

A Comparative Study and Performance Analysis of Poly and Mono Si Photovoltaic Modules

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August 2019

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A thesis submitted to the Department of Electrical and Electronic Engineering in partial
fulfillment of the requirements for the degree of
Master of Science in Electrical & Electronic Engineering



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August 2019

Declaration

It is hereby declared that

1. The thesis submitted is my own original work while completing degree at Brac University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

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Approval

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Abstract

Interest on generating power from photovoltaic (PV) system is increasing day by day. This study investigates the performance of commercially available poly and mono Si photovoltaic (PV) modules under different temperature and illumination conditions. While mono Si module shows better solar cell features in terms of series resistance, reverse saturation current and fill factor. On the other hand, the photo generated current and output power of mono Si module are found to be much lower than those obtained with poly Si module. Lower photo-generated current in mono Si module is attributed to higher recombination in thick bulk layer of mono Si cell, which is probably due to the lower than required crystal grade of mono Si module. Furthermore, the performance of power generation from PV systems can be affected by certain factors which can be detected early by proper monitoring technique. Infrared (IR) thermography is a well-known non-destructive technique which can detect localized heating and identify hotspot. In this study active thermography has been applied to detect possible anomalies considering visual inspection. One of the main findings is that PV modules have some defects which is visually observable. Junction box creates heat that may impact on the module performance. The findings of this work suggest the importance of preventive maintenance for quality control of commercially available PV modules.

Keywords: PV module; temperature; series resistance; comparative study; defect; infrared thermography.

Dedication

This study is wholeheartedly dedicated to my beloved parent, who have been my source of inspiration and gave me strength when I thought of giving up.

Acknowledgement

At first I would like to offer my heartiest gratitude to my thesis supervisor Prof. Dr. Md. Mosaddequr Rahman. His sage advice, insightful criticisms, and patient encouragement aided the writing of this thesis in innumerable ways. I would also like to thank my co-supervisor Prof. Dr. Shahidul Islam Khan, Chairperson of the EEE department, whose steadfast support of this work was greatly needed and deeply appreciated. Also I am thankful to Mr. Atiqul Islam for his support with the thermal camera. Lastly, I have acknowledged the all kind of support and funding provided by the department of EEE, Brac University.

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List of Acronyms

PV	Photovoltaic
FF	Fill Factor
STC	Standard Test Condition
NREL	National Renewable Energy Laboratory
IEC	International Electrotechnical Commission
IRT	Infrared Thermography
PID	Potential Induced Degradation
AM	Air Mass
MJ	Multi-junction
PVSC	Perovskite
BHJ	Bulk hetero-junction
PSC	Polymer Solar Cell
MPP	Maximum Power Point
CIGS	Copper Indium Gallium Diselenide

List of Symbols

q	Electronic charge
E_g	Bandgap
I_{SC}	Short circuit current
V_{OC}	Open circuit voltage
I_s	Saturation Current
η	Efficiency
n	Ideality factor
R_{sh}	Shunt Resistance
R_s	Series Resistance
I_{ph}	Light generated current
K	Boltzmann's constant
T_C	Cell temperature
G	Solar irradiance
N_P	No. of cell in parallel
N_S	No. of cell in series
IRT	Infrared Thermography

Chapter 1

Introduction

1.1 Introduction

The entire world is facing a challenge to overcome the hurdle of energy crisis. Fossil fuel resources are decreasing while the world energy consumption is increasing day by day. Moreover, the consumption of fossils fuels causes air pollution and also may contribute to climate change. Renewable energy resources will be an increasingly important part of power generation in the new millennium. Solar energy has the largest potential among all renewable energy resources. The average solar power resource on the earth's surface is 36,000 billion watts ($3.6 \times 10^4 \text{ TW}_{\text{avg}}$) when the wind power resource is $72 \text{ TW}_{\text{avg}}$, geothermal power resource is $9.7 \text{ TW}_{\text{avg}}$ [1]. Today solar energy is captured through two technologies: photovoltaic (PV) modules and solar thermal collectors. This work concerns the first type of solar energy converters: PV modules. These types of modules directly convert solar radiation into electricity. Although PV has been known since more than a hundred years, it is evolved considerably as a renewable energy in recent years. PV systems are easy to install. They are simple in design and require less maintenance [2, 3]. There are three main types of PV modules: mono silicon, poly silicon and amorphous. In this study performance analysis has been carried out for mono and poly Si photovoltaic modules.

1.2 Background

Now a days, Photovoltaic (PV) modules are widely used to meet the ever-growing energy demand. Among all the renewable sources, solar energy is the most readily available energy source. The conversion of solar energy into electricity using PV modules is simple, noise-free and needs little maintenance. This has led to the widespread popularity of PV modules in

electricity production not only in rural and remote areas, but also in urban areas. To promote the use of Renewable Energy to meet the increasing demand of electricity, Bangladesh Government has already launched "*500 MW Solar Power Mission*" [4]. This policy has led to widespread import and manufacturing of PV modules. The modules that are available commercially are predominantly based on silicon technology and come in two different crystalline forms, mono-crystalline and polycrystalline. While the price of the mono-crystalline module per watt is higher than that of the polycrystalline module, the crystal structure and the other cell properties of mono-crystalline cells give better output than the polycrystalline solar cells [5].

Performance of a solar cell in outdoor operation is affected by various parameters [6] such as, temperature, wind-speed and dust density. From these factor, temperature is one of the important factors that significantly affect the module performance [7]. This works aims to carry out a systematic study of commercially available mono-crystalline and ploy-crystalline Si PV modules, in order to determine how they will perform in actual environmental condition.

Defects and cracks are very much detrimental to the PV performance and their detection is necessary before ultimate failure [8]. Among different methods and non-destructive testing techniques, infrared (IR) thermography plays a vital role in defect detection of photovoltaic cells and modules. This method is simple, fast and can be implemented with a handheld portable equipment [10].

Long term performance of PV modules can be drastically affected by faults mainly occurring in field condition. However, it can also occur during the post-manufacturing stages of transportation and installation [9]. Defects can be observed in both new and in used PV modules, without interrupting the operation of the rest of the PV system. Degradation or defects such as cracks or interconnection mismatches in solar cells are a major problem for PV

modules. This kind of defects cause high temperature area known as hotspots [11]. In this work, two poly and mono Si modules have been used to assess the performance analysis.

1.3 Aims and Objective

This work investigates the performance of commercially available poly and mono Si photovoltaic modules under different temperature and illumination under indoor conditions that will enable to assess their outdoor performance. Also Infrared thermography is used to identify defects and analyze the comparative performance of poly and mono Si PV modules.

1.4 Scope of the Work

The focus of this study is performance analysis between two commercially available photovoltaic modules. Here two poly and mono Si photovoltaic modules have been used for comparative study while varying the temperature over the range in 25 °C to 50 °C. In this study temperature effects have been analyzed in an indoor experimental set up. The experiment is conducted in indoor to make a suitable environment and to collect the data easily. In an outdoor environment the irradiation and ambient temperature fluctuate vibrantly. Also a thorough investigation has been carried out using infrared thermography. Active thermography is used to examine the PV defects and faults. This study can help the concerns to understand the quality of available modules and to take proper steps.

1.5 Outline of the Thesis

The book is structured as follows: **Chapter 2** presents the literature reviews; Theoretical background of Solar cell is discussed in **Chapter 3**. **Chapter 4** describes the basic of Infrared Thermography; **Chapter 5** describes the experimental setup and methodologies for this study **Chapter 6** provides Results Analysis and discussions and finally **Chapter 7** provides the Conclusion and Future Works.

Chapter 2

Literature Review

Different researches and scientists have worked on the performance evaluation of photovoltaic module under different conditions. Module temperature affects the output of PV modules. The temperature effect of the module output has been reported by different researchers [12-15]. Meneses-Rodriguez et al. investigated the effect of ambient temperature on PV modules for three years and found a linear behavior between output power and ambient temperature [15]. Michael J Morgan et al. proposed a simple experimental method for analyzing the I-V and P-V characteristics of silicon solar cells. This method is still using for measuring the PV cell or module characteristics [16]. Ewan D. Dunlop et al. showed the influence of outdoor weathering on performance of 40 silicon crystalline based PV modules from six different manufacturers. These module were tested by authors after 20-22 years of continuous operation at outdoor environments. It was observed that, there is degradation in the performance levels [17]. A. Hunter Fanney et al. compared the operating characteristics of three different PV modules that were tested in the outdoors at the National Institute of Standards and Technology (NIST) and Sandia National Laboratories (SNL) [18]. Bashir et al. conducted a comparative performance evaluation of three commercially available photovoltaic modules (monocrystalline, polycrystalline, and amorphous silicon) in Taxila, Pakistan. The authors were able to conclude that output power of modules increases linearly with the increase in solar irradiance [19]. To identify the more appropriate PV module technology, a series of performances of the two PV module technologies as part of the main grid-connected PV system installed in Pristina, Kosovo, were consequently measured during twelve months. The objective of this study is to compare the performance of two PV module technologies (m-Si and p-Si) operating under the same fluctuations of solar irradiance and mild continental climatic conditions of Kosovo [20]. Akhmad *et al.* [21] investigated the outdoor performance of polycrystalline and amorphous

silicon module and found that amorphous silicon module has better efficiency and output power in summer. A similar study was conducted by Midtgard et al at the site of Norway to investigate the performance of three PV modules (monocrystalline, polycrystalline, and micromorphsilicon). They concluded that monocrystalline module was better in terms of module efficiency and overall power production [22]. A summary of recent studies about the PV failures is provided in [23].

Infrared thermography (IRT) has been used for detecting shunts in solar cells under reverse bias in the dark since 1990 [24]. A significant amount of published research studies have been reported in the literature through the last decade [25]. In the early steps of such studies investigated under outdoor conditions. For PV array-scale applications, IRT is used to assess the condition of a building integrated, grid-connected PV array [26].

The importance of further interpretation of the thermal images and the correlation between performance degradation, fault types and thermal signatures of PV modules was introduced in [27-32].

Experimental results and observations presented in several recent studies focused on the need for better understanding of the degradation and their interrelation with the resultant thermal signatures of PV modules, obtained by field measurements. The degradation impact on the thermal signature can be investigated following either real-time exposure to field conditions or accelerated-time ageing in an environmental chamber [33-36]. Moreover, IRT observations of aged PV modules, after longer field exposure periods (18-22 years), were made in [34,35]. IR thermography was proved an effective and reliable tool for diagnosis of occurring and propagating defects, particularly revealing the existence of hot cells, hot spots on the busbars, and optical degradation in the form of colder bubbles (delamination). Accelerated ageing tests, by thermal cycling, were attempted in [36], in order to study the propagation of existing hot

spots and the evolution of abnormal thermal signatures, through the module's lifetime. One study proposed hot spot evaluation procedures and well defined acceptance/rejection criteria, on the basis of several observations of 200 field exposed and defective modules [37]. These evaluation procedures address both the lifetime and the operational efficiency of the modules. Advances in the field of fault analysis and characterization for installed PV modules, based on IRT imaging, were recently reported in [38, 39]. All investigated faults were distinguished by the authors as three different types; areal/planar defects, cell defects ,where an individual cell is heated up, and point-shaped defects which are considered much smaller (e.g. solder joints).

Considering that IRT is a relatively new method, especially for fault diagnosis of PV modules, the need of reliable measurements and accurate interpretation of the inspected thermal signatures becomes increasingly important. A missed fault diagnosis, either as nondetected fault or as “false alarm” may lead to wrong performance assessment and maintenance decisions. For these reasons, the upcoming international standards and technical specifications of IRT for PV applications (IEC 60904-12, IEC 60904-14 and IEC 62446-3) should be established and followed [40, 41].

To assess the performance of PV modules, indoor based analysis has been chosen in this work. There are several studies which are done in outdoor condition. But to maintain a controlled weather condition indoor based study is suitable. Moreover, infrared thermography can additionally help in this assessment of PV modules to better understanding of their performance.

Chapter 3

Solar Cells: Behavior and Properties

This chapter covers the theoretical background of solar photovoltaic. The basic operation of the photovoltaic cell is discussed in brief. Also the extracted parameters of PV module is described. The electrical circuit model is described along with the reverse saturation current and ideality factor calculation method. Furthermore effects of resistance, temperature and irradiance are also explained.

3.1 Description of a solar cell, module and array

Solar cells are made up with semi-conductor materials. A solar cell can be represented as a diode sensible to light. When a photon with sufficient energy knocks an atom on part of the diode, it excites the electrons and pulls it out from its molecular structure, creating a free electron on this part. The material is made up such as the excess of energy will be used by the electron to go through an external circuit. Solar cell produces continuous current, but its energy yield will be in function to the sun light received by the cell primarily [42].

In fact the semi-conductor are poor electrical conductors. So they must be doped by adding impurities in such material to increase its electrical conductivity. Thus, by diffusing phosphorus or boron (impurities) in the silicon material, electron-hole pairs that are separated spatially by an internal electric field is created into the semiconductor on either side of an interface known as a p-n junction. This process is called doping. It creates negative charges on one side of the interface and positive charges are on the other side (Figure 3.1). The resulting charge separation creates a voltage. When the two sides of the illuminated cell are connected to a load, current flows from one side of the device via the load to the other side of the cell [42].

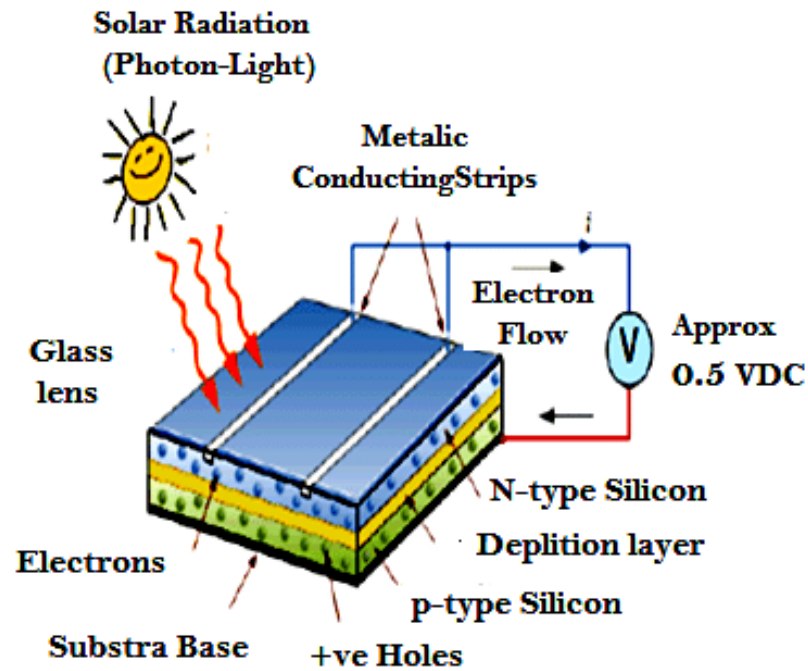


Figure 3.1. Basic Structure of Solar Cell

The basic steps in the operation of a solar cell are [43]:

- the generation of light-generated carriers;
- the collection of the light-generated carries to generate a current;
- the generation of a large voltage across the solar cell; and
- the dissipation of power in the load and in parasitic resistances.

A PV module consists of many PV cells wired in parallel to extend current and in series to provide a better voltage. The module is encapsulated with tempered glass on the front surface, and with a protective and waterproof material on the back side. The edges are sealed, and an aluminum frame holds everything together in a mountable unit. At the back of the module, a junction box holds all the electrical connections. In a PV panel, large series–parallel connections are established in order to improve the available amount of output power.

3.2 Solar Cell Materials

The various types of materials applied for photovoltaic solar cells includes mainly in the form of silicon (single crystal, multi-crystalline, amorphous silicon), cadmium-telluride, copper-indium-gallium-selenide, and copper-indium-gallium-sulfide [72]. On the basis of these materials, the photovoltaic solar cells are categorized into various classes as shown in Figure 3.4.

The 1st generation comprises photovoltaic technology based on thick crystalline films, namely cells based on Si, which is the most widely used semiconductor material for commercial solar cells (~90%) of the current PVC market [71]), and cells based on GaAs, the most commonly applied for solar panels manufacturing. These are the oldest and the most used cells due to their reasonably high efficiencies, albeit are relatively expensive to produce.

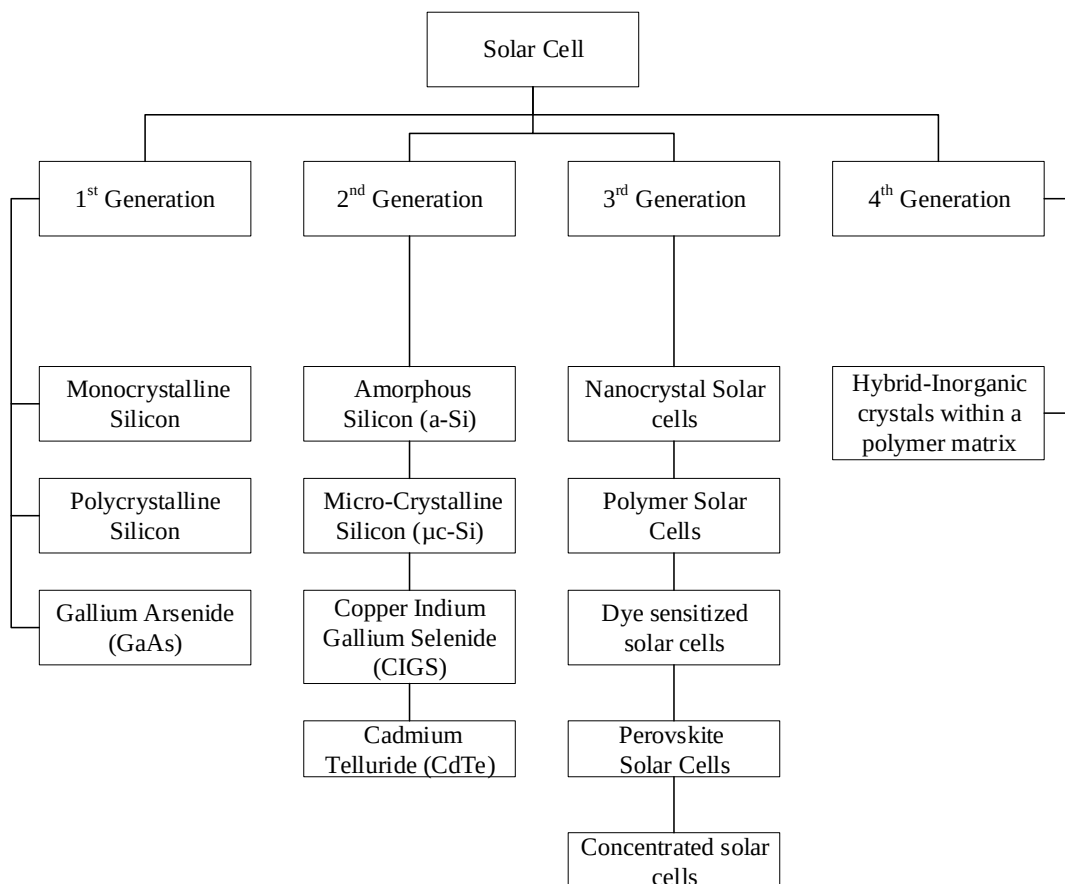


Figure 3.2 Solar Cell Technologies and current trends of development [72]

The 2nd generation focuses on thin-film technologies with the aim of reducing the high costs associated with the 1st generation by using lower amount of material and of poorer quality, deposited on cheap substrates. It is based on materials identified as potentially useful during the development of the 1st generation and was extended to include a-Si, μ c-Si, CIGS, and CdTe [73].

The 3rd generation arises from the idea of increasing device efficiency and reducing the distance to the Carnot limit, which is ~62% above the Shockley- Queisser limit (33%) [74]. Its aim is to develop devices with high efficiencies using the thin layer deposition techniques employed for the 2nd generation and/or new architectures or materials; this may lead to an increment in the area cost, but the cost per watt peak would be reduced. In addition, like Si- based cells, 3rd generation- PVCs use non- toxic and very abundant materials, hence are suitable for the large- scale implementation of photovoltaic cells. Further, they may employ new nanostructured or organic materials that could achieve high conversion efficiencies (greater than 60%) using phenomena such as the hot carriers collection [74], the generation of multiple carriers (impact ionization), or new semiconductor architectures that contain multiple energy levels. Considerable attention is paid to charge and energy transfer processes, and routes to optimize charge collection and improve the energy capture within the solar spectrum [75].

The 4th generation combines the low cost/flexibility of polymer thin-films with the good stability of nano-materials like metallic nanoparticles, metal oxides, carbon nanotubes, graphene, and its derivatives. These architectures will maintain the advantage of solution processable devices, hence cheap manufacture, but also incorporate nanomaterials to improve the charge dissociation and charge transport within the cells. In particular, special emphasis is placed on graphene (G), which has become the nanomaterial with the highest scientific and technological expectations.

Solar cells are usually categorized by the materials comprising the cells. Silicon solar cells and thin film solar cells are common and commercially available. This includes expensive mono-crystalline Si, polycrystalline Si solar cells and comparatively less expensive thin film solar cells. Other emerging solar cell technologies are currently under development and mass production and reliable lifetimes cannot yet be achieved. A summary of the photovoltaic technologies, production methods, characteristics and efficiencies attained is given in Table 3.1.

Table 3.1 Summary of PV technologies [76]

Gen.	Technology	Production Method	Characteristics	Efficiency (%)
1 st	m-Si	Czochralski	Expensive, Stable	24.4
1 st	p-Si	Siemens	Low cost, high defect content	19.9
1 st	GaAs	Expitaxial Growth	Expensive, good design control	18.4-28.8
2 nd	a-Si	Large area deposition	Non-toxic, short life cycle	10.2-12.7
2 nd	μ c-Si	Roll to roll	Low defect content, good degradability	11.9-14.0
2 nd	CIGS	Deposition, co-evaporation	Tunable band gap	22.3
2 nd	CdTe	Deposition	High temperature tolerance	21.0
3 rd	DSSC	Roll to roll	Work in low light conditions	5.0-20.0
3 rd	QDs	Solution Casting	Efficient conductivity	11.0-17.0
3 rd	OPSCs	Solution Casting	Thermally stable	9.7-11.2
3 rd	PVSC	Sputtering/Printing	Cheap ,simple	21.1-21.6
3 rd	MJ	Stacking	Wide range of design	35.8
3 rd	IMM	Monolithic growth	High band gap, cheap	40.0-44.4
4 th	BHJ PSC with GO/PEDOT:PSS	Solution casting	Stable	4.28
4 th	PSC with G/PEDOT:PSS	Solution casting	Good functionality	2.82-11.8
4 th	PVSC with Li-GO	Spray deposition	Long lifetime	1.07-11.14
4 th	PVSC with rGO/PEDOT:PSS	Solution casting	Reduced electron hole recombination	5.7-11.95
4 th	PSCs with B-doped CNTs	Solution Casting	Improved electron transport	4.1-8.6

MJ: Multi-junction, IMM: Inverted metamorphic multi-junction, BHJ: Bulk hetero-junction, PSC: polymer solar cell, PVSC: Perovskite.

Mono-crystalline Silicon Solar Cells

Mono-crystalline Si (c-Si) solar cells, also called single-crystal Si solar cells, are usually made from single crystal silicon wafers with high purity silicon. They have the advantages of high efficiency and a long lifetime. Most commercial solar modules have efficiencies of more than 15% and a 20-year expected lifetime. A premium commercial solar panel from SunPower Inc. can achieve efficiency as high as 20.4% [59]. From this perspective, this type of solar cell is ideal for residential use. However, because this type of solar cell is made from single crystalline silicon wafers, it is relatively expensive. From Fig. 3.5 visual difference between the cells is observed.

Polycrystalline Si Solar Cell

Poly-crystalline Si, also known as multi-crystalline silicon (mc-Si), is produced by casting and cooling molten silicon, followed by a cutting process to make a silicon wafer. A polycrystalline silicon solar cell is made from such a silicon wafer. This process is less expensive than growing mono-crystalline silicon, so the cost of polycrystalline silicon solar cells is much lower than mono-crystalline Si solar cells. Polycrystalline solar cells are slightly lower in efficiency. However, the ease of production and resulting lower cost make them commercially viable [60].

3.3 Basic Solar Cell Theory

3.3.1 Single Diode Model

The solar cells are basically semiconductor p-n junctions fabricated in a thin layer of semiconductor materials. When it is exposed to light a photo current is generated. The photo current is proportional to the solar radiation. The equivalent circuit of the single diode PV cell is shown in Fig. 3.6 where a constant current source I_{ph} representing the light-induced current

generated in the cell is in parallel with a diode representing the pn junction. R_s represents series resistance and R_{sh} represents the shunt resistances of the cell. The output current (I) of the PV module can be expressed as equation (3.1) [46].

$$\begin{aligned} I &= I_{ph} - I_D - I_{R_{sh}} \\ &= I_{ph} - I_s \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V+IR_s}{R_{sh}} \end{aligned} \quad 3.1$$

In the above equation, I_s is the reverse saturation current, q is the charge of an electron, V is the output voltage of the PV cell, n is the ideality factor of the p-n junction and k is the Boltzmann's constant. . For a complete PV panel, I can be calculated as follows [48-51]:

$$I = N_p I_{ph} - N_p I_s \left(e^{\frac{q(N_p V + N_s I R_s)}{N_p N_s n k T}} - 1 \right) - \frac{N_p V / N_s + I R_s}{R_{sh}} \quad 3.2$$

where N_p is the number of PV cells connected in parallel with one other and N_s is the number of PV cells connected in series with one other. It is worth noting that there are several equations needed to fully calculate the equivalent circuit of PVs [51–54].

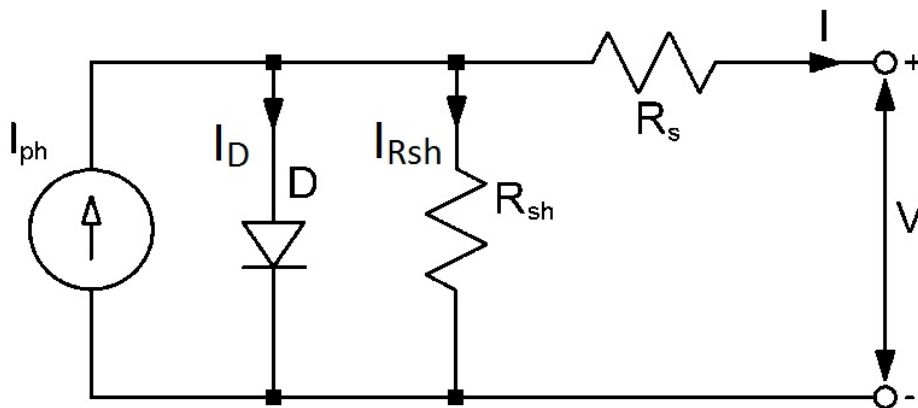


Figure 3.3. Equivalent circuit diagram of a solar cell using single diode model.

3.3.2 Calculation of cell parameters

Short Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC} , the short-circuit current is shown on the I - V curve below in Figure 3.7.

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell. [43]

Open Circuit Voltage

The open-circuit voltage, V_{OC} , is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open circuit voltage is shown on the I - V curve.

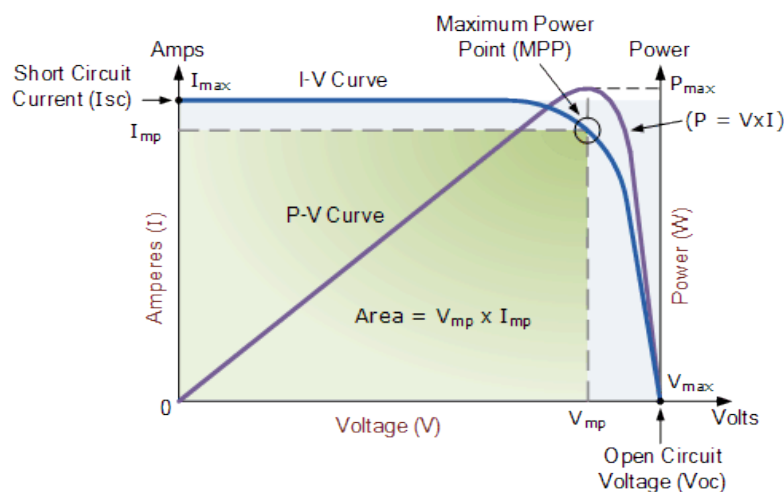


Figure 3.4. I - V and P - V curve of a solar cell showing the open circuit voltage, short circuit current and maximum power point

An equation for V_{OC} is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{nKT}{q} \ln\left(\frac{I_{Ph}}{I_S} + 1\right) \quad 3.3$$

The above equation shows that V_{OC} depends on the saturation current of the solar cell and the light-generated current. While I_{SC} typically has a small variation, the key effect is the saturation current, since this may vary by orders of magnitude. The saturation current, I_S depends on recombination in the solar cell. Open-circuit voltage is then a measure of the amount of recombination in the device. Figure 3.7 shows the V_{OC} and I_{SC} point of a conventional solar cell.

Fill Factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{OC} and I_{SC} , determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{OC} and I_{SC} . Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the I - V curve. It shows the influence of the serial resistance on efficiency of solar cell, in other words, it shows how much the solar cell is close to ideal one [44,58]. The FF is illustrated in Fig. 3.7.

As FF is a measure of the "squareness" of the I - V curve, a solar cell with a higher voltage has a larger possible FF since the "rounded" portion of the I - V curve takes up less area. The variation in maximum FF can be significant for solar cells made from different materials. The

FF is most commonly determined from measurement of the I - V curve and is defined as the maximum power divided by the product of I_{SC} * V_{OC} , i.e.:

$$FF = (V_{MP}I_{MP}/V_{OC}I_{SC}) \quad 3.4$$

Efficiency

Efficiency is one of the most common words which are used to apply in the solar cell application. Efficiency is the ratio of output and input. In solar cell the ratio of output of the cell and the input of the sunlight is the solar cell efficiency. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Conditions needs to measure very carefully from one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions.

Efficiency can be determined by:

$$P_{max} = V_{OC}I_{SC}FF \quad 3.5$$

$$\eta = \frac{V_{OC}I_{SC}FF}{P_{in}} \quad 3.6$$

Where V_{OC} is the open-circuit voltage;

I_{SC} is the short-circuit current; and

FF is the fill factor

η is the efficiency.

Reverse Saturation Current Calculation

Under open circuit condition, voltage $V=V_{oc}$ and current $I=0$. Then Eq. (1) can be as,

$$I_{SC} = I_s \left(e^{\frac{q V_{oc}}{n k T}} - 1 \right) \quad 3.7$$

From equation (3.7) reverse saturation current at any reference temperature can be expressed as equation (3.8), after ignoring the -1 inside the bracket on the right,

$$I_s = \frac{I_{SC}}{e^{\frac{V_{oc}}{n V_t}}} \quad 3.8$$

where, $V_t = \frac{kT}{q}$ is the thermal voltage.

At a new temperature T_i , the reverse saturation current can be calculated as [47],

$$I_{S(new)} = I_{S(ref.)} \left(\frac{T_i}{T_o} \right) \exp \left(\left(\frac{-E_g}{k/q} \right) * \left(\frac{1}{T_i} - \frac{1}{T_o} \right) \right) \quad 3.9$$

where T_o is the initial temperature and $I_{S(ref.)}$ is the reverse saturation current at the initial temperature T_o .

Ideality Factor Calculation

If the I - V measurement of the panels are taken at two different illumination levels while keeping the panel surface temperature constant, then Eq. (3.8) can be written as,

$$I_{SC1} = I_s \left(e^{\frac{q V_{oc1}}{n k T}} \right) \quad 3.10$$

$$I_{SC2} = I_s \left(e^{\frac{q V_{oc2}}{n k T}} \right) \quad 3.11$$

Here I_{SC1} , V_{OC1} and I_{SC2} , V_{OC2} are short-circuit current and open-circuit voltage, respectively, for two different illumination levels.. It is assumed that the reverse saturation current remains same for the two illumination levels as the surface temperature of the panel is kept constant.

Solving equation (3.10) and (3.11), the ideality factor, n , of the cell can be expressed as,

$$n = \frac{(V_{OC1} - V_{OC2})}{V_t \ln \frac{I_{SC1}}{I_{SC2}}} \quad 3.12$$

3.3.3 Effects of temperature and irradiance on the module performance

The output of a module is obviously directly proportional to the incident irradiance; a high module temperature in turn impacts negatively on the performance of a module. Roughly speaking, the module current is dependent on the incident irradiance and independent on the module temperature, and for the module voltage the situation is reversed. The higher the intensity of radiation incident on a solar module, the more there are photons to excite electrons in the semiconductor and hence the higher is the current; the short circuit current is almost directly proportional to the incident irradiance.

However, as may be seen from equation, the open circuit voltage has a logarithmic dependence on the I_{SC} and thus also on the irradiance. Thus the voltage increases only slightly with increasing irradiance. When the module temperature increases, the reverse saturation current across the p-n junction increases and the band gap energy decreases. This results in a decrease in the module voltage. On the other hand, due to the smaller band gap there are more electrons excited to the conduction band, and thus the module current increases slightly [56].

3.3.4 Resistive Effects on the module performance

Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. The most common parasitic resistances are series resistance and shunt resistance. In most cases and for typical values of shunt and series resistance, the key impact of parasitic resistance is to reduce the fill factor. Both the magnitude and impact of series and shunt resistance depend on the geometry of the solar cell, at the operating point of the solar cell. Since the value of resistance will depend on the area of the solar cell, when comparing the series resistance of solar cells which may have different areas, a common unit for resistance is in Ωcm^2 .

Series resistance in a solar cell has three causes: firstly, the movement of current through the

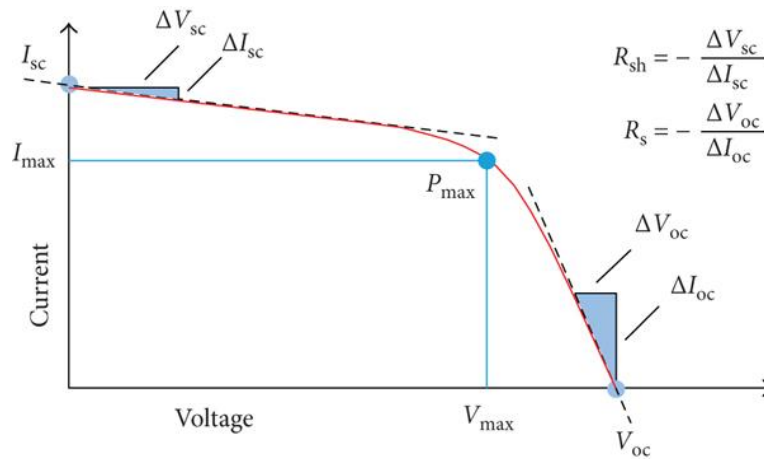


Figure 3.5 Series and shunt resistance calculation method

emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current as shown in Eqn. 3.13 [57].

$$I = I_{ph} - I_s \left(e^{\frac{q(V+IR_s)}{nkT}} \right) \quad 3.13$$

where: I is the cell output current, I_{ph} is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, n is the ideality factor, and R_s is the cell series resistance. The formula is an example of an implicit function due to the appearance of the current, I , on both sides of the equation and requires numerical methods to solve.

However, near the open-circuit voltage, the I - V curve is strongly affected by the series resistance. A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the I - V curve at the open-circuit voltage point.

Significant power losses caused by the presence of a shunt resistance, R_{sh} are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large. The equation for a solar cell in presence of a shunt resistance is [58]:

$$I = I_{ph} - I_s \left(e^{\frac{qV}{nkT}} - 1 \right) - \frac{V}{R_{sh}} \quad 3.14$$

Where: I is the cell output current, I_{ph} is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, n is the ideality factor, and R_{sh} is the cell shunt resistance.

An estimate for the value of the shunt resistance of a solar cell can be determined from the slope of the I - V curve near the short-circuit current point. The impact of the shunt resistance on the fill factor can be calculated in a manner similar to that used to find the impact of series

resistance on fill factor. The maximum power may be approximated as the power in the absence of shunt resistance, minus the power lost in the shunt resistance.

Chapter 4

Infrared Thermography Based Fault Detection of Solar Cells

4.1 Heat Development in PV Module

Heat transfer occurs by three basic mechanisms, i.e., conduction within solids, convection between a solid surface and a fluid, and radiation from solids. All of three modes of heat transfer are involved in an operating PV module. During the active approach of IR thermography measurement, step heating thermal stimulation, by means of conductive heat transfer process, is applied to identify defects on the inspected module's surface [35]. It is a useful tool for detecting defects during the manufacturing process. In this method sample module is heated for a specific period of time in a dark environment. The aim is to achieve a temperature difference (2 °C-5 °C) between the sample module and the ambient temperature. In principle, a significant difference between these two values, resulting to a ΔT value over 5 °C, can be indicative of a hot spot, as a result of a possible defect [46].

4.2 Faults and Hotspots in PV Module

To assess their performance over time and therefore their lifetimes, it is important to identify modes of degradation failure for PV modules. The identification of degradation failure modes on PV modules is important to evaluate their performance along time and so their lifetime. The functioning capability within the suitability standards describes the lifetime of the PV module. The main causing factors for degradation are temperature, humidity, irradiation and mechanical shock. Dismantling causes can be divided widely into three levels: packaging, interconnection and equipment. Over time, module power degradation is built into project expectations and manufacturers warrant. The current 25-year guarantee is typically designed to reduce modules to more than 3% in the first year and 80% of their initial plate power in a linear rate in year 25. [61]. Some suppliers define it as if 80% of the specified power output in standard (STC) test

conditions is achieved by the PV panel. Figure 4.1 shows an elaborated picture of the type of faults that can occur in a PV module [62].

A. Packaging

Glass breakage is very common in persistent exposure modules in the field. According to statement of Djordjevic et al [26], this kind of failure occurs due to internal factors like low encapsulation quality, poor or incorrect lamination and external factors, like high temperature. Degradation due to glass breakage can usually be detected by simply visual inspection or even a naked eye before significant losses occur at the power output of the PV module. The result is an undesirable optical reflection and the reduction of sharp solar flux, resulting in a loss of

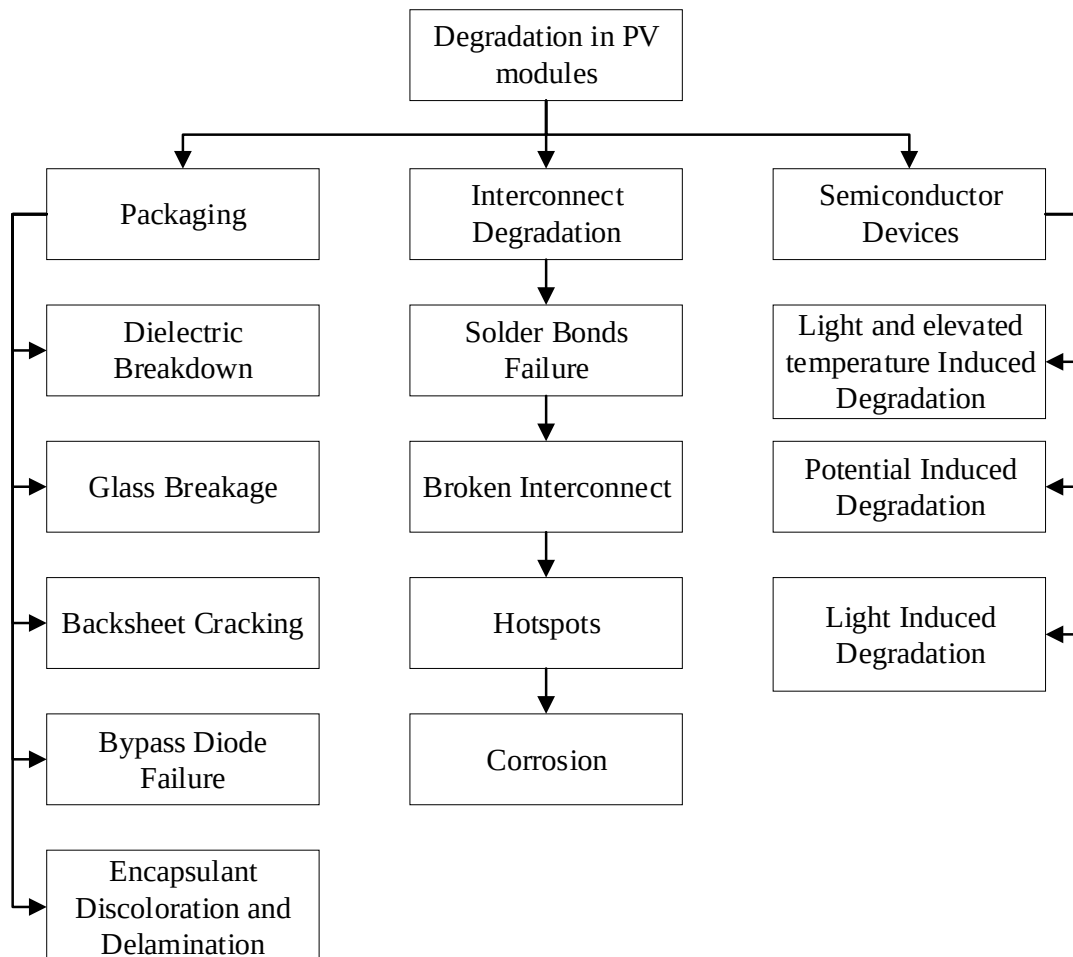


Figure. 4.1: Different possible modes for the degradation of photovoltaic modules from packaging, interconnections and device levels [66]

generated current and thus power output from the defective PV module. If the reverse capacity is restricted by voltage or a low shunt resistance reduces the reverse performance, cells can either have a high shunt resistance. Usually the bypass diode reduces the heating incident. If the PV module does not have a bypass diode, the power output will be lost, which will reduce the working PV module's lifetime. Due to damage in packaging, materials become incapable of giving proper service to the whole system and so degradation occurs that cause loss in every knot of the system making its lifetime shorter.

B. Interconnect Degradation

Hot spot is a term used normally to describe an overheating due to faults in cell. In other words, hotspot is the localized heating phenomena. The most common indicator of solar cell faults, such as cracking, weak soiling, polarization, shading etc. is localized heating [63]. Normally cells display almost uniform current density in reverse bias. In this case the thermal load is distributed over the entire cell and the temperature on the local surface of the cell only increases slightly. Cells that hold a large number of small shunts can usually survive a reverse bias without degradation. Yet, this type of cell will probably exhibit poor current output during cell testing but will not suffer further degradation in the field. By contrast, defective cells with large shunts can handle current flow via a small silicon area which causes high temperature in a few seconds that can damage the cell. The cell properties eventually suffer damage if the maximum temperature is high enough. Mismatch or broken interconnect occurs in the strings of connected cells cause cells to overheat.

At this moment, reverse biased current occurs in the cells and their junctions have to disperse to adjoining media while the incoming solar energy changed into electrical energy approaching from the other part of the arrangement. Depending on the environment temperature, cells or modules reach a thermal equilibrium. When the balance temperature reaches above the

essential value, hot spot occurs. In addition, there can also be hot spots between cells and contact ribbons not or in resistive weld bonds (RSBs). All current must flow through the cell interconnect ribbons and then through distinct solder before finishing flowing in the whole module. Due to field aging, the current fluctuates through a small number of solder bonds rather than all solder bonds failure. Hence, a localized heating at the operating solder bond location occurs due to increased current density. Furthermore, due to corrosion in cells or modules, the power output gets reduced causing loss and degradation.

C. Semiconductor Devices

Potential Induced Degradation is achieved when the voltage and leakage potential of the module leads to ion mobility within the module between the material of the semiconductor and other module elements such as glass, mount, and frame. Luo et al.[64] recently studied PID's causes, shaped the current trajectories of leakages and preventive PID measures in a recent publication. The PID effect can be classified in these categories:

- System level
- Module level
- Cell level

Temperature and humidity environmental parameters are important at the module level. The water interruption into the module increases conductivity and therefore the leakage current. The processing and quality of the basic material are critical at cell level. In large PV systems with silicone crystalline solar cells p - type this effect is stronger. Because the PV module and its structure are potentially different, electrons may discharge from the grounded wires if the insulation is deficient. This generates leak current and causes a progressive deterioration in performance by this electric current induced by this module. In this study, degradation for

packaging, interconnect degradation and junction box have been observed thoroughly. Observation of degradation due to semiconductor devices wasn't done in this study.

On the other hand, three basic mechanisms involve heat transfer, i.e. conduction in solids, convection between a solid surface and a fluid and radiation from solids. All three heat transfer modes are included in the operational PV module. When localized heating in a photovoltaic (PV) module occurs, it is referred to as hotspot [65]. When monitoring with IR camera localized overheating in a PV module is detected as hot-spot, it will have higher temperature compared to rest of the object surface. This might be caused by various kind of cell defects i.e. cracks, cell mismatch, bad soldering etc. During the active approach of IR thermography measurement, step heating thermal stimulation, by means of conductive heat transfer process, is applied to identify defects on the inspected module's surface. It is a useful tool for detecting defects during the manufacturing process. In this method sample module is heated for a specific period of time in a dark environment. The aim is to achieve a temperature difference (3°C-5°C) between the sample module and the ambient temperature. It is to be noted that due to convective heat transfer, a slight temperature gradient of 3–5°C is present within PV module. [46]. In principle, a significant difference between these two values, resulting to a ΔT value over 5°C, can be indicative of a hot spot, as a result of a possible defect .

4.3 Methods for Fault Detection

To identify the degradation mechanisms acting in field aged modules, some of the frequently used techniques [65, 66] are illustrated in Fig. 4.2 and are briefly reviewed. The first step in the failure mode analysis is to evaluate the conditions of the physical location where the PV system is operating. The most used techniques to analyze the modules are described in this section.

A. Field I-V measurements

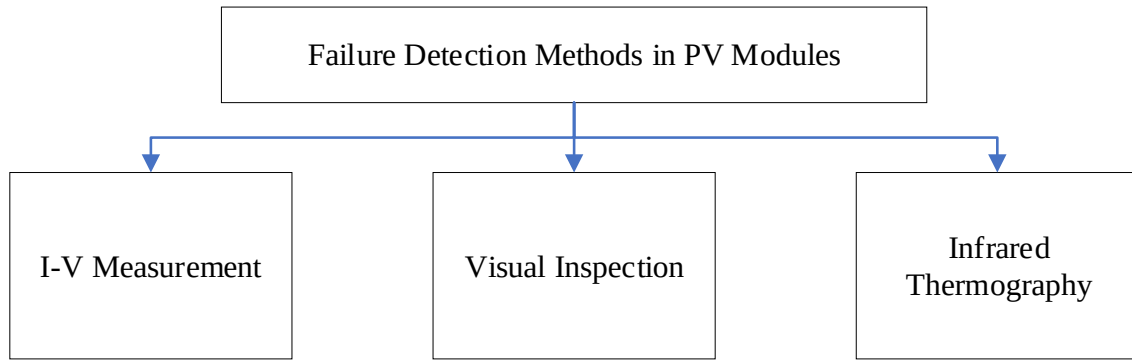


Figure 4.2. Various methods to investigate PV degradation.

Standardized PV module accelerated aging tests and qualification tests are performed to ensure the module stability, lifetime, and performance. The standard test conditions (STC) are

- Irradiance: 1000 W/m^2
- Cell temperature: 25°C
- Spectral distribution of irradiance: AM 1.5G
- Normal incidence over the cell.

B. Visual inspection

In this step of analysis, the modules are inspected for visual defects such as burns, delamination, encapsulant yellowing, corrosion of busbars and interconnectors, and broken glass. It is the first diagnostic step to troubleshoot any mechanical or electrical installation deficiencies and wear and tear on any system component. For future, reference photographs are taken. The inspection should be done in different angles as a way to differentiate the layer where the defect occurred and to avoid reflected images. Visual inspection of a PV module is performed before and after the module has been subjected to environmental, electrical, or mechanical stress testing in the laboratory. Stress tests are usually used to evaluate module designs in the pre-phase of production, production quality, and lifetime of the module [68].

The following failure modes were considered in this study [69]:

- a. Front Glass Damage (Superstrate)
- b. Backsheet
- c. Wires/Connectors
- d. Junction Box
- e. Metallization Browning
- f. Encapsulant Browning
- g. Cell damage
- h. Cell delamination
- i. Cell discoloration

4.4 Infrared Thermography and Approach

Infrared thermography is the process of acquisition and analysis of the emitted radiation without direct contact with an object and converting the acquired data to an image format. IR thermography uses mid-wave (3 to 5 μm) or long wave (7 to 14 μm) infrared sensors. Based on Planck's black body radiation law, all bodies emit IR radiation when their temperature is higher than 0K and is proportional to their temperature. So, IR thermography makes it possible to determine the surface temperature of any inspected equipment. Figure 4.3 shows a process to have a infrared image of PV module.

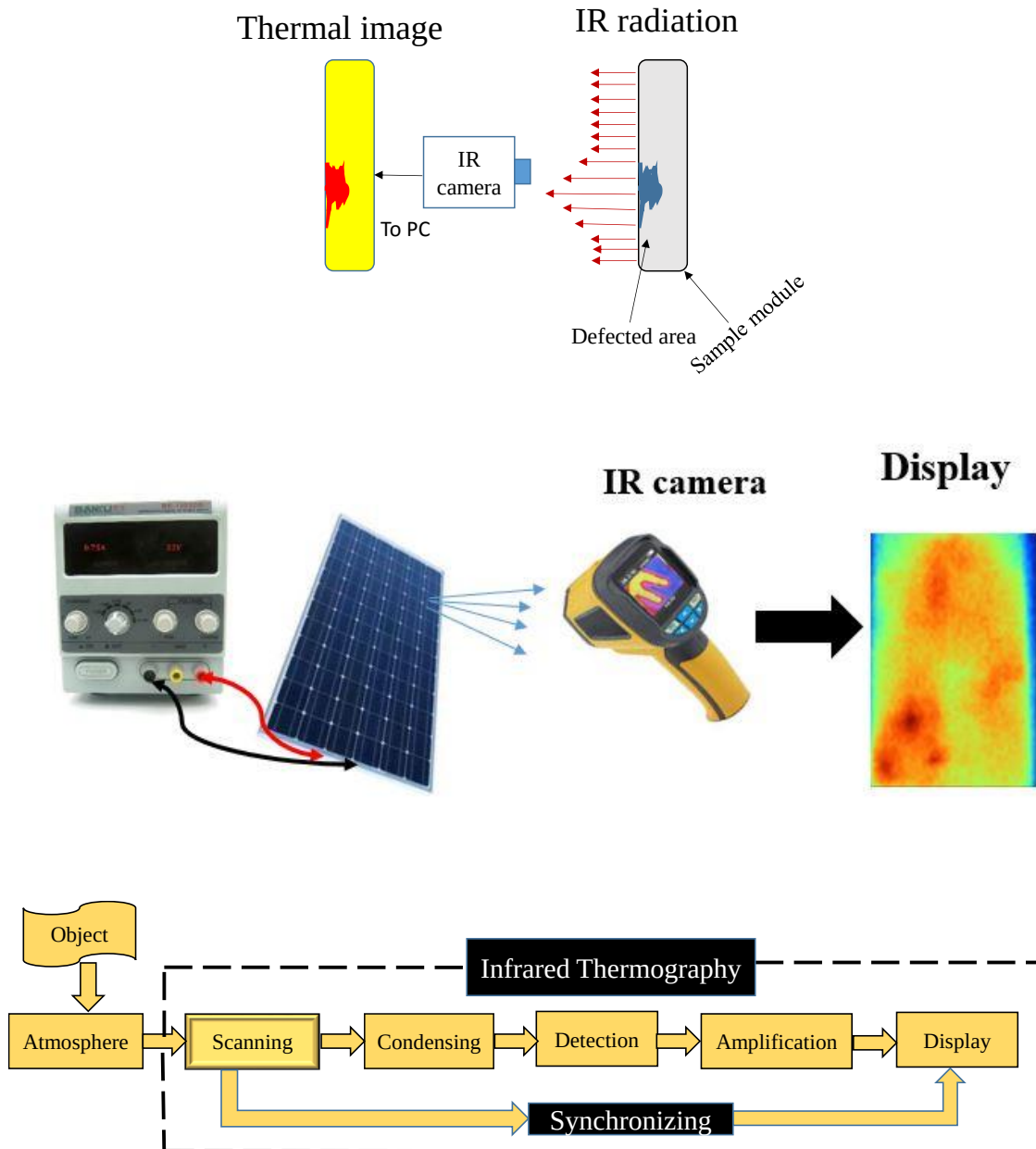


Figure 4.3: Process of capturing infrared image of PV modules

There are basically three different types of thermography methods to detect failures in PV modules. The most common and easiest to apply technique is the thermography under steady state conditions. This method allows the analysis of PV modules in the field under working conditions. The pulse thermography and the lockin thermography allow a more detailed view into the PV module but both techniques need to be done under lab conditions. This thesis thus

used the IRT approach for its inexpensive, portable and fast result. The characteristics of IR thermography is given below:

- i) Temperature is captured as a real temperature distribution, and it can be displayed as a visible information.
- ii) Temperature can be measured at a distance from any object without contact.
- iii) Temperature can be measured in real time.
- iv) It has large dynamic temperature range ($-50^{\circ}\text{C} - 2000^{\circ}\text{C}$)
- v) High accuracy (Minimum Resolvable Temperature Difference $< 0.1^{\circ}\text{C}$)

IR thermography has two approaches i.e. the passive and active approach. In passive thermography, interested areas are naturally at a higher or lower temperature than the background. Abnormal temperature difference indicates a potential defect, and a key parameter is temperature difference with respect to a reference value. This temperature difference is denoted by ΔT . On the other hand, in active thermography, it is necessary to inject current into the specimen inspected in order to obtain significant temperature differences to observe the presence of possible anomalies [11]. In this study active approach of thermography is used to detect the defects. In principle, according to the type of thermal stimulation, there are four active thermographic test procedures:

1. Pulsed thermography
2. Step heating thermography
3. Lock-in thermography
4. Vibro-thermography

Aircraft deficiencies and aerospace components are found in pulsed thermography. Pulsing thermography allows for very rapid inspection of materials for defects and link weaknesses close to the surface. It is a short pulse technique for thermal stimulation. Step thermography is the technique of long-term thermal pulse stimulation. Generating thermal waves through regular heat deposition on the area of the specimen is done by lock-in thermography. Last but not the least; vibro-thermography is the technique where Mechanic vibrations is induced outside the structure leading to friction release of thermal energy.

Chapter 5

Experimental Setup and Methodology

A proper experimental setup is needed to the standard data collection process of a study. At first indoor I-V measurement is done under different temperature and illumination level. The solar module can be tested outdoor but in that case there are many restrictions, as it is not possible to control many parameters i.e. temperature, irradiation etc. while being there. So an indoor system of testing the modules is developed. The system is very simple, where ten bulbs of 200 watt each are placed in a wooden box. The whole box is wrapped with shiny paper from inside so that the light reflected from the box can fall in the solar module. This technique will help to have more illumination on the module and temperature can be controlled. For the IR thermography, the experiment is done to capture the module's hotspot regions. A visual inspection is performed also to collect data about the defects on the surface of modules. A comparison of the real image of the panel with the IR image of the respective panel has been made possible through these two experiment. Also the module's IR 3D histogram has shown the hotspots in the respective module. The whole experimental process and its setup is sectioned in this chapter.

5.1 Setup for I-V measurement of PV module

In order to perform the I-V measurement test under different illumination, a wooden box is fitted with ten incandescent light bulbs of 200 watts each as shown in Fig. 5.1. To measure the ambient and the panel surface temperature, digital temperature sensor DS18B20 is used. Figure 5.2 shows the connection diagram that is used to record the I-V measurement data of the modules. A 100 ohm rheostat is used as the load for the modules. By varying the load resistance, the voltage and current data of testing module are recorded under different temperature and illumination conditions. To measure the open circuit voltage, switch S-1 is

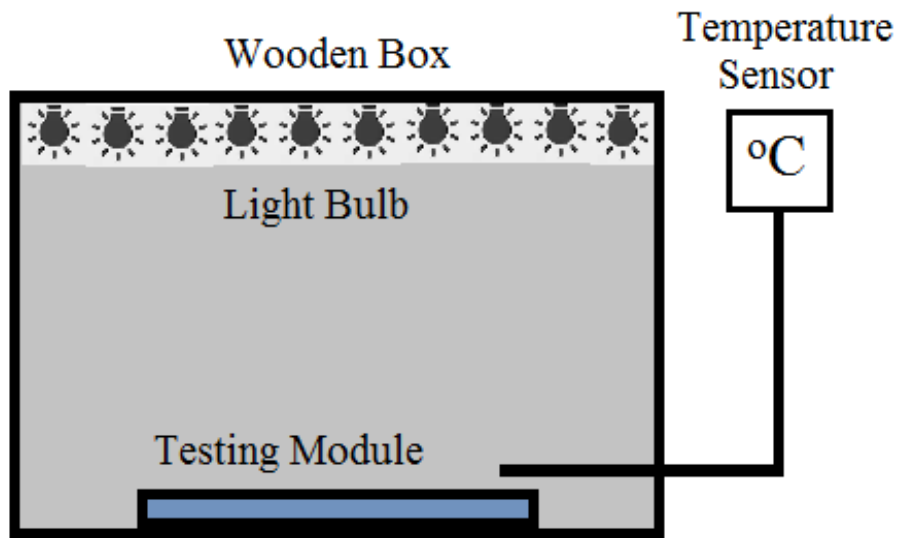


Figure. 5.1. Schematic diagram of the experimental set up for the I-V measurement of the PV modules.

kept open. For the short circuit current, both S-1 and S-2 switches are kept closed. For measurements under standard temperature condition, a temperature of 25°C is maintained with the help of room air conditioner. For measurement at higher temperatures, temperature is first allowed to rise at the desired level in the closed box under illumination and then a fan is used to control the panel surface temperature.

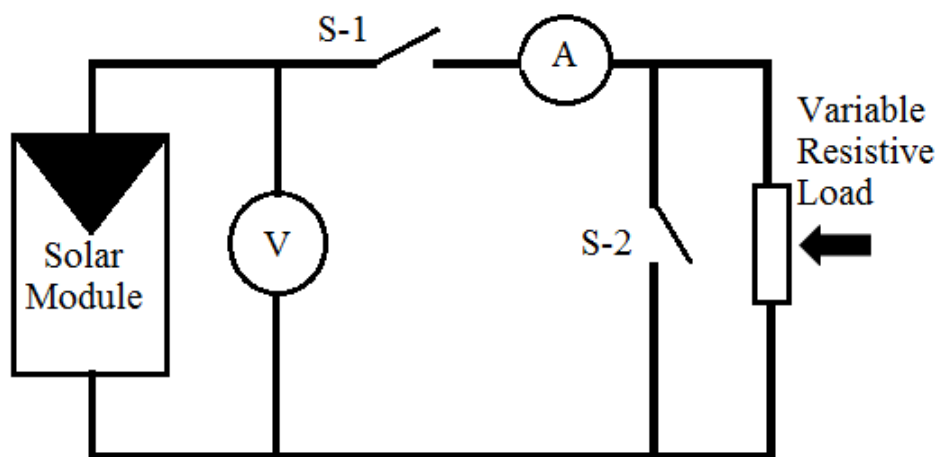


Figure. 5.2. Schematic circuit diagram of experimental setup for I-V measurement of PV module

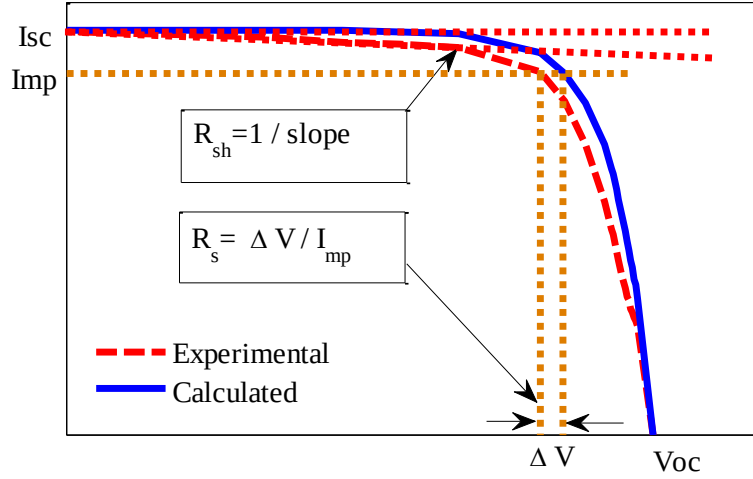


Figure. 5.3. Graphical method to determine series resistance and shunt resistance of PV module

Firstly, I-V measurement data are recorded for two different illumination levels set with four and eight bulbs while maintaining a constant panel temperature. Then I-V data were recorded at a fixed illumination while varying the temperature over the range from 25 °C to 50 °C.

5.2 Determination of Series and Shunt Resistance

Series and shunt resistance of the modules are determined from the I-V characteristics of the two PV modules. In order to determine the series resistance (R_s), first I-V plot of the module is reproduced using Eq. (4.1) for zero series resistance, i.e. $R_s = 0$, and using the same values for I_{sc} and V_{oc} as those obtained experimentally.

$$\begin{aligned}
 I &= I_{ph} - I_D - I_{R_{sh}} \\
 &= I_{ph} - I_s \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V+IR_s}{R_{sh}}
 \end{aligned} \tag{4.1}$$

Figure 5.3 shows the I-V plot of a PV module obtained experimentally (dashed line) at 25 °C with 8 bulbs along with the calculated one (solid line) obtained using Eq. (4.1) with $R_s = 0$. The experimental value of terminal voltage is less than that in the calculated one by the amount ΔV

and represents this amount the voltage drop due to series resistance. The series resistance of the module for the given measurement condition therefore can be calculated as,

$$R_s = \Delta V / I_{mpp} \quad (4.2)$$

Where I_{mpp} represents the current at the maximum power point. As can be seen from Fig. 4.3, the current starts decreasing from its initial value, I_{SC} , as the voltage increases from zero. This loss in current at low voltage is due to leakage of current through the shunt resistance. Therefore, shunt resistance of a module under the measurement condition can be obtained from the I - V characteristics by taking the inverse of the slope at $V=0$, as indicated in Fig. 4.3.

5.3 Setup for PV module inspection using IR Thermography

In this study Fluke TiS 10 infrared camera was used to record the IR images of the PV modules. Table 5.1 presents the specifications of the Fluke TiS 10. This camera can display the object temperature within the range of -20°C to +250°C [70].

An experimental platform was set up as shown in Fig. 5.4. Center to the setup is a wooden box, shown as the shadowed region in the figure, which is used to provide the non- illuminated environment for the sample module. An external DC power supply (30V/3A) was used to

Table 5.1 Specifications of Thermal Imaging Camera

Parameter	Value
IR Resolution	80 x 60
Thermal Sensitivity	≤150mK
Minimum Focus Distance	15cm
Spatial Resolution	7.8mRad
Image Frequency	9Hz
Accuracy	±2°C or 2%

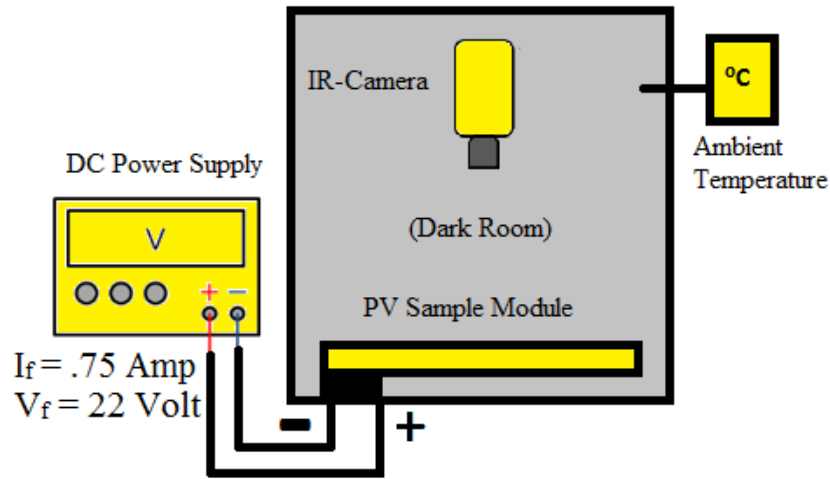


Figure. 5.4. Experimental set-up for inspection of PV modules

provide forward voltage 22 V and forward current 0.75 A to the PV modules. In order to measure ambient temperature using a microcontroller, a digital temperature sensor DS18B20 was used. The distance was set to 1 meter between the camera and the PV module. Three images have been taken for each PV sample. For the image processing purpose, SmartView software, version 4.3 was used. The emissivity of the glass is 0.95. So the infrared camera is adjusted to 0.95 emissivity.

In brief, at first module was placed inside the box. Then it was connected with the DC supply to provide necessary voltage and current for one minute. After that three images were taken for better quality. After taking images of all the modules, images were analysed in image processing software.

Chapter 6

Results and Discussions

6.1 Introduction

In this chapter the performance of poly and mono Si PV modules under different temperature and illuminations have been discussed. Temperature effects on solar module parameters play a vital role of consideration. Here, the different parameter of the solar module is measured using indoor monitoring system, where temperature and illumination of light can be controlled. The main purpose is to understand how this parameter varies with temperature. Such parameters are open circuit voltage- V_{oc} , short circuit current- I_{SC} , series resistance of a photovoltaic module- R_s , shunt resistance- R_{sh} , reverse saturation current- I_{Ro} , maximum power point output- P_{max} , fill factor-FF, maximum working current- I_{mp} , maximum working voltage- V_{mp} .

After that infrared thermography based performance analysis have been studied. Based on the I-V curve, performance degradation assumption is made. Then visual inspection is done. Junction box and the surface temperature of sample PV module are examined to relate the performance with the visual inspection. Finally all the results correlate with the comparative analysis of poly and mono Si modules.

6.2 Comparative Analysis of Poly and Mono Si PV Modules

Firstly different I - V sweep curves have been analyzed for different temperature and illumination conditions. Then the different extracted and output parameters are discussed in a comparative way.

6.2.1 I-V Sweep Curves of PV Modules at Different Temperature

From the indoor testing set up a total of six sets of voltage and current data have been collected from each module at a fixed irradiation with different temperatures. In this case, temperature

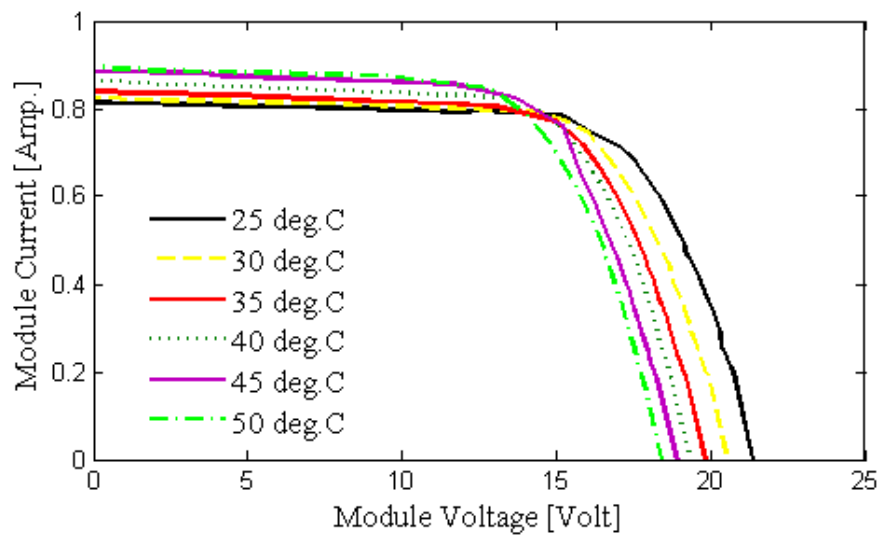


Figure 6.1: I - V sweep curves of poly Si module of 36 cells recorded over temperature range from 25 °C to 50 °C

varies from 25 °C to 50 °C and the irradiation is fixed at 8 light bulbs condition. From the Fig. 6.1 I - V sweep curves of poly Si module of 36 cells have been observed. It shows that short circuit current rises whereas the open circuit voltage decreases with the increase of temperature. The values of open circuit voltage vary from 21.4 volt to 18.44 volt with the variation of temperature from 25 °C to 50 °C; whereas the short circuit current varies from 0.815 A to 0.896 A.

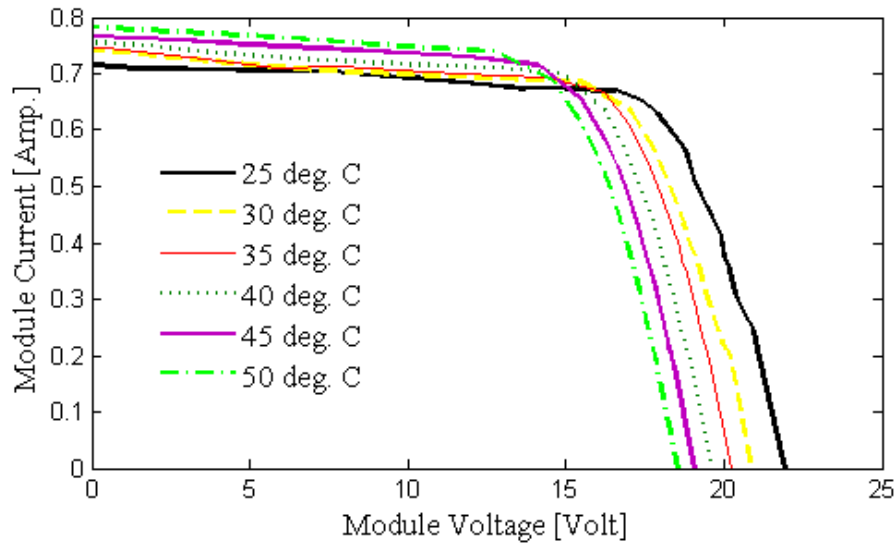


Figure 6.2: *I-V* sweep curves of mono Si module of 36 cells recorded over temperature range from 25 °C to 50 °C

From the Fig. 6.2, *I-V* sweep curve of mono Si module is observed. Same as poly Si module, temperature affects the open circuit voltage and decreases its value when the temperature increases. Also the short circuit current increases with the rise of temperature. The open circuit

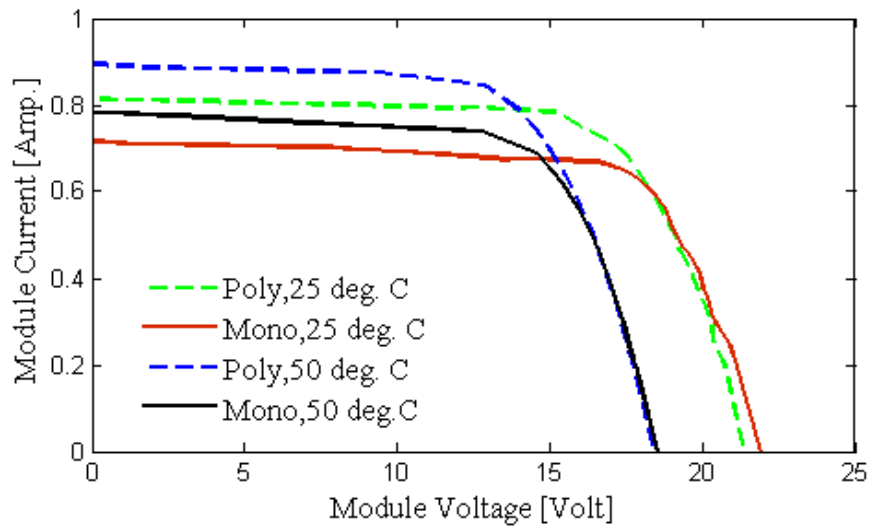


Figure 6.3: *I-V* sweep curves of poly and mono Si module of 36 cells at 25 °C and 50 °C

voltage varies from 21.94 V to 18.55 V and the short circuit current 0.718 A to 0.784 A over a temperature range from 25 °C to 50 °C. It is noticeable that the open circuit voltage for poly Si module decrease 2.96 V with the rise of temperatures is less than that of mono Si module i.e. 3.39 V. For the short circuit current, poly Si module gives better result than the mono Si one. The I_{SC} of poly Si increase 81 mA and for the mono Si the value increase 66 mA with the rise of temperature range in 25 °C to 50 °C. All the explanation can easily be understandable from the Fig. 6.3. It is also be seen that the short circuit current of mono Si module is less than the poly Si module for certain temperature. This conforms to our discussion on the effect of temperature in section 3.3.3.

6.2.2 I-V Sweep Curves of PV Modules at Different Illumination Levels

To collect the voltage and current data of different illumination level, temperature is fixed at 25°C and illumination is varied by using 2 bulbs to 8 bulbs. After that temperature value then fixed at 50 °C and again illumination is varied using 2 bulbs to 8 bulbs. Each bulb represents 100 W/m². To make the plot easily understandable only 4 bulbs and 8 bulbs illumination have been plotted as shown in Figure 6.4 It shows that due to the increase of illumination levels for

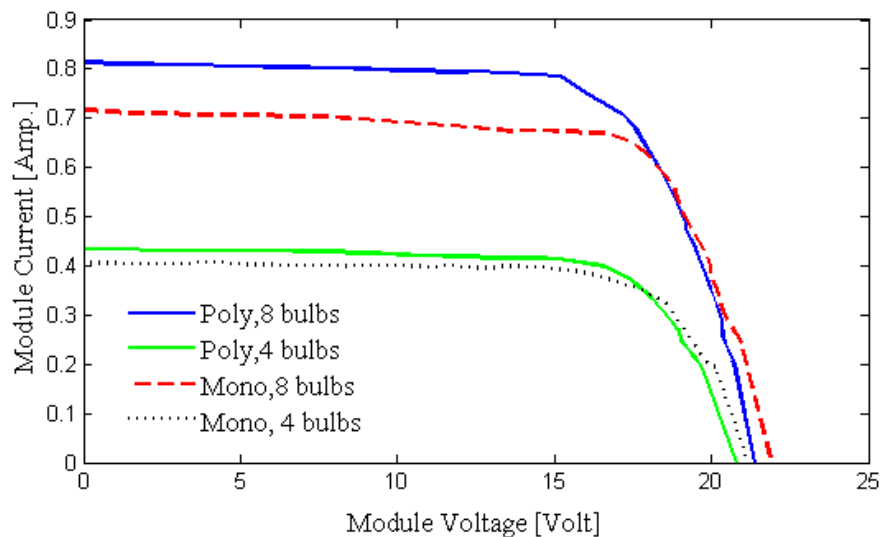


Figure 6.4: *I-V* sweep curves of poly and mono Si module of 36 cells under two different illumination levels (4 and 8 bulbs), recorded at 25 °C

poly and mono Si modules, the open circuit voltage and short circuit current increase. When the illumination level is doubled from 4 bulbs to 8 bulbs, it is noticeable that the short circuit current increases proportionally. The I_{SC} for poly Si module varies from 0.435 A to 0.815 A for 4 bulbs to 8 bulbs. For mono Si module, I_{SC} varies from 0.408 A to 0.739 A and it is almost 1.81 times increment in short circuit current which is close to double. But the change of illumination does not affect the open circuit voltage much. For poly Si module, the open circuit voltage change is 0.6 V and for the mono Si module the value is 0.74 V.

Figure 6.5 shows the I-V sweep curves of poly and mono Si module of 36 cells at 50°C under variable irradiation (4 bulbs and 8 bulbs). The I_{SC} for poly Si module varies from 0.471 A to 0.896 A for 4 bulbs to 8 bulbs which is almost 1.90 times increase in current values. For mono Si module I_{SC} varies from 0.437 A to 0.784 A and it is almost 1.79 times increment in short circuit current close to double. Also illumination does not affect the open circuit voltage much. For poly Si module, the change in open circuit voltage level is 0.14 V and for the mono Si module the value is 0.55 V.

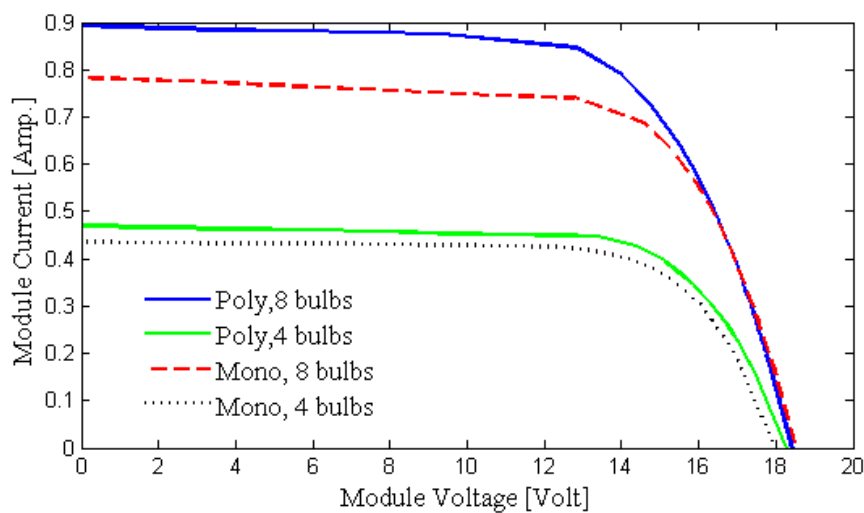


Figure 6.5: I-V sweep curves of poly and mono Si module of 36 cells under two different illumination levels (4 and 8 bulbs), recorded at 50 °C

Table. 6.1. Manufacturers specifications of the selected modules at Standard Testing

Condition

Module Type	Mono Si module	Poly Si module
I_{SC} (A)	1.27	1.33
V_{OC} (V)	21.16	21.6
P_{max} (W)	20	20
I_{mp} (A)	1.16	1.15
V_{mp} (V)	17.35	17.5

6.2.3 Effect of illumination on PV modules

The results shown here are those for the two commercially available 20W, mono- and poly-crystalline, PV modules. Table 6.1 summarizes the specifications of the two panels, as provided by the manufacturer.

. Figure 6.6 shows the variation of open circuit voltage (V_{OC}), and short circuit current (I_{SC}) of the two modules under different light intensity level at two temperatures, 25 °C and 50 °C. As expected, both the I_{SC} and V_{OC} increases with the level of illumination.

One interesting point is that while mono-crystalline panel shows higher V_{OC} at both the temperatures, poly-crystalline one shows higher I_{SC} . Further, it can be observed that the rate of increase of I_{SC} in poly Si module is higher than that in mono Si module at higher level of irradiation.

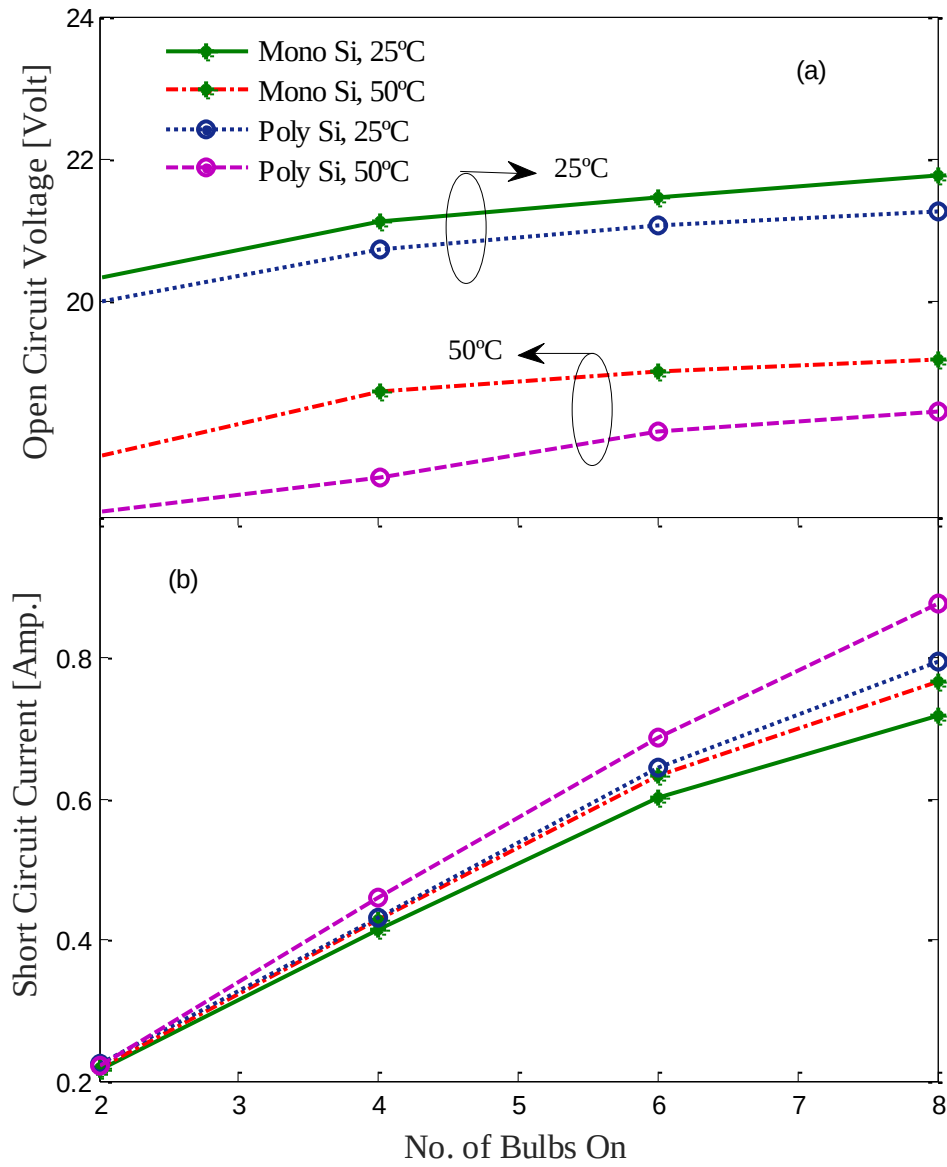


Figure. 6.6. Plots of (a) Open circuit voltage and (b) short circuit current under different light intensity, obtained by keeping different number of bulbs on, recorded at two different temperatures, 25 °C and 50 °C.

6.2.4 Effect of Temperature on PV module Performance

Figure 6.7 shows the variation in (a) series resistance, (b) shunt resistance and (c) reverse saturation current with temperature for the two modules, which are extracted from I-V characteristics.

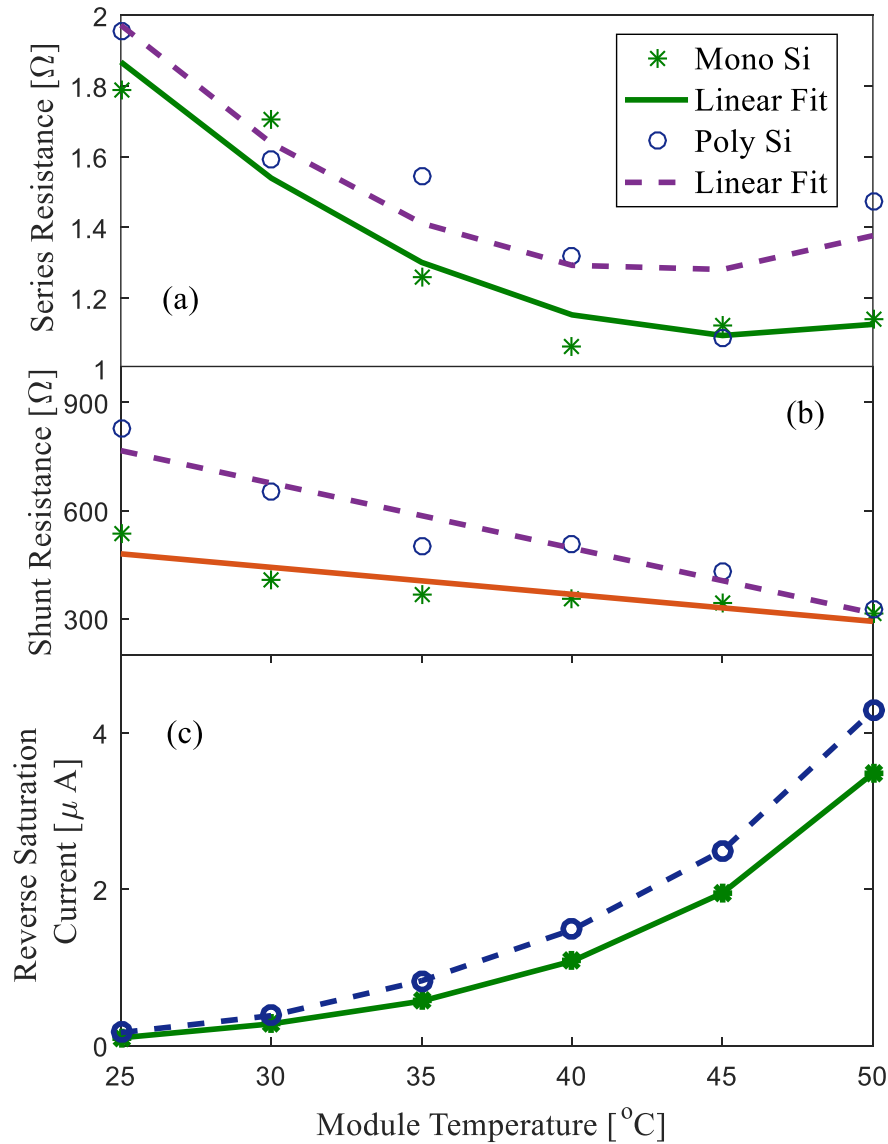


Figure. 6.7. Plots of (a) Series resistance, (b) shunt resistance, and (c) reverse saturation current of poly and mono Si modules with respect to module temperature at a fixed irradiation with 8 bulbs.

As it can be seen from the figure that initially series resistance for both the modules decreases with temperature before it starts increasing at a sufficiently high temperature. The reason behind this is that the resistance of metal connectors increases with the temperature while that of semiconductor layer decreases with temperature. These two phenomena affect each other due to the change in temperature. As expected, poly Si module shows higher series and shunt resistances than the mono Si module. However, for both mono and poly, the trend is decreasing shunt resistance with temperature. It can be observed that the rate of decrease in shunt resistance with temperature in poly Si module ($19.88 \Omega/^{\circ}\text{C}$) is higher than that in mono Si module ($8.88 \Omega/^{\circ}\text{C}$).

The plot of reverse saturation current as shown in Fig. 6.7(c) shows an exponential increase with temperature with slightly higher values for poly Si. This is due to the inferior crystal quality of poly Si than that of mono Si module. Also ideality factor has been calculated for these modules. At the room temperature ideality factor of poly Si module (1.03) is better than mono Si (1.35) module.

Figure 6.8 shows the variation of (a) open circuit voltage, (b) short circuit current, (c) fill factor and (d) maximum power with respect to module temperature under a fixed illumination with 8 bulbs. The open circuit voltage decreases linearly with temperature due to increase in the reverse saturation current, as is evident from Fig. 6.8 (c). The short circuit current gradually increases with temperature, probably due to increase in carrier mobility at higher temperature. The open circuit voltage of mono Si module is slightly larger than that of poly Si module. The short circuit current flowing in poly Si is much larger than that in mono Si module. The short circuit current of poly Si module is about 0.1A, which is almost 13% higher than that in mono Si module. Also, it can be observed that the rate of increase of I_{SC} with temperature in poly Si module ($0.00324 \text{ A}/^{\circ}\text{C}$) is higher than that in mono Si module ($0.00264 \text{ A}/^{\circ}\text{C}$). The probable reason behind higher short circuit current in poly Si module is lower cell thicknesses. On the

other hand, cells in mono Si module are made using thick Si wafers. This requires photo-generated electrons in mono Si cells travel a much longer distance through the cell than they need to do in poly Si cells. This significantly increases the probability of photo-generated electrons to get lost through recombination before they are collected in mono Si cells.. Mono crystalline module shows better fill factor than the poly crystal module observed in Fig. 6.8 (c).

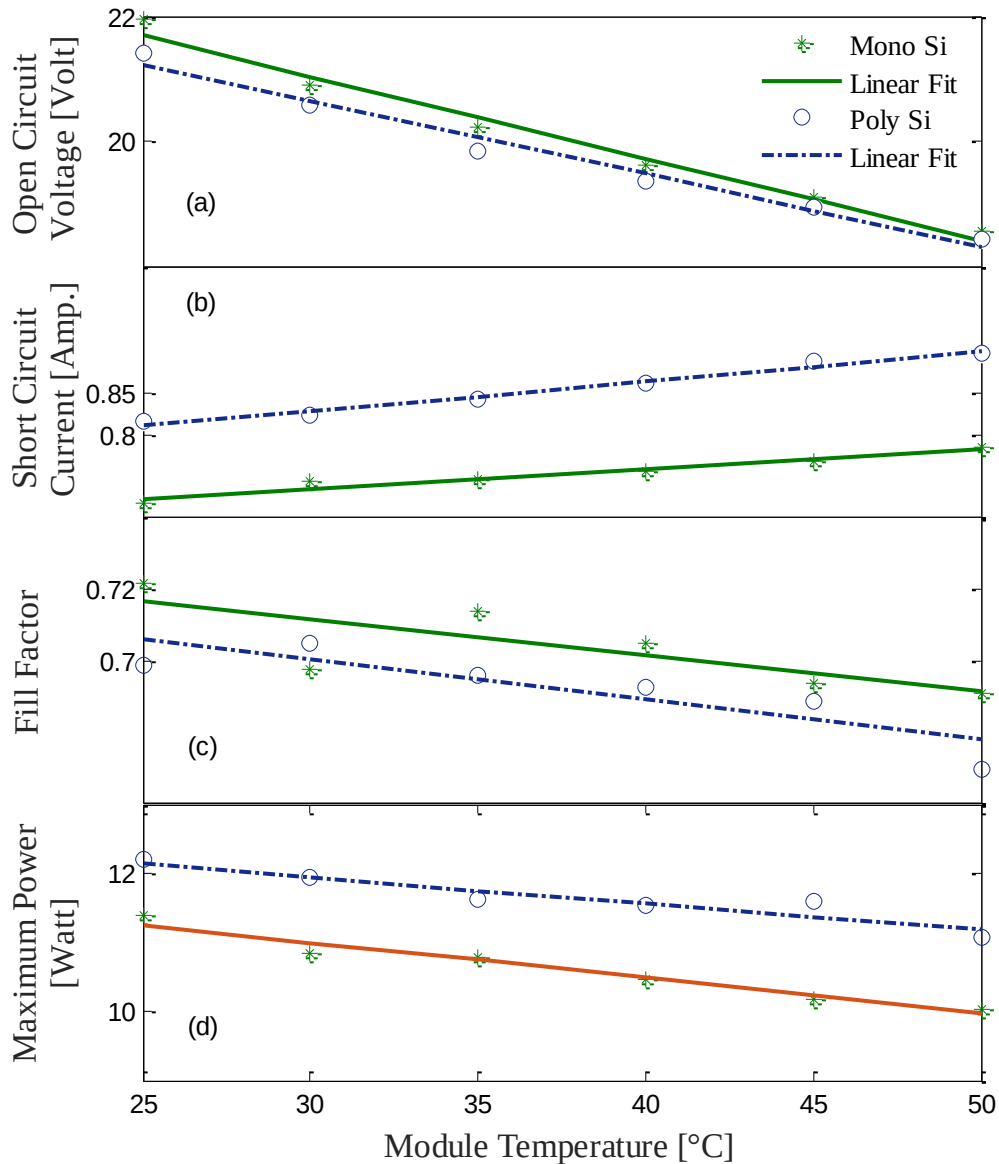


Figure. 6.8. Plots of (a) open circuit voltage, (b) short circuit current, (c) fill factor, and (d) maximum power of poly and mono Si modules with respect to module temperature at a fixed irradiation with 8 bulbs.

This can be attributed to the slightly lower series resistance of mono Si module as observed in Fig. 6.8 (a). However, the degradation of fill factor (FF) with the temperature for both the mono- ($-0.126\ \%/^{\circ}\text{C}$) and poly-Si modules ($-0.113\ \%/^{\circ}\text{C}$) is about the same level.

The plot of maximum power with temperature in Fig. 6.8 (d) shows much less power for mono Si, almost 0.8W which is about 6% less than that for poly Si. Further the rate of decrease of power with temperature is greater in mono Si module ($-0.053\ \text{W}/^{\circ}\text{C}$) than that in poly Si module ($-0.044\ \text{W}/^{\circ}\text{C}$). Higher power output of poly Si modules is attributed to the significantly much larger short circuit current in poly module than that in mono Si module.

6.3 Infrared Thermography based Analysis

In this part, the first few sections deal with the conventional performance analysis. The later sections analyze the thermographs of the whole PV module. First, the I-V curve analysis is done. Then visual inspection is done to find visible faults. After that the thermographs of the module junction box shows how solder joints is translated into huge heat loss. Then the infrared images of the panel surface is analyzed.

6.3.1 Performance measurement of PV modules

Figure 6.9 shows the I-V plots of the sample PV modules, measured with an indoor solar simulator at 25 °C under the same irradiation level. Table 6.2 summarizes the different PV parameters extracted from the experimental I-V characteristic curves of the sample PV modules as shown in Fig. 6.9 From the Table 6.2 it can be seen that the short circuit current and the output power of poly Si module is slightly lower than that of the mono Si module. This performance degradation is the key indication of possible defects in PV modules.

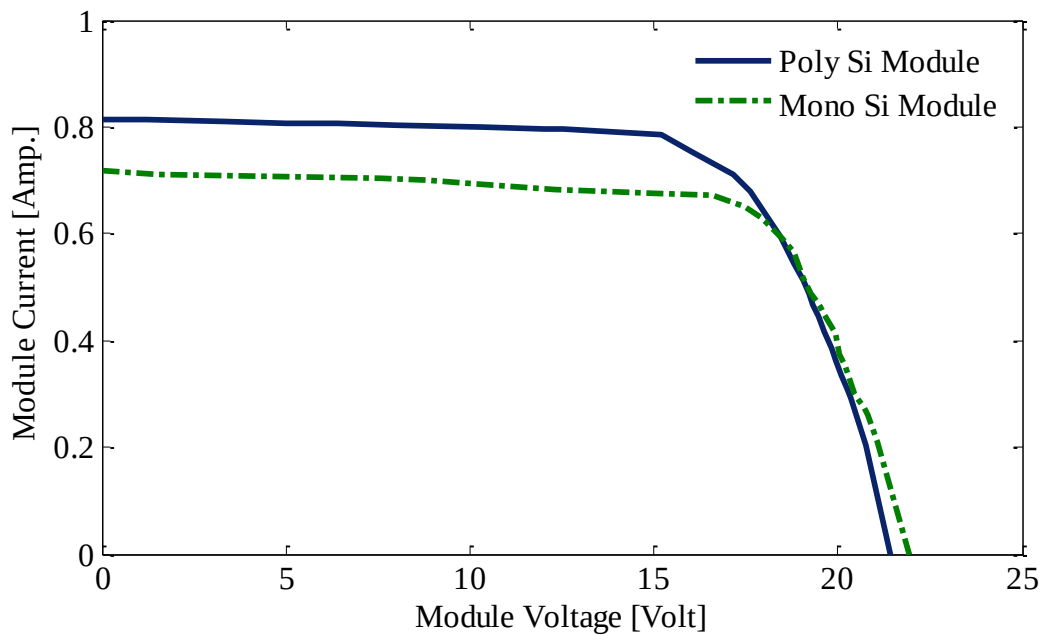


Figure. 6.9: I-V characteristics of poly and mono Si sample modules measured at 25°C and under 800 W/m² irradiation level.

For the purpose of comparative study, poly Si module, with the highest maximum power output as per Table 6.2 has been taken as a reference module. It shows that maximum power of mono Si module is 6.64% lower than the poly Si module. So, mono Si module has some possible defects or faults.

Table 6.2 Module parameter of the PV modules extracted from I-V measurements

Parameter	(Mono Si)	(Poly Si)
$P_{mpp}[W]$	11.38	12.19
$V_{mpp}[V]$	17.45	17.14
$I_{mpp}[A]$	0.652	0.711
$V_{oc}[V]$	21.94	21.40
$I_{sc}[A]$	0.718	0.815

6.3.2 Visual Inspection

The PV modules were inspected visually to check for defects. It was observed that PV modules have discoloured cell gridlines in it. The cell cracks were seen in poly Si PV module. Also, some disjointed connection lines between module cells were observed. Resistive solder bonds were observed in all modules. Frames, front glass and back sheets were observed to be in good condition. The results of visual inspection are summarized in table summarized in Table 6.3 possible hotspot region in chalked out as there were some resistive solder bonds in between cell interconnects and some cell cracks. For further inspection thee possible defected zones are marked.

Table 6.3 Observations from Visual Inspections of PV Modules

Error Type	Observation(s)
Cell gridlines	Discolored effects were observed on gridlines of mono Si module. Also corrosion effects were observed on the gridlines
Back sheet	No burn marks, no chalking or other damage was visible
Wires/connectors	No browning was observed
Delamination	No delamination was observed
Cell Gaps	No encapsulation and brown discoloration were observed.
Frames	There was no discoloration or any corrosion was seen on metal joints
Metallization	Bus-bar and cell interconnects showed no burns, discoloration or corrosion
Junction box	No Browning was observed
Interconnect Ribbons	Interconnect ribbons were all okay
Front Glass	No damage, no animal dropping or dust particles were observed
Bypass diode	Bypass diode was available
Cell crack	Cell cracks were observed on poly Si module
Resistive solder bonds	The cell interconnects of the two modules were observed possible resistive solder joints

6.3.3 IR thermography: Module Junction Box

Localized heating may take place in a faulty junction box. To find this, active approach was used to determine which junction is resistive. Figure 6.10 shows thermal images of two sample module's junction box which were tested under dark condition in forward bias. The ambient temperature was kept 25°C. Here in this approach 23 volt and 1 ampere current was applied to the modules for 60 seconds. From Fig. 6.10 it is observed that junction box of two modules create hotspot. Temperature of the encircled hotspot regions of poly and mono Si module are 29.4 and 30.1°C respectively. This temperature is much higher than the ambient temperature. The probable reason behind the rise of temperature is heat loss due to resistive joint. This was perhaps one of the main reasons of performance degradation of solar PV modules.

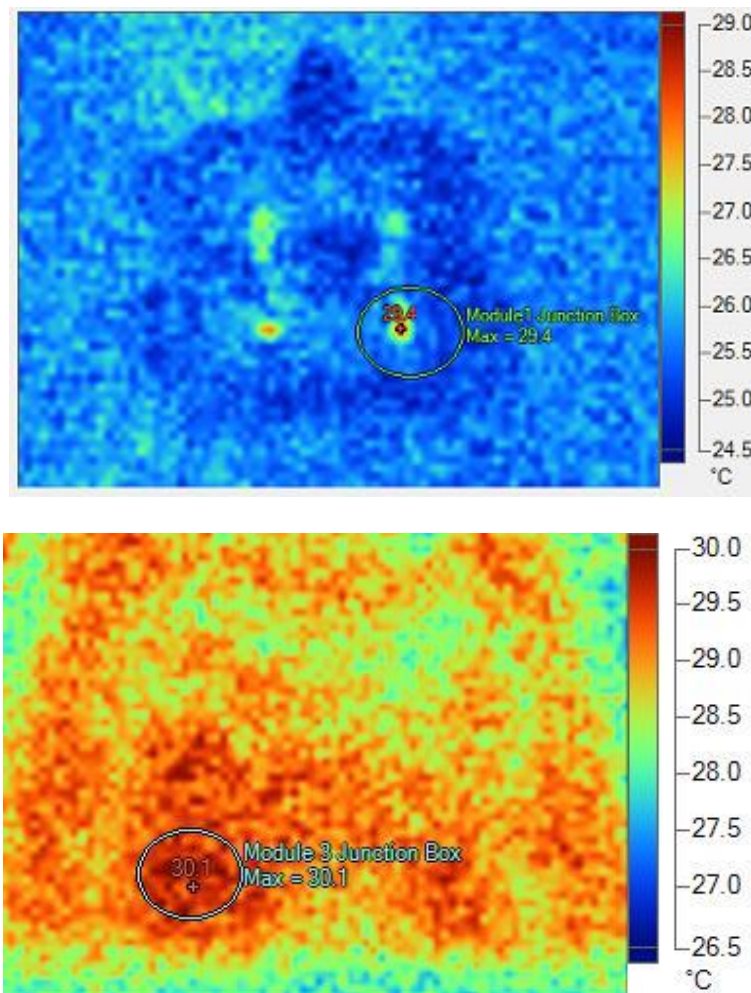


Figure. 6.10: IR thermal image of poly Si module (top) and mono Si module (down) junction box indicates hotspots

6.3.4 IR thermography: Module Surface

Figure 6.11 shows (a) the IR thermal image of poly Si module and (b) the 3D view of temperature distribution on the module surface. It shows that cell interconnector of module 1 shows hotspot. Beside the interconnectors, temperature distribution is moderate. Solar cells within the interconnecting regions shows high temperature. Circle indicates the hottest region which is the probable hotspot area. The ambient temperature during the test was 23°C and the highest Temperature in hotspot region was 26.3°C. Temperature difference is 3.3°C for poly Si module for the marked region.

Mono Si module shows 6.64% less power output than the poly Si module. 3D image in Fig. 6.12 (b) also shows hotspot region in the cell interconnectors. The marked region shows the highest temperature that means probable hotspot region. Ambient temperature was 23 °C and temperature difference is 5.3 °C on the marked region. Probable resistive interconnectors and visually observed discoloured cell gridlines are the main cause of the hotspot. Also temperature difference shows that the mono Si module is defected greatly than poly Si module

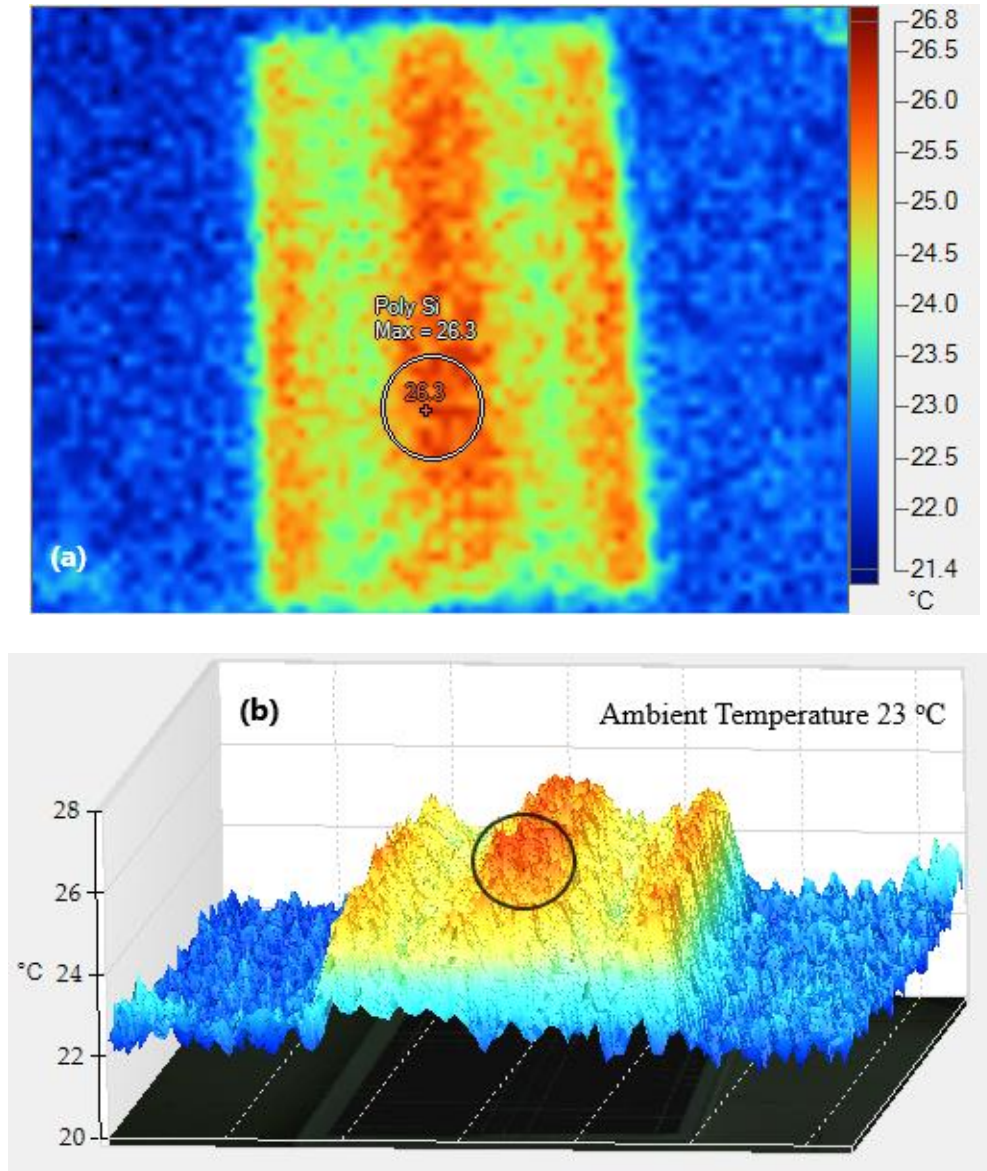


Figure. 6.11: (a) Thermal image of Poly Si module (b) 3D diagram of surface temperature distribution.

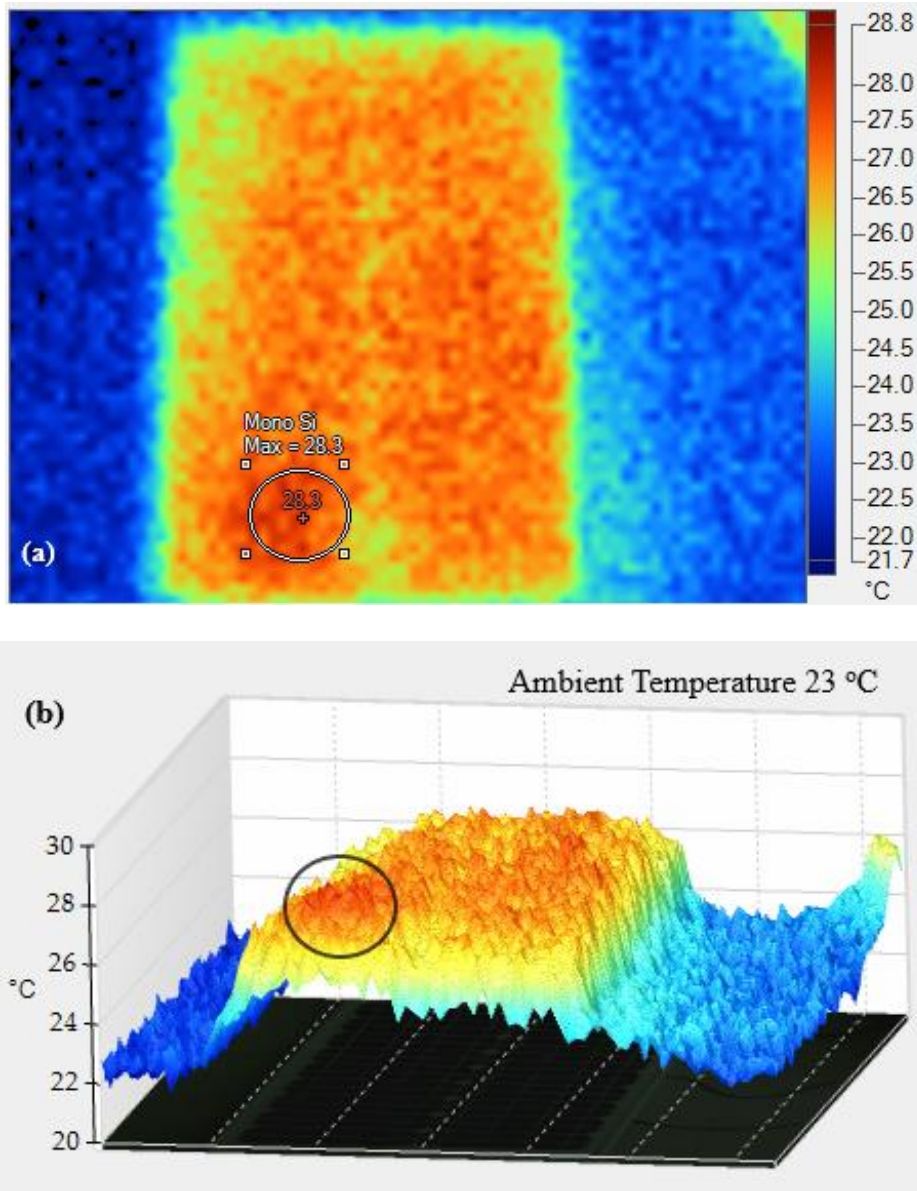


Figure. 6.12: (a) Thermal image of Mono Si module (b) 3D diagram of surface temperature distribution

6.4 Chapter Summary

This chapter covers the results and analysis of this thesis work. Performance analysis and comparative study is discussed for poly and mono Si module. Observation shows poly Si module shows better photo generated current in comparison to mono Si module. Though other cell parameters shows better features for mono Si. From the infrared thermography, possible hotspot region have been analyzed considering the visual inspection data. Results shows that mono Si module is observed high temperature difference in hotspot region greater than 5°C. Also it is found that junction box may cause heat loss which affects the module performance.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The main objective of this thesis was to study comparative performance analysis of two commercially available photovoltaic modules under different temperature and illumination conditions. For this purpose indoor I-V measurement is done under different temperature and illumination levels to extract different module parameters. Though mono Si module shows better cell features in terms of series resistance, reverse saturation current and fill factor, it shows a much lower photo generated current and output power than those of poly Si module. Lower photo current in mono Si module is attributed to the loss of photo-generated electrons due to recombination in the thick layer of mono Si, which electrons generated in poly Si are collected more efficiently because of thin layer of poly Si cell. This indicates that crystal quality of Si in commercially available mono Si module does not match the required standard to maintain the high cell performance as is expected from a mono Si module.

Also in this experimental study infrared thermography is used to evaluate the performance of PV modules and detect possible defects. Temperature distribution analysis confirms hotspot region. Temperature difference in hotspot region of mono Si module is higher than the poly Si module. As a result the performance is lower than the poly Si module. Visual inspection and thermographs confirms that the possible resistive solder joints in interconnectors are the main cause of heat dissipation. Junction box soldering is also observed to produce heat losses for the two PV modules. So proper measures should be taken for the junction box connection. Since, this is a non-destructive method, it is easy to use and safe. This types of study can be useful for rooftop solar power projects and for grid connected PV to understand the performance and degradation of PV modules.

7.2 Future Works

Present work investigates the module performance over the temperature range 25°C to 50°C. Due to the technical limitation to further raise the module temperature, impacts could not be studied here at higher temperature. Further work can be done investigating the high temperature effects on poly and mono Si PV module over the range from 50°C to 80°C to find out how the temperature affects the performance of commercially available mono and poly Si PV modules. Besides present study is limited to only indoor study of poly and mono Si PV modules. A detailed investigation is needed to find out how poly and mono Si PV module perform in outdoor condition under different climatic conditions.

Furthermore in this study only active thermographic approach is used to evaluate the performance of the PV modules. In future the passive thermography approach will be studied along with the outdoor experiment. Also image processing feature extraction and characterization of defects will be studied. To make a greener country PV can play important role. For this proper care and development is necessary to building up research facility and experts to meet up the future challenges regarding PV cells and module. In this contexts this work can help to assess the performance of PV module and to find out the probable defects.

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Appendices

Appendix A. List of Publications

1. **M. Islam**, M. M. Hasan Shawon, S. Akter, A. Chowdhury, S. I. Khan and M. M. Rahman, "Performance Investigation of Poly Si and Mono Si PV Modules: A Comparative Study," *2019 International Conference on Energy and Power Engineering (ICEPE)*, Dhaka, Bangladesh, 2019, pp. 1-5.
2. **M. Islam**, G. Hasan, I. Ahmed, M. Amin, S. Dewan and M. M. Rahman, "Infrared Thermography Based Performance Analysis of Photovoltaic Modules," *2019 International Conference on Energy and Power Engineering (ICEPE)*, Dhaka, Bangladesh, 2019, pp. 1-5.
3. M. Amin, **M. Islam**, G. Hasan, S. Dewan, I. Ahmed and M. M. Rahman, "Active Thermography Based Performance Analysis & Defected Area Calculation of PV Modules," submitted at *5th IEEE International Women in Engineering (WIE) Conference on Electrical and Computer Engineering 2019*, Bangalore, India, 2019.

Appendix B. Matlab Code

B1.Function of Maximum Power Calculation

```
function [ P,Pmax,Vmax,Imax,x ] = maxpower( V,I )
a=length(V);
for i=1:1:a
    P(i)=V(i)*I(i);
end
Pmax=max(P);
for i=1:1:a
    if P(i)==Pmax;
        Vmax=V(i);
        x=i;
    end
end
Imax=Pmax/Vmax;
end
```

B2.Function of Series Resistance Calculation

```
function [ I,Is,z ] = find2_Rs( V,Voc,Isc,T )
q=1.6*10^-19;
k=1.3806*10^-23;
z=(q*Voc)/(1.5*k*T);
Is=Isc/exp((q*Voc)/(1.5*k*T));
a=length(V);
for i=1:1:a
    I(i)=Isc-Is*exp((q*V(i))/(1.5*k*T));
end
end
```

B3.Function of Ideality Factor Calculation

```
function [ n ] = calc_n( Voc1,Voc2,Isc1,Isc2,T )
Ns=36;
k=1.3806*10^-23;
q=1.6*10^-19;
Vt=(k*T)/q;
n=(Voc1-Voc2)/(Ns*Vt*log(Isc1/Isc2));
end
```

B4.Function of Reverse Saturation Current Calculation

```
function [ Io2 ] = find_Io2( Io1,Eg,To,Ti )
q=1.6*10^-19;
k=1.3806*10^-23;
for i=1:1:length(Ti)
    Io2(i)=Io1*((Ti(i)/To)^3)*exp((-Eg/(k/q))*(1/Ti(i)-1/To));
end
end
```

B5.I-V data for Poly Si module

```
v25=[21.4 20.75 20.69 20.62 20.52 20.45 20.37 20.34 20.23 20.10 19.93 19.81 19.62 19.45
19.19 19.20 19.04 18.79 18.42 17.6 17.14 16 15.2 12.5 12.03 10.34 8 6.40 5.01 3.3 1.2 0];
i25=[0 .204 .209 .221 .234 .245 .257 .291 .310 .334 .365 .384 .418 .445 .475 .489 .511 .546
.595 .68 .711 .754 .787 .797 .795 .799 .803 .805 .807 .811 .813 .815];
%plot(v25,i25,'g');
hold on;
v30=[20.59 19.93 19.88 19.83 19.75 19.7 19.62 19.56 19.5 19.44 19.3 19.12 19.01 18.81 18.7
18.42 18.12 17.65 16.94 16.07 15.24 14.38 13.3 11.69 9.99 7.14 5.89 3.01 .9 0];
i30=[0 .195 .2 .208 .225 .234 .248 .259 .27 .281 .311 .346 .368 .408 .439 .475 .522 .591 .669
.743 .775 .795 .798 .803 .808 .814 .816 .820 .823 .823];
%plot(v30,i30,'y');
hold on;
```

```
v35=[19.85 19.23 19.2 19.17 19.15 19.14 19.13 19.1 19.07 19.03 19 18.98 18.92 18.87 18.79
18.68 18.61 18.48 18.41 18.26 18.09 18.02 17.87 17.7 17.44 17.04 16.43 15.87 15.02 13.04
11.37 9.58 7.2 5.59 4.60 1.503 0];
```

```
i35=[0 .188 .192 .197 .2 .201 .203 .208 .213 .221 .227 .234 .244 .256 .274 .299 .322 .344 .357
.391 .421 .433 .462 .492 .532 .594 .665 .721 .773 .808 .814 .818 .824 .828 .832 .838 .841];
```

```
%plot(v35,i35,'r');
```

```
hold on;
```

```
v40=[19.36 18.75 18.72 18.69 18.66 18.63 18.60 18.56 18.50 18.43 18.35 18.24 18.06 17.91
17.76 17.62 17.43 17.18 16.85 16.47 16.14 15.40 14.53 13.51 11.57 9.4 7.9 6.47 4.56 1.03 0];
```

```
i40=[0 .183 .189 .196 .203 .209 .219 .229 .243 .260 .280 .306 .349 .382 .412 .441 .476 .521
.573 .627 .666 .740 .795 .826 .834 .840 .843 .847 .852 .861 .861];
```

```
%plot(v40,i40,'m');
```

```
hold on;
```

```
v45=[18.94 18.27 18.25 18.22 18.20 18.18 18.16 18.11 18.08 18.05 18 17.97 17.91 17.85
17.70 17.57 17.48 17.38 17.22 17.10 16.97 16.79 16.51 16.17 15.82 15.20 13.69 11.61 8.96
6.69 4.27 3.54 0];
```

```
i45=[0 .183 .186 .192 .196 .201 .208 .215 .222 .229 .243 .248 .262 .275 .309 .341 .361 .382
.414 .439 .464 .493 .544 .598 .646 .762 .827 .858 .865 .872 .875 .883 .887];
```

```
%plot(v45,i45,'c');
```

```
hold on;
```

```
v50=[18.44 17.86 17.84 17.81 17.8 17.77 17.73 17.7 17.66 17.63 17.61 17.55 17.49 17.43
17.36 17.23 17.16 17.09 17.01 16.84 16.69 16.52 16.28 16.01 15.80 15.52 14.78 14.02 12.87
9.33 7.4 5.43 3.61 2.3 .95 0];
```

```
i50=[0 .176 .178 .186 .19 .198 .207 .216 .224 .232 .237 .253 .268 .285 .302 .334 .349 .364 .382
.418 .448 .482 .527 .569 .599 .640 .727 .790 .848 .877 .880 .883 .886 .889 .892 .896];
```

```
plot(v50,i50, 'k');
```

```
hold on;
```

B6.I-V data for Mono Si module

```
v25=[21.94 21.08 20.95 20.80 20.68 20.56 20.46 20.38 20.20 20.03 19.93 19.63 19.52 19.41
19.28 19.05 18.80 18.48 17.91 17.45 16.58 14.97 13.70 12.33 10.14 8.8 7.56 1.5 0];
```

```
i25=[0 0.212 0.245 0.262 0.275 0.288 0.299 0.310 0.354 0.375 0.414 0.449 0.463 0.472
0.488 0.516 0.565 0.591 0.631 0.652 0.671 0.675 0.675 0.683 0.694 0.7 0.705 0.711 0.718];
```

```
%i25i = smooth(i25);
```

```
%plot(v25,i25,'g');hold on;
```

```

v30=[20.90 20.22 20.19 20.15 20.09 20.04 20.01 19.97 19.90 19.83 19.80 19.7 19.60 19.50
19.32 19.20 19.14 18.93 18.73 18.37 17.83 17.07 15.50 11.20 7.2 3.75 0.4 0];

i30=[0 0.199 0.202 0.209 0.213 0.215 0.219 0.222 0.237 0.249 0.249 0.266 0.284 0.303 0.337
0.365 0.370 0.4 0.436 0.495 0.565 0.635 0.688 0.698 0.707 0.724 0.742 0.743];

%i30i = smooth(i30);

%plot(v30,i30,'y');hold on;

v35=[20.22 19.56 19.49 19.42 19.38 19.33 19.26 19.20 19.12 18.96 18.88 18.77 18.69 18.59
18.32 18.03 17.58 17.02 16.19 14.36 11.65 9.67 7.79 5.9 3.05 0.46 0];

i35=[0 0.192 0.205 0.218 0.225 0.235 0.250 0.264 0.282 0.317 0.333 0.356 0.369 0.391 0.437
0.485 0.549 0.607 0.666 0.694 0.7 0.706 0.712 0.71 0.73 0.745 0.747];

%i35i = smooth(i35);

%plot(v35,i35,'r');hold on;

v40=[19.63 18.93 18.89 18.86 18.82 18.77 18.71 18.66 18.59 18.51 18.42 18.31 18.16 18.07
17.93 17.75 17.52 17.24 16.77 16.215 14.9 12.64 9.22 6.33 3.57 1.77 0];

i40=[0 0.193 .203 .206 .216 .227 .239 .251 .267 .286 .305 .328 .359 .378 .405 .439 .477 .518
.579 .638 .702 .712 .721 .729 .740 .751 .756];

%i40i = smooth(i40);

%plot(v40,i40,'m');hold on;

v45=[19.09 18.45 18.42 18.39 18.36 18.32 18.28 18.23 18.18 18.12 18.05 17.96 17.86 17.71
17.61 17.48 17.30 17 16.62 16.24 15.50 14.13 11.9 9.89 7.22 5 2.8 0];

i45=[0 0.182 .187 .193 .199 .207 .215 .227 .239 .255 .272 .296 .319 .350 .368 .392 .430 .480
.537 .585 .656 0.718 0.732 0.739 .747 .753 .762 .768];

%i45i = smooth(i45);

%plot(v45,i45,'c');hold on;

v50=[18.55 17.93 17.91 17.89 17.85 17.82 17.77 17.73 17.68 17.63 17.55 17.43 17.33 17.22
17.03 16.85 16.65 16.35 15.94 15.41 14.60 12.77 10.76 9 7.18 4.89 2.66 0.43 0];

i50=[0 0.177 .181 .187 .195 .203 .212 .221 .233 .245 .267 .297 .319 .341 .381 .417 .455 .505
.562 .622 .688 .741 .747 .754 .761 .769 .777 .783 .784];

%i50i = smooth(i50);

plot(v50,i50, 'k');hold on;

```

B7.Data of Delta T vs Time for Poly and Mono Si PV module

```

x=[1 5 10 15 20];
y1=[3.3 6.5 9.3 10.8 12.2];
y3=[5.3 10.6 12.5 13.6 15.2];

```

```
p = polyfit(x,y1,2);  
f = polyval(p,x);  
plot(x,y1,'o',x,f,'-'); hold on;
```

```
p = polyfit(x,y3,2);  
f = polyval(p,x);  
plot(x,y3,'+',x,f,'-'); hold on;
```


Appendix C. Equations

C1. Effect of temperature on reverse saturation current:

The current through the cell is given by the equation below

$$I = -I_{SC} + I_s \left(e^{\frac{q V_{oc}}{nkT}} - 1 \right)$$

When the current through the cell is zero ($I=0$), the equation is as follows

$$I_{SC} = I_s \left(e^{\frac{q V_{oc}}{nkT}} - 1 \right)$$

Then the equation for I_s in terms of I_{SC} is

$$I_s = \frac{I_{SC}}{e^{\frac{q V_{oc}}{nkT}} - 1}$$

where, $V_t = \frac{kT}{q}$ is the thermal voltage.

Ignoring 1, the equation becomes

$$I_s = \frac{I_{SC}}{e^{\frac{q V_{oc}}{nkT}}}$$

For finding the temperature dependence on the reverse saturation current, the following equations have been analyzed:

For a regular p-n junction the ideal saturation current is

$$I_s = A_q N_C N_V(B) \exp \frac{-E_g}{KT}$$

I_s = reverse saturation current,

A = area

q = charge of an electron

N_C = effective density of states in conduction band

N_V = effective density of states in valence band

E_g = energy band gap

K = boltzmann's constant

T = temperature

and “ B ” is a constant

The effective density of states can be expressed as:

$$N_{C1} = 2 * \left(\frac{2\pi m_e K T_1}{h} \right)^{1.5} \quad \text{C.1}$$

At a new temperature the effective density changes as follows:

$$N_{C2} = 2 * \left(\frac{2\pi m_e K T_2}{h} \right)^{1.5} \quad \text{C.2}$$

Dividing equation C.1 and C.2,

$$\frac{N_{C2}(T_2)}{N_{C1}(T_1)} = \left(\frac{T_2}{T_1} \right)^{1.5}$$

Therefore,

$$N_{C2}(T_2) = N_{C1} * \left(\frac{T_2}{T_1} \right)^{1.5}$$

Hence, the effective density of states in valence band can also be expressed as

$$N_{V2}(T_2) = N_{V1} * \left(\frac{T_2}{T_1} \right)^{1.5}$$

At T_2

$$I_S(2) = A_q N_{C1} * \left(\frac{T_2}{T_1} \right)^{1.5} * N_{V1} * \left(\frac{T_2}{T_1} \right)^{1.5} \exp \frac{-E_g}{K T_2}$$

$$I_S(1) = A_q N_{C1} N_{V1} (B) \exp \frac{-E_g}{K T_1}$$

$$\frac{I_s(2)}{I_s(ref)} = \frac{\left(\frac{T_2}{T_1}\right)^3 \exp \frac{-E_g}{KT_2}}{\exp \frac{-E_g}{KT_1}}$$

At new temperature the reverse saturation current can be calculated as

$$I_{s(new)} = I_{s(ref)} \left(\frac{T_i}{T_o}\right) \exp\left(\left(\frac{-E_g}{k/q}\right) * \left(\frac{1}{T_i} - \frac{1}{T_o}\right)\right)$$

C2. Calculation of the series resistance (R_s) of the solar module:

At maximum power point the current flowing through the solar panel can be rated as the maximum operating current, and voltage can be said as maximum operating voltage and can be denoted by the equation:

$$I_{mpp} = I_{sc} - I_0 \exp\left(\frac{V_{mpp} + I_{mpp} * R_s}{nV_T}\right)$$

$$\frac{V_{mpp} + I_{mpp} * R_s}{nV_T} = \ln\left(\frac{I_{sc} - I_{mpp}}{I_o}\right)$$

$$R_s = \left[nV_T \ln\left(\frac{I_{sc} - I_{mpp}}{I_o}\right) - V_{mpp} \right] * \frac{1}{I_{mpp}}$$

Where,

R_s = series resistance of a solar cell,

I_{mpp} = maximum operating current of the cell,

V_{mpp} = maximum operating voltage of the cell,

I_{sc} = short circuit current,

n = ideality factor of the cell,

I_o = reverse saturation current,

V_t = thermal voltage of the cell.

C3. Calculation of the ideality factor (n) of the solar module

The reverse saturation current is kept constant by keeping the surface temperature of the panel constant and varied the illumination. So for different illumination we can rewrite equation of I_{sc} as:

$$I_{sc1} = I_o \exp\left(\frac{V_{oc1}}{nV_t}\right)$$

$$I_{sc2} = I_o \exp\left(\frac{V_{oc2}}{nV_t}\right)$$

Then by dividing equation (4.7) by equation (4.8):

$$\frac{I_{sc1}}{I_{sc2}} = \frac{\exp\left(\frac{V_{oc1}}{nV_t}\right)}{\exp(V_{oc2}/nV_t)}$$

From this relation the equation for n becomes

$$n = (V_{oc1} - V_{oc2})/V_t \ln(I_{sc1}/I_{sc2})$$

Using this equation it shows the value of ideality factor for the whole 20W solar panel, so to get the value of n for one cell it is needed to divide the n of the whole panel by number of cells in the solar panel, . Hence, the equation for one cell:

$$n = (V_{oc1} - V_{oc2})/(N_S V_t \ln(I_{sc1}/I_{sc2}))$$

Appendix D. Sample Modules data

Table D-1. Sample modules data

Description	Poly Si	Mono Si
Max. Power (P_{max})	20Wp	20Wp
Max. Power Voltage (V_{mp})	17.5V	17.35V
Max. Current (I_{mp})	1.15A	1.16A
Open ckt Voltage (V_{oc})	21.6V	21.2V
Short ckt Current (I_{sc})	1.33A	1.32A
Max. System Voltage	DC600V	1000VDC
Operating module Temperature	(-40 °C ~ +85°C)	(-40 °C ~ +85°C)
Nominal operating Cell Temperature (NOCT)	(47°C±2°C)	(47°C±2°C)
Cell Efficiency	14%	N/A
Solar Cell Type	Polycrystalline	Mono Si
No. of Cells	36	36
Dimension (mm)	538x364x25	510x360x25
Power Tolerance	+/-3%	+/-3%
Brand	XIHE(Importer G-Tech Solar)	Sourav
Max. Series fuse rating	10A	10A
Application Class	N/A	Class A
Protection Class	N/A	N/A
Weight (Kg)	N/A	2.1
Model	XH20P	SV20-18-M
Country of Origin	China	China