safe, free and abundantly source of renewable energy that available. Capturing sunlight and turning them into electricity for a daily usage is a very good idea. However to capture the sunlight and generate electricity, it's require certain technologies and this technologies have its limitation. Solar electricity suffers one major drawback at present, and that is the high capital cost of photovoltaic (Markvart, 1994).

According to William (1986), wiring in photovoltaic system accounts for 2 percent loss and power conditioning accounts for a 10 percent loss in energy in overall system efficiency and suggest that the future market for photovoltaic is highly dependent upon the technological breakthroughs that are being made in cell efficiencies and in lower cost materials.

Solar photovoltaic are an expensive mean to set energy, even compared to other renewable. Haris (2006) mentioned that, based on the International Energy Agency (IEA) Photovoltaic Power System Programme (PVPS) 10 year market assessment, the PV system cost can decrease by 15 percent to 20 percent if there is a doubling of the market size. Unfortunately, a sustainable market cannot be established for as long as the economics of BIPV technology is unfavorable. Haris also added that, it is a “chicken and egg” situation.

The cost of such devices and their application can be reduced through improvement in materials, more sophisticated control system and large scale manufacture. Solar photovoltaic have other potential advantage, they are safe, environmentally benign and are potentially available anywhere with almost unlimited quantities. With advance technologies and methods of increasing the efficiencies of PV panels, it could provide the secure, affordable and environmentally sustainable energy source.

Commonly in Malaysia, PV panels were installed fixed to the building either on the roof or at the façade of building and this installation considered as static system. These static systems only maximize sun availability at certain time during daytime. While a dynamic system use a Solar Tracker device for orienting Photovoltaic Panel (PV) toward the sun. This is to ensure that the concentration sunlight is directed to the focal point of the PV and this will improve the amount of power produced by the system by enhancing morning until evening performances.

Past studies on solar tracking process show that by setting the solar panels using sun tracking system, very significant improvement in energy conversion can be achieved (Sharan, 2008). Although solar tracker can boost energy gain of PV arrays, some problem such as cost, reliability, energy consumption, maintenance and tracking system's performance must be considered. Furthermore, details studies on local climate condition, especially on sun's position throughout the year have to be done before installing the tracking system with PV panel.

Malaysia has relatively high solar radiation intensities on most of the days (Sayigh, 1998). This is because Malaysia lies in the equatorial doldrums area between 1^{o}N and 7^{o}N, and 100^{o}E and 119^{o}E (Kamaruddin, Bailey & Montero, 2002). With these factors, Malaysia has high potential to implement solar tracking to the photovoltaic system. But being in tropical climate's country has a few disadvantages. The formation of clouds create sky patches and resulting in obstruction of the sun, therefore the solar radiation penetration is not constant (Ahmad, Hamdan, Dilshan, Ossen & Chia, 2004)

This research focuses on the three common types of solar panels that available in the Malaysian market and to identify which type of those solar panels are the most efficient in term of power conversion using the solar tracking system by optimizing the sunlight during daytime and also to compare the performance between static system and dynamic system. It is hoped that this experiment helps to explore optimization of efficiency not only by manufacturer's technical panel specification but also by design strategies for creating Green Building.

1.3 Hypothesis and Research Questions

Combining photovoltaic system with solar tracker mechanism has the potential to increase the performance of the photovoltaic module install. As the modules rotate according to the sun movement and the photovoltaic panels will be as perpendicular as possible toward the sun, the amount of solar radiation that hit the PV panels will be high especially during mid-day. Although the solar radiation in this country is predictable, the presence of unpredictable cloud in the sky might influence the performance of solar panel as the cloud will block the radiation from the sun. These surely affect the performance of the tracking system and the PV panels. Therefore, more specific research question should be formulated:

I. What are the performances of different type of photovoltaic panels by using the dynamic (time-tracking) system?

II. Which types of photovoltaic panel and installation are more efficient under Penang's climate condition?

1.4 Objective of the Study

The aim of this research is to maximize the available solar radiation in local climate condition for conversion into usable energy and to identify the most efficient in terms of power conversion using the time-tracking system with commonly available photovoltaic system in Malaysia.

The objectives of this study are:

i. To measure the performance of photovoltaic installation system between dynamic (single axis time/date tracking) and static.

ii. To determine the type of photovoltaic panel and installation that are most efficient under Penang's climate condition.

1.5 Scope of the Study

This thesis presents a study to find way on how to increase the efficiencies of photovoltaic module and to ensure it applicable according our local climate condition by applying solar tracker method to the overall photovoltaic installation. Although there are another way to increase the efficiencies, that is by creating or manufacturing a solar cells with higher efficiency which required electromagnetic breakthrough. This thesis only focuses on electrical device that keeps the Photovoltaic module in an optimum position perpendicular to the solar radiation during daylight hour.

The development of solar cells technologies became more advances each year as new type of solar cells have been found and created each year with higher module efficiency depending on manufacturer details. However in Malaysia there are a few types of photovoltaic panels that are commercially available in local market; poly-crystalline, mono-crystalline, amorphous silicon and copper indium-diselenide. Due to the limitation of materials, this study only investigates the performance of poly-crystalline, mono-crystalline and amorphous silicon photovoltaic modules.

In solar tracking concepts, there are a few methods on how to track the sun position in the sky e.g. Single-axis, Dual-axis tracker, electro-optical sensor based, auxiliary bifacial solar cell based and time/date based. The method used to track the sun position and the movement of the photovoltaic panels in this thesis was single-axis time/date based tracking system. The selections of this method were based on literature review from other researcher considering the cost, reliability, energy consumption, maintenance and performance.

Malaysia as one of the countries that lies entirely in the equatorial region has an advantage to implement the photovoltaic system because of the weather condition that is very suitable with availability of sunlight for more than 10 hours daily. Meanwhile Penang Island, in the northern region of Peninsular Malaysia is reported to have the highest potential for solar energy application due to high solar radiation throughout the year and for these reason this research was done in Penang Island. The data collection for this research was done in December 2009 until February 2010.

This research will focus on determining the best type of photovoltaic module and photovoltaic panel installation under Penang's climate condition in term of performances. However, other aspects of photovoltaic panel and environmental element such as mismatch and wiring losses, wind speed and direction, humidity, air pressure and accumulated dirt and dust will not be comprehensively covered in this thesis.

1.6 Significance of the Study

The aim of this study is to determine the most efficient type of photovoltaic panels that is commonly available in Malaysian market by applying tracker system. Therefore it will help to identify critical technical factors in maximizing the energy output in photovoltaic technologies under the Malaysian climate conditions by adding the tracker system to the overall of photovoltaic installation system.

This research investigates the performance of photovoltaic module between dynamic and static system installation, with a view to reduce the quantity of photovoltaic panels installed. Hence, this study will determine the best type of photovoltaic module and installation system in Malaysia. Furthermore, these will influence the cost of the overall installation of photovoltaic system.

As to response to the MBiPV Program, a collaboration program between Malaysian Government and UNDP to find ways to increase the efficiencies of photovoltaic technologies and to ensure it is applicable to the Malaysian climate. With the solar tracking system, the efficiency of photovoltaic module is expected to increase under Malaysian climate condition.

Thus, it will influence on building envelope as future possibilities in designing green building. In built environment, by replacing the conventional type of solar installation with solar tracking installation, it's not only increase the performance of the PV panels installed but also, it can be integrated to the overall building design as part of Building Integrated Photovoltaic (BiPV) to perform specific function to the building envelope (e.g., provide shades on top of parking lot, minimize direct heat from sun at roof top, minimize direct sunlight for natural lighting).

This research also provides general information about photovoltaic technologies and solar tracking method in enhancing the efficiency of photovoltaic module to the built environment and manufacture. It's also for the end users to understand the various means of saving electricity while maintaining cleaner, healthy and sustainable environment.

1.7 Outline of the Thesis

This thesis consist 5 chapters, which can be explained as follows:

Chapter 1 gives an overview of the content from this thesis and introduces the issues on how to increase the performance of photovoltaic panels as a potential technology to generate renewable energy from the sun. Its starts with the background of this research and follow by addressing the problem statement of the energy resources in this country and current issues that rise in the development of photovoltaic technologies. This chapter also describes the objectives, scopes and the significant of the research as well as brief overview of the thesis.

Chapter 2 presents a fundamental concept and literature review on the topic relate to photovoltaic technologies and solar tracking method, focusing on the basic operational principal, type of technologies involved, important factors that will affect the performance of photovoltaic module. This chapter also includes a comparative study of previous academic research on the performance of photovoltaic technologies and solar tracking method. The review is done to get a clear understanding of the important aspects involving the main topics. This chapter also gives an overview on Malaysian climate condition which focusing on solar radiation and some astronomy on sun position in this country. Finally, an overview of real application of the photovoltaic technologies in the architectural context also known as Building Integrated Photovoltaic (BIPV).

Chapter 3 discusses the research approaches and the methodologies that were used in this research. The reasons why and how the selected methodologies are used for this study are also described based on the previous literature. This chapter also explains the detail physical research investigation which includes the site study and full-scale field measurement study.

Chapter 4 will present the analyzed results of the fieldwork measurement studies which encompass the two stages of these experimental studies on performance of the three type of photovoltaic module with dynamic (tracking device) and static system installation under Penang's climate condition. First part of this result will show the comparative analysis of power output efficiency for each type of photovoltaic module with local climate parameters which is solar radiation and ambient temperature. Second part is comparative analysis of average module efficiency in period of this experiment and lastly a comparative analysis on performance ratio for each type of photovoltaic module.

Chapter 5 indicates the conclusion of overall finding in this research. This chapter also summarizes the possible implementation of tracking system on photovoltaic installation at building envelope in Malaysia.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review on the topics related to photovoltaic and solar tracking. It starts with the fundamental of photovoltaic (PV) system, which is include the basic operation and structure of PV system, type of PV available and the performance of the PV available base on previous research. Second part of this chapter presents the concepts of Solar Tracking method in enhancing the performance of PV panels, covering the type of tracker and the method of tracking the sun position. Then it is followed by a comprehensive review on some experimental and analytical studies on the performance of photovoltaic solar tracking. In this chapter also presents a brief overview on Malaysian climate condition, which includes the introduction of Solar Radiation and some astronomy of sun position. Finally, about the integration of photovoltaic in building design which is known as Building Integrated Photovoltaic (BIPV) system; and this is includes criteria and consideration in designing BIPV, architectural application for PV integration and BIPV in Malaysian context.

2.2 Fundamentals of Photovoltaic System

United Nation Environment Program - UNEP, (2011) has described photovoltaic system from the architectural point of view as an active solar design which is generally very visible with collector on roofs, control system and storage tanks. It requires an external source of energy to transfer the collected solar heat into building and consists of solar collector and solar electric.

Photovoltaic panels are made of thermal element which becomes charged electrically when subjected to sunlight. Photovoltaic is a direct conversion of light into electricity at the atomic level. The panel works on the principle of photovoltaic effect.

2.2.1 Photovoltaic Basics

Photovoltaic power systems combine within a single technology a source of energy in its most versatile form (electric); the means to directly convert energy from virtually infinite source (the sun); and desire to generate power via non-polluting process (photovoltaic effect) (Gupta & Young. 1981).

In 1839, Edmund Becquerel observed that 'electrical current arose from certain light-induced chemical reactions' and from that moment start the solar cells technology and soon became photovoltaic technology (Markvart, 1994). According to Prasad & Snow (2005), the substantial creation of useable electric current in a solar cell takes place at the atomic level, when light energy (photons) strikes the face of the cell; it excites the electron within the cell. Figure 2.1 show the operation diagram of photovoltaic cell, the flow of electrons (current) from the negative semi-conductor (phosphorous) to the positive semi-conductor (boron) is called photovoltaic (PV) effect and this process is called 'doping'.

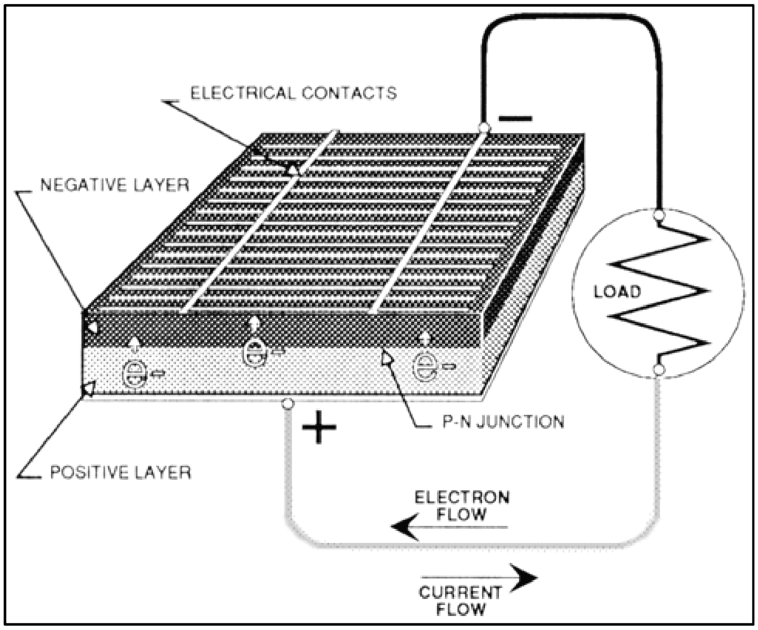


Figure 2.1: Operation of a photovoltaic cell (Source: Polar Power, 2011)

2.2.2 Structure of Photovoltaic (PV) System

Solar cell is the basic unit in a PV system. An individual solar cell can vary in size from about 1 cm (0.4 inch) to about 15 cm (6 inch) across and typically produces between 1 and 2 watts (Prasad & Snow, 2005). A typical photovoltaic module consist 6 layers (from the light-facing side to the back) of material in order it to function properly. Figure 2.2 shows the basic layered structure of PV module and below are the details description for each layer according to Green Rhino Energy in *The Principal of Photovoltaic* (2010):

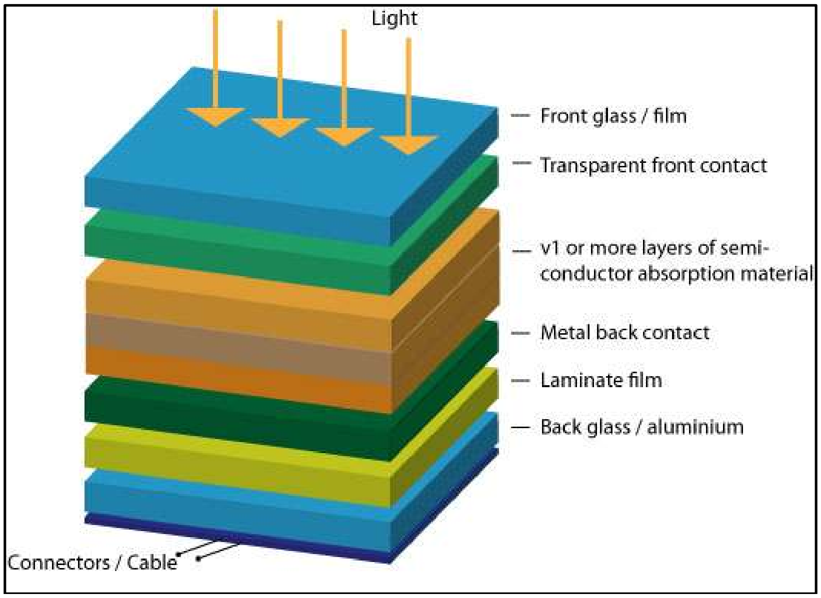


Figure 2.2: Photovoltaic module layered structure (Source: Green Rhino Energy, 2010)

I. **Protection Layer:** Usually made from glass to protect the layers in between.

II. **Front Contact:** A transparent layer that allow light to penetrate in to the cell.

III. **Absorption Material:** semiconductor materials to absorb light and convert to electric current.

IV. **Metal back contact:** conducting layer to complete the electric circuitry.

V. **Laminate Film:** water-proof and insulated the structure from heat.

VI. **Back glass:** to protect the module from the back side.

VII. **Connectors:** for wiring purposes.

In photovoltaic technology, to produce or increase the voltages, currents and power levels photovoltaic cell need to connect electrically in series and/or parallel. Figure 2.3 shows the combination of numbers of photovoltaic cells create a module. To increase power output, many PV cells are connected together to form modules, which are further assembled into larger units called arrays (National Solar Power

Research Institute - NSPRI, 1998). Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit and a photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels (Oman Solar System, 2009)

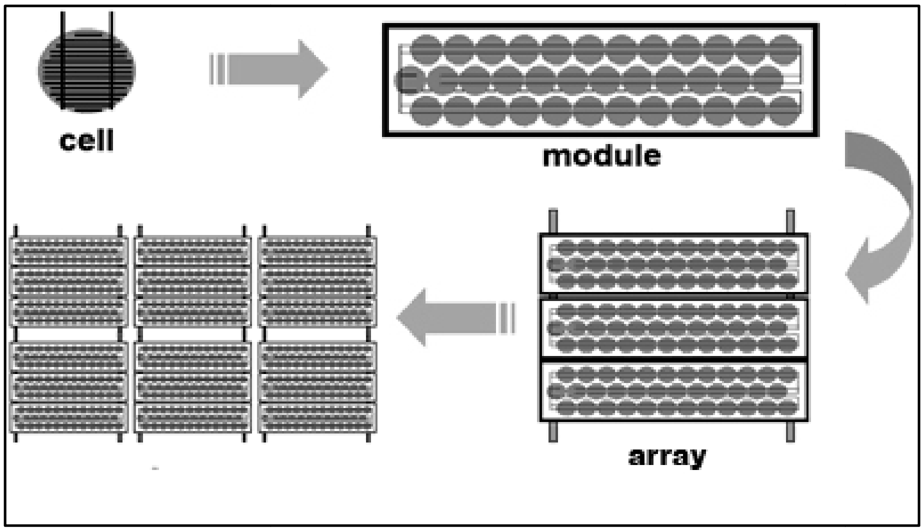


Figure 2.3: Photovoltaic cells, modules, panels and arrays (Source: Oman Solar System, 2009)

A single photovoltaic modules itself cannot create useable power without integrate with other supporting appliances. A photovoltaic system consists of a number of parts or subsystems as shown in Figure 2.4 to create useable power. While Figure 2.5, shows the diagram of stand-alone photovoltaic system.

I. The photovoltaic generator with mechanical support and possibly a sun-tracking system
II. Batteries (storage subsystem)
III. Power conditioning and control equipment, including provision for measurement and monitoring
IV. Back-up generator

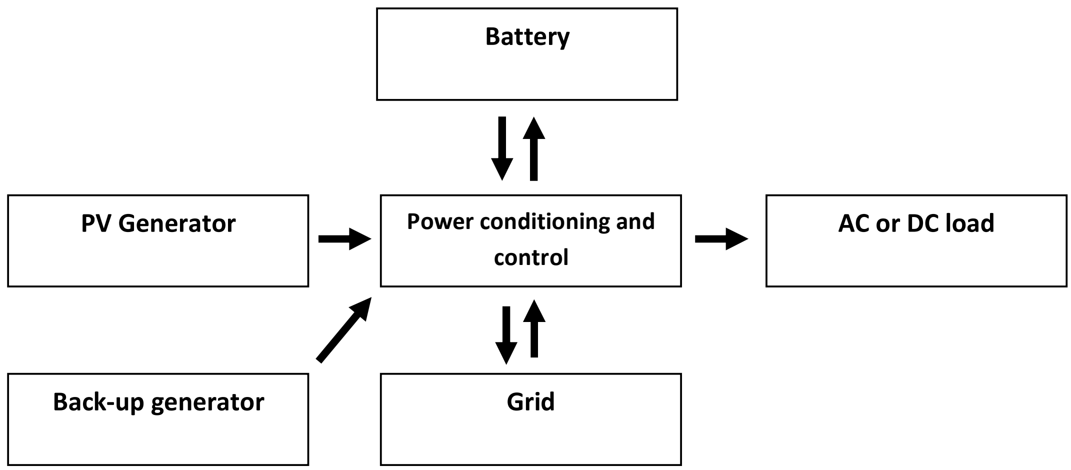


Figure 2.4: Schematic diagram of photovoltaic system (Source: Markvart, 1994)

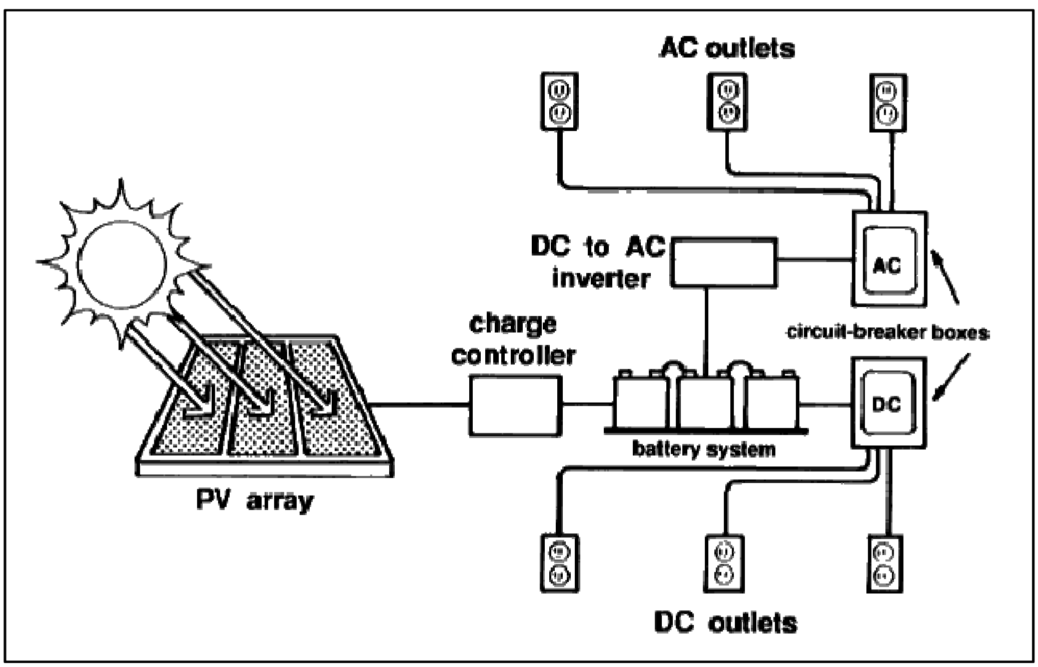


Figure 2.5: Diagram of stand-alone photovoltaic system (Source: Goffman, 2006)

2.2.3 Type of Photovoltaic Panels

Semiconductor is the main materials to produce PV cells. There are 2 major types of semiconductor materials available today to manufacture PV cells, which are crystalline and thin films. According to NSPRI (1998), these 2 materials are varies from each other in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology and cost of production. Table 2.1 show the summaries different types of PV module that is available in today's market.

Table 2.1: Summary the types of PV module available today.

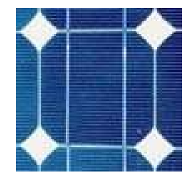
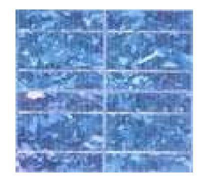
Types of PV		Characteristics (Prasad & Snow, 2005)	Appearance	Figure
			(Chelsfield Solar, 2004)	
Crystalline Materials	Monocrystalline silicon (mono) (m-Si)	Mono-crystal silicon has a uniform molecular structure.	Charcoal or dark blue	
		The conversion efficiency ranges between 15-20%.		
		Manufacturing process complicated, resulting in slightly higher costs than other technologies.		
	Polycrystalline silicon (p-Si)	Consisting of small grains of single-crystal silicon.	Shiny and spangly blue or a darker blue	
		The conversion efficiency ranges between 10 to 14%.		
		Cheaper to produce than mono-crystalline cells, due to simpler manufacturing process.		
	Gallium Arsenide (GaAs)	Has a crystal structure similar to that of silicon.	Silver or white	
		Higher energy conversion efficiency than crystal silicon, reaching about 25 to 30%.		
		High cost of the single-crystal substrate that GaAs is grown on.		

Table 2.1: *Continued*

Types of PV		Characteristics (Prasad & Snow, 2005)	Appearance (Source: Chelsfield Solar, 2004)	Figure
Thin Film Materials	Amorphous Silicon (a-Si)	Amorphous silicon is a non-crystalline form of silicon.	Dark brown or dark blue	
		Less efficient with typical efficiencies of around 9 %.		
		Low cost in manufacturing.		
		Rigid and flexible, which is makes it ideal for curve surfaces and 'fold-away' modules.		
	Cadmium Telluride (CdTe)	Has a high light absorptive level.	Reflective dark green to black	
		Conversion efficiency is about 7%, similar to that of a-Si.		
		Relatively easy and cheap to manufacture.		
		Cadmium is a toxic substance and extra precautions have to be taken in manufacturing process.		
	Copper Indium Selenide (CuInSe2, or CIS)	A polycrystalline semiconductor compound of copper, indium and selnium.	Matte-black	
		Energy conversion efficiency of 17.7%.		
		CIS is an efficient but complex material. Its complexity makes it difficult to manufacture		

2.2.4 Temperature and Irradiance Effects

The most significant effect on the power output of photovoltaic module is the temperature (Figure 2.6) dependence of the voltage which decrease with increasing temperature (its temperature coefficient is negative). The voltage decrease the silicon cell is typically 2.3mV per ^{o}C (Markvart, 1994).

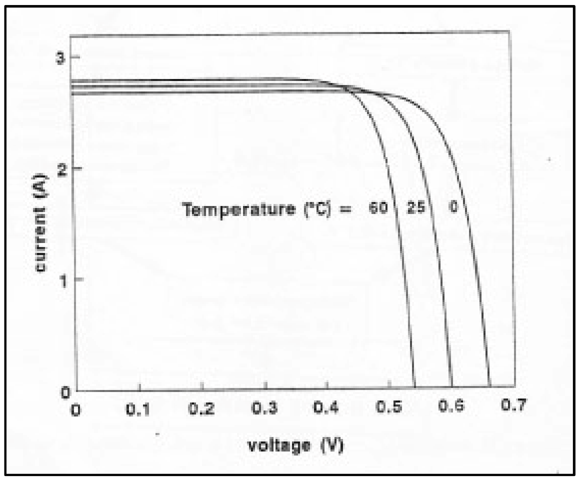


Figure 2.6: Temperature dependence of the the I-V characteristic of a solar cell (Source: Markvart, 1994)

According to Armstrong and Hurley (2010), the photovoltaic panel operating temperature is dependent upon many factors; solar radiation, ambient temperature, wind speed and direction, panel material composition and mounting structure. Tonui & Tripanagnostopoulos (2007) in their studies on air-cooled PV/T solar collectors with low cost performance improvements mentioned that for a typical commercial PV panel, a proportion of solar radiation is converted into electricity, typically 13-20%, and the remainder is converted to heat.

In addition, the photovoltaic panel also generates it own heat due to the photovoltaic action and further heating occurs due to the energy radiated at the infrared wavelength of the solar spectrum. With increasing temperature, it decreases the amount of power available (Hussein *et al.*, 1995; Midya *et al.*, 1996). The irradiance increase at same proportionate with higher current. Therefore, the short-circuit current of a solar cell is directly proportional to the irradiance (Figure 2.7).

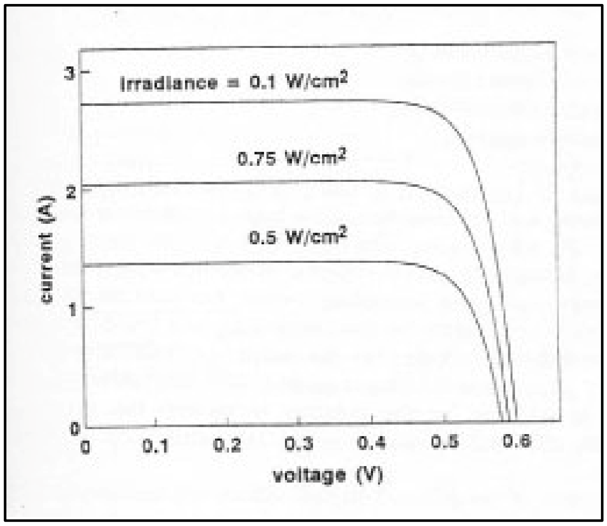


Figure 2.7: Irradiance dependence of the the I-V characteristic of a solar cell (Source: Markvart, 1994)

2.2.5 The Performance of Photovoltaic Panels

In 1989, William concluded her book '*The Handbook of Photovoltaic Applications: Building Applications and System Design Considerations*' that silicon cells commonly have efficiencies in the range of 12 to 14 percent but experimental cells, which have been tested in the laboratory condition, have achieved efficiencies as high as 22 percent. The experiments have involved multi-junction cells built with materials with different responses to sunlight and with each material providing the most optimum conversion of the spectrum wavelength. Amorphous silicon cell efficiencies have risen dramatically from about 3 to 4 percent about 10 years ago to 7 to 8 percent for overall system efficiency.

Meanwhile, according to Markvart (1994), solar cells convert sunlight into electricity by exploiting the photovoltaic effect and the maximum conversion efficiencies observed in laboratory is more than 30% but typical efficiencies for production cells are between 10-15%. He also suggested that crystalline silicon cells technology is well establish with production efficiency almost 18% and the modules have a long lifetime (20 years or more), while amorphous is cheaper (but also less efficient) types of silicon cells.

However, for the past 13 years (1998 – 2011), many experiment either it's a laboratory test or field test have been made by researcher to investigate the performance of photovoltaic cell. Table 2.2 shows the summary of previous research on the performance of different type of photovoltaic panels.

Table 2.2: Summary of previous research on the performance of different type of photovoltaic panels.

RESEARCHER	TYPE OF SOLAR CELLS MEASURED	LOCATION/ SITE	CLIMATE	EVALUATION: LAB TEST	EVALUATION: FIELD STUDY	CONCLUSION
Camani, Cereghetti, Chianese & Rezzonico (1998)	Mono-crystalline (m-Si) Poly-crystalline (p-Si) Amorphous Silicon (a-Si)	Switzerland	Seasonal (30^oC to -5^oC)	•	•	The c-Si module are more sensitive to meteorological variation compared to a-Si modules
Mieke (1998)	Poly-crystalline (p-Si) Triple junction amorphous (3j a-Si)	Darwin, Australia	Tropical savannah (10^oC to 45^oC)		•	Overall power output of 3j a-Si is between 20% to 30% higher than p-Si modules.
Eikelboom & Jansen (2000)	Mono-Si, LGBG Multicrystalline Si (c-Si) Copper indium diselenida (CIS) Mono-Si (m-Si) Amorphous Si triple stack (a-Si) EFG Si sheet (p-Si) Amorphous Si (a-Si) Amorphous Si double stack (a-Si) Multicrystalline Si (c-Si)	Petten, Netherlands	Maritime (7^oC to 11.4^oC)	•	•	Thin-film show high performance in low light level. Crystalline silicon shows highest efficiencies
Fanney, Dougherty, & Davis (2001)	Single-crystalline Poly-crystalline (p-Si) Silicon Film Triple-Junction Amorphous (3j a-Si)	Maryland, U.S	Humid Subtropical		•	Mid-day measured efficiency; m-Si (10.4%), p-Si (10.2%), silicon film (6.5%), 3j a-Si (6.1%)

Table 2.2: *Continued*

RESEARCHER	TYPE OF SOLAR CELLS MEASURED	LOCATION/ SITE	CLIMATE	EVALUATION		CONCLUSION
				LAB TEST	FIELD STUDY	
Cueto (2002)	Crystalline silicon (c-Si) Poly-crystalline Silicon (p-Si) Amorphous silicon (a-Si) Cadmium telluride (CdTe) Copper indium diselenida (CIS)	Colorado, U.S	Semi-arid		•	c-Si and p-Si perform better
Carr & Pryor (2004)	Crystalline silicon (c-Si) Laser grooved bureid contact (c-Si) Poly-crystalline silicon (p-Si) Triple junction amorphous (3j a-Si) Copper indium diselenide (CIS)	Perth, Australia	Temperate (16.5^oC and 28^oC)	•	•	Thin-film modules generate the most energy in this site
Kasim (2005)	Amorphous silicon (a-Si) Mono-Crystalline (mono-Si) Multi-Crystalline (multi-Si)	Malaysia	hot-humid tropical (42^oC)		•	a-Si give highest normalized yield power. a-Si worked best in equatorial climate counrty
Jansen, Kadam & Groelinger (2006)	Amorphous silicon (a-Si) Crystalline silicon (c-Si)	Florida, U.S	Hot coastal (31^oC - 36^oC)		•	low temperature coefficient, thermal annealing, and blue light absorption – help a-Si outperform c-Si technology