OUTDOOR TESTING OF SOME COMMERCIAL SOLAR PANELS FOUND ON THE ZAMBIAN MARKET IN TERMS OF THEIR FILL-FACTOR AND EFFICIENCY

BY

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A dissertation submitted to the University of Zambia in partial fulfilment of the requirements for the degree of Master of Science in Physics.

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ABSTRACT

The power utility company in Zambia, the Zambia Electricity Supply Corporation (ZESCO) introduced load-shedding in urban and rural areas in 2015 when the country experienced severe drought and caused low water levels in our hydropower stations for power generation and distribution. To mitigate load-shedding the Government of the Republic of Zambia (GRZ) encouraged citizens to consider using solar energy for lighting, TV or radio operations or water heating and run small businesses such as saloons and barber shops using solar power. Most solar solutions are in the form of photovoltaic (PV) systems, solar heaters and solar geysers. Solar panels, for example, have output ratings displayed on their back side. These values give the solar panel output power specifications and the quality of the solar panels. However, there has been no technical report (from the author) on the data provided by different solar panel manufacturers and the locally tested data as a validation of the quality of solar panels on the Zambian market. It is a known fact that solar panels are tested under standard test conditions such as solar irradiance of 1000 W/m^2, temperature of 25℃, and air mass of *AM* 1.5 different from out-door environmental conditions. The aim of this research is to validate the quality of solar panels available on the Zambian market by comparing the manufacturer's claims with outdoor tested parameters based on local conditions. The study will collect data on the types and sizes of solar panels supplied in Zambia and test each category of power ratings, fill factor and efficiency. The study will use the I-V curve tracer to determine I-V characteristics and a Solar Survey Meter 200R instrument to obtain solar irradiance, panel tilt and panel temperature. The findings showed that there are substandard solar panels on the Zambian market with an average power output drop as high as 45%, much higher than the recommended power drop of 16.5%. One of the major reasons for this power drop is the degradation of the cells and hence an increase in series resistance of the panels arising from an increase in temperature of the solar cells and thermo-mechanical fatigue of the solder bonds and interconnections. Based on the above findings, the study recommends regulatory measures for manufacturers and suppliers as well as education and assistance for citizens on the usage, maintenance and choice of solar photovoltaic systems.

DEDICATION

I dedicate this dissertation to my dear wife Precious Akishi Ndumba Chiyesu, my young brother Abel Katongo Chiyesu and my friend Kahilu Emmanuel Sakawa who have been very supportive and a great source of inspiration in my life.

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LIST OF ABBREVIATIONS/SYMBOLS

ABBREVIATIONS

AC	Alternating Current
AM	Air Mass
$a - Si$	Amorphous Silicon
DC	Direct Current
eV	Electron Volt
EVA	Ethylene Vinyl Acetate
IEA	International Energy Agency
IEC	International Electro-technical Commission
ISP	International Science Program
$I - V\ Curve$	Current - Voltage Curve
$Mono\ c - Si$	Monocrystalline silicon
$n - factor$	Ideality factor
$NOCT$	Nominal Operating Cell Temperature
$NREL$	National Renewable Energy Laboratory
$Poly\ c - Si$	Polycrystalline silicon
PVs	Photovoltaics
PTC	PV-USA Test Conditions
REC	Renewable Energy Corporation
$REN21$	Renewable Energy Policy Network for the 21st Century
SDG	Sustainable Development Goal
STC	Standard Test Condition
TV	Television
$ZESCO$	Zambia Electricity Supply Corporation

SYMBOLS

I	Total current from the solar cell
I_0	Current when no light is falling on the solar cell
e	Electronic charge
V	Potential difference across the solar cell
k	Boltzmann's constant
T	Absolute temperature depicting the cell temperature.
I_{sc}	Short circuit current
I_m	Maximum current
V_m	Maximum voltage
V_{oc}	Open circuit voltage
P_m	Maximum power
E	Photon energy
h	Planck's constant
v	Frequency of photon
E_v	Valence band edge
E_c	Conduction band edge
E_g	Bandgap Energy
$\vec{E}$	Electric field
I_{ph}	Photo-generated current
P_{sc}	Short circuited power
P_{oc}	Open circuit power
R_{sh}	Shunt Resistance
R_s	Series Resistance
FF	Fill factor
$\frac{d}{dV}$	Differentiate with respect to voltage
ln	Natural log
η	Efficiency
Ω	Ohm
$k\Omega$	kilo-Ohm
A	Ampere
A	Area

^{o}	Degrees
^{o}C	Degrees Celsius
V	volt
%	Percentage
W	Watt
W_p	Peak Power
m^2	Meter squared
μ	Micro
μm	Micrometer
cm	Centimeter
v_g	Cut-off frequency
V_g	Cut-off voltage
T_s	Sun's temperature
T_c	Panel temperature

CHAPTER 1

1.0 INTRODUCTION

Solar photovoltaics (PVs) have been promoted widely in Zambia with almost every district having consumers of PV systems and the provinces with large PV projects. There is growing evidence that solar PV projects and usage have increased in the country because of power deficits experienced. During drought, Zambia has had many challenges concerning power generation and distribution. In trying to maintain the load balance, the power utility company Zambia Electricity Supply Corporation (ZESCO) introduced load-shedding in both urban and rural areas. To minimize load-shedding and achieve Sustainable Development Goal [SDG 7: Affordable and Clean Energy], the government of the Republic of Zambia considered and has prioritized solar energy as an alternative to the dominant hydro power. The government is encouraging citizens to consider using solar energy for lighting, TV or radio operations and water heating (solar heaters/geysers) and for running small businesses such as salons and barber shops.

This development alongside the favourable environmental solar conditions, call for clean energy and climate policy, economic conditions, advancement in photovoltaic technologies, energy security considerations and job creation [1]. In view of these factors, the government has been considering expanding the solar energy power market. As a result, manufacturers and suppliers of solar energy products have flocked to this rapidly expanding market, and the ensuing competition has put an emphasis on supply, which has unfortunately resulted in the appearance of some poor quality products on the market.

Regulatory measures are essential to ensure that the quality and safety of imported solar panels and related components meet the required standards. In Zambia, all solar panels and related components are imported; government has set standards and policies to regulate the importation of these devices [2].

Further, government is educating people through relevant institutions on the use and installation of solar panels to generate electricity. However, it is necessary to assist citizens especially in rural areas on maintenance and choice of solar photovoltaic systems that are available on the market. In order to provide meaningful help to the community, it is imperative to carry out field tests on the suitability of the solar panels and to validate data pertaining to the fill-factor and efficiency of the panels and related components against the manufacturer's claims [3]. This research therefore seeks to compare the data given by the manufacturers and the outdoor tested parameters based on the local conditions.

1.1 Statement of the problem

There are many solar companies in Zambia providing solar solutions, but there is no comparison of the data provided by different solar panel manufacturers with locally tested data to validate the quality of the solar panels being sold in the country. This is a significant problem because customers rely on the information provided by the manufacturers to make purchasing decisions. As a result, there is a risk that consumers may purchase low quality solar panels that do not meet their needs or expectations. This research seeks to address this problem by comparing the data provided by solar panel manufacturers with locally tested data [4] to validate the quality of solar panels on the Zambian market.

1.2 Aim

The aim of this research project was to determine and validate fill-factor and efficiency of some commercial solar panels found on the Zambian market.

1.3 Objectives

The objectives of this research were to:

i. record and ascertain whether all the information pertaining to the fill-factor and efficiency of some selected solar panels on the Zambian market were given on the panels,
ii. carry out measurements and calculate the fill-factor and efficiency of these solar panels, and

iii. compare the given values of the fill-factor and efficiency on the solar panels to the values measured in the study.

1.4 Research questions

The study attempted to answer the following questions;

i. What are the types (make) of solar panels found on the Zambian market?
ii. What information pertaining to fill-factor and efficiency are displayed on the solar panels?
iii. Are the manufacturer's specifications on solar panel ratings useful to the Zambian consumer?

1.5 Significance of the study

The widespread use of solar panels in Zambia has the potential to greatly improve access to electricity in both urban and rural areas. However, the quality of solar panels available on the market is uncertain and many potential consumers maybe buying substandard products. The results of this study can be used to set standards and regulations for the importation and usage of solar systems in Zambia, which will help to ensure that citizens have access to high quality and reliable solar products.

1.6 Outline of this dissertation

The background and objectives of the research are given in chapter one. In chapter two, a review of the physics of solar cells, solar panels and solar energy systems are provided. The detailed review of the literature is given in chapter three. In chapter four the research method and measurement techniques including the instruments that were used in this work are described. Presentation of analyses of the experimental results is done in chapter five. In chapter six, outline of the conclusions and recommendations for future work is given.

CHAPTER 2

2.0 THEORETICAL FRAMEWORK

This study is guided by Becquerel's (1839) theory of Photovoltaic effect [5]. The Photovoltaic effect is a process that when sunlight is incident on the boundary layer of semiconductor materials, electric current can be generated. The study is further guided by the Shockley-Queisser's (1961) detailed balance limit of maximum theoretical efficiency of a solar cell made from silicon [6]. The Shockley-Queisser calculation places the theoretical maximum solar conversion efficiency around 33.7% assuming a single p-n junction with a band gap of 1.4 eV, at Standard Test Condition (STC).

2.1 Solar Photovoltaic Panels

A solar photovoltaic panel is the main building block of a photovoltaic (PV) system comprising a number of solar cells. The maximum voltage given by a silicon solar cell is about 0.6V [7]. Solar cells are connected in series to increase the voltage and in parallel to increase the current. Many solar panels are connected together in parallel and series combination to give the desired electrical power output. There are three main types of photovoltaic panels on the Zambian market today and these are: Monocrystalline silicon (Mono c-Si), Polycrystalline silicon (Poly c-Si) and Amorphous Silicon (a-Si) [8] as shown in Figure 2.1.

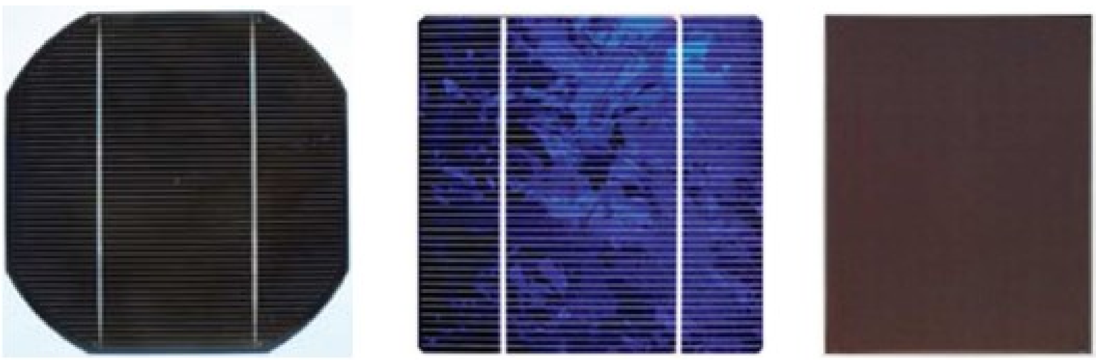


Figure 2.1: Mono c-Si solar Panel, Poly c-Si solar Panel and Amorphous a-Si solar Panel [9]

Polycrystalline silicon or poly-Si solar panels are very similar to monocrystalline solar panels, but they are fabricated using a different process. Poly-Si cells are fabricated from pure molten silicon in a square-like tank. The obtained ingots are cut in bars with a cross-section of 15.6 cm x 15.6 cm; finally they are sawn into thin wafers. The other difference in Polycrystalline solar panels is that the cell modules are typically rectangular, rather than "pseudo-square" compared to mono-Si, so they can be packed very closely in the panels. The appearance of the poly-Si is distinctly blue (see Figure 2.1) due to the lack of absorption of higher energy photons [10]. Amorphous silicon (a-Si) is the non-crystalline form of silicon and is fabricated using the vapour-deposition process to create a thin layer of silicon material of about 1μm thickness on a substrate material such as glass or metal. One disadvantage of amorphous thin Si films is the significant degradation in their power output when exposed to the sun. The stability can be improved when using thinner layers. Amorphous Silicon panels have an efficiency of up to 12% [11].

2.2 Principal Operation of Photovoltaic Panels

The working principle of solar cells is based on the photovoltaic effect which is closely related to the photoelectric effect [5, 12]. During the photoelectric effect, an electron is emitted from a material that has absorbed light with a frequency above the material's threshold frequency. Albert Einstein referred to this absorbed light as a quanta of energy called a photon. The energy of each photon is given by

$$E = h\nu \tag{2.1}$$

where h is the Planck's constant and v is the frequency of the light.

In a semiconductor, a photon of energy greater than the band gap energy will excite an electron from the valence band edge (E_v) to the conduction band edge (E_c). Between these two bands no allowed energy states exist which can be populated by electrons. This energy difference is called the forbidden gap (E_g) as shown in Figure 2.2.

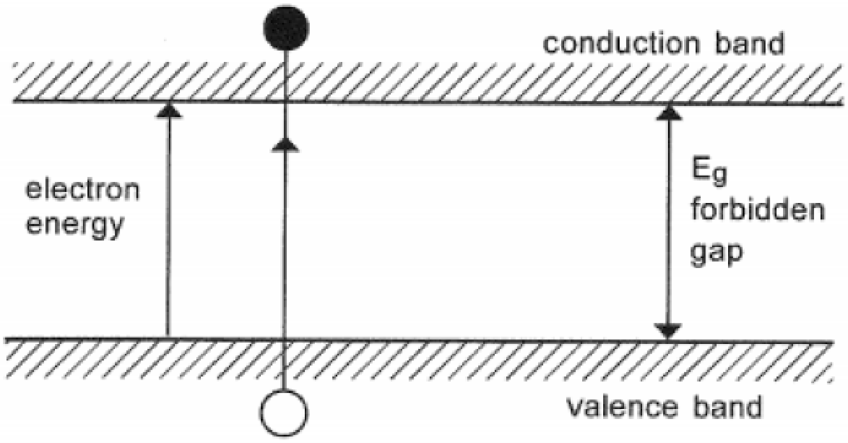


Figure 2.2: Scheme of the energy bands in a semiconductor [13]

The bandgap energy is given by the equation

$$E_g = E_c - E_v \tag{2.2}$$

If a photon with an energy smaller than E_g reaches an ideal semiconductor, it will not be absorbed but will traverse the material without interaction. However, if the photon's energy is greater than or equal to the band gap energy, the electron excited from the valence band to the conduction band creates a void in the valence band (Figure 2.2). This void behaves like a particle with a positive elementary charge and is called a hole. The absorption of a photon therefore leads to the creation of an electron-hole pair [5, 14]. The radiative energy of the photon is converted to the chemical energy of the electron-hole pair where the maximal conversion efficiency from radiative energy to chemical energy is limited by thermodynamics. This thermodynamic limit lies in between 67% for non-concentrated sunlight and 86% for fully concentrated sunlight [15].

As the electrons and holes diffuse in opposite direction, an electrostatic potential is set across the junction which causes the electrons to move towards the n-type material and holes move towards the p-type material as shown in Figure 2.3.

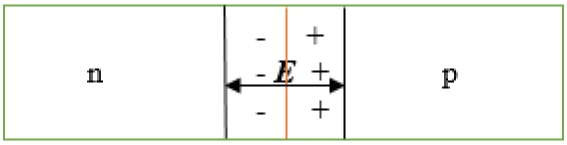


Figure 2.3: Creation of the depletion region across the p-n junction

When there are no electric fields the electron-hole pair will recombine, such that, the electron will fall back to the initial energy level. The energy will then be released either as photon (radiative recombination) or transferred to other electrons or holes and at times may cause lattice vibrations (non-radiative recombination).The photo-generated charge carriers at the terminals of the junction are extracted from the solar cell through electrical contacts such that electrons flow out through one membrane and holes flow out through the other membrane [16] as illustrated in Figure 2.4. After the electrons pass through the circuit, they will recombine with holes at a metal-absorber interface. A solar cell has to be designed in such a way that the electrons and holes can reach the membranes before they recombine, i.e. the time it requires the charge carriers to reach the membranes must be shorter than their lifetime [13, 14]. This requirement limits the thickness of the absorber.

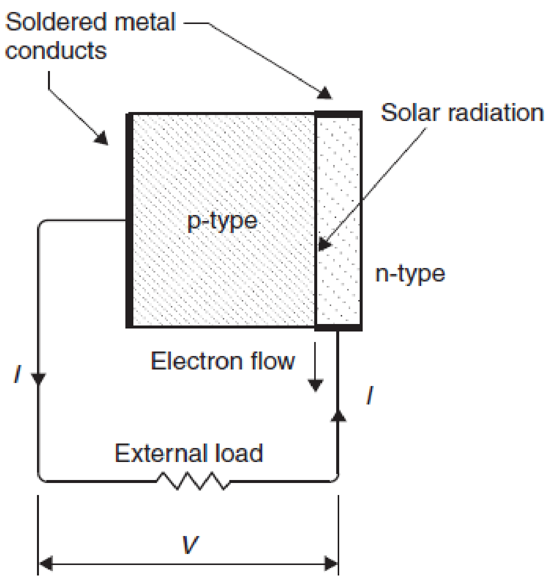


Figure 2.4: Biasing a p-n junction through an external load [14]

2.3 Characteristic Parameters of Photovoltaic Current-Voltage (I-V) Curve

The parameters related to the I-V curve include the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum voltage (V_m), maximum current (I_m) and maximum power (P_m) as shown in Figure 2.5. These are used to determine the solar panels performance at various levels of insolation and temperature [17].

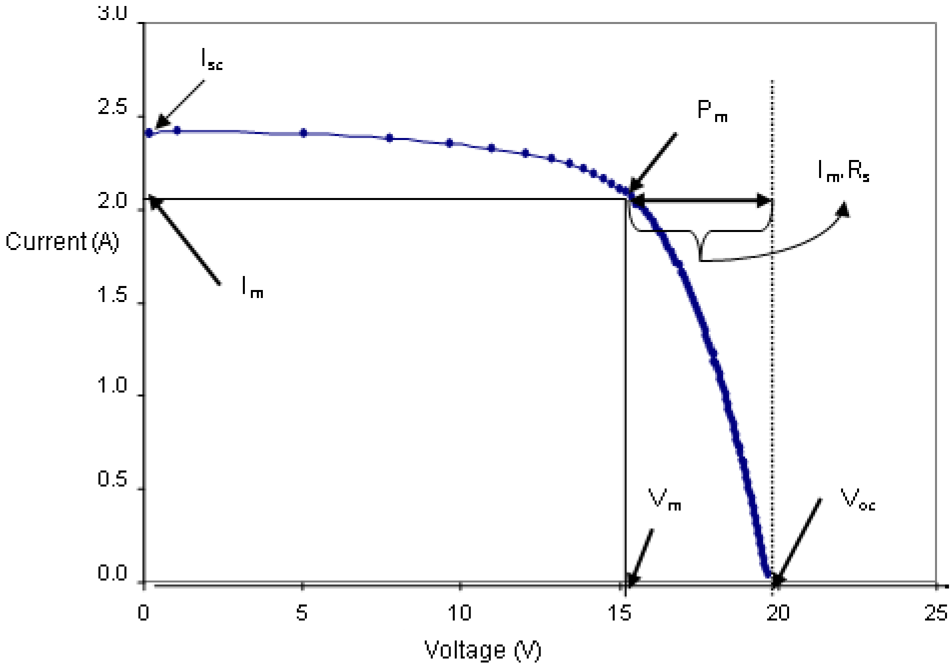


Figure 2.5: Characteristic parameters of a solar cell on an I-V curve [18]

2.3.1 Short circuit current, I_{sc}

The short-circuit current (I_{sc}) also called photo-generated current (I_{ph}) is generated when a solar cell is illuminated. It is the current through the cell when the voltage across the solar cell is zero [19]. It can be measured by connecting a low impedance ammeter in series with the solar cell. The output voltage of the solar cell under short circuit condition is zero because all the current flows through the low impedance ammeter instead of the high impedance voltmeter. The total circuit current is given by the equation

$$I = I_{sc} - I_0[\exp(\frac{eV}{kT}) - 1] \quad (2.3)$$

where:

- I is the total current from the solar cell.
- I_0 is the current when no light is falling on the solar cell. It increases as temperature increases as well as when the material quality increases. For a silicon solar cell, $I_0 = 1.5 \times 10^5 exp\left(\frac{-Eg}{kT}\right)$A/cm^2.
- e is the electronic charge.
- V is the potential difference across the solar cell.
- k is the Boltzmann's constant.
- T is the absolute temperature, depicting the cell temperature.
- I_{sc} is the short circuit or light-generated current.

The output power of the solar cell under short circuit conditions is

$$P = IV = P_{sc} = I_{sc} \times 0 = 0W \tag{2.4}$$

2.3.2 Open circuit voltage, V_{oc}

The open-circuit voltage (V_{oc}) is the maximum possible voltage measured across a cell in sunlight when no current is flowing [20]. It is measured by connecting a high impedance voltmeter across the terminals of the solar cell. It is mostly determined by the electronic structure of the photovoltaic device. The open circuit voltage is given by the formula

$$V_{oc} = \frac{kT}{e} ln\left(1 + \frac{I_{sc}}{I_0}\right) \tag{2.5}$$

The output power of the solar cell under open circuit conditions is

$$P = IV = P_{oc} = 0 \times V_{oc} = 0W \tag{2.6}$$

2.3.3 Maximum power, P_m

Maximum power is the product of maximum current (I_m) and maximum voltage (V_m) derived from the I-V curve (Figure 2.5). It is the point on the I-V curve where the area of the resulting rectangle is largest [19, 20] and is given by the formula

$$P_m = I_m \times V_m \tag{2.7}$$

2.3.4 Parasitic resistances

The I-V curve describes the ideal solar cell. An ideal solar cell is modelled by a current source, representing the photo-generated current (I_{ph} or I_{sc}) in parallel with a diode representing the p-n junction of a solar cell. In a real solar cell, there exist other effects. Two of these extrinsic effects are: (1) current leaks proportional to the terminal voltage of a solar cell characterized by a parallel (shunt) resistance (R_{sh}) and (2) losses of semiconductor itself and the metal contacts with the semiconductor characterized by a series resistance (R_s) [21]. The schematic solar cell with parasitic resistances is shown in Figure 2.6.

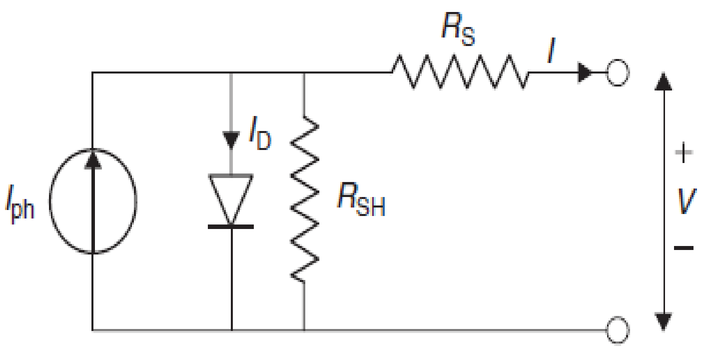


Figure 2.6: Different Parasitic resistances of a solar cell [21]

The photo-generated current including the impact of the parasitic resistances is given by

$$I = I_{sc} - I_0 \left[\exp\left(\frac{eV}{kT}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{2.8}$$

It should be noted that the shunt resistance is much larger than the load resistance while the series resistance is much smaller than the load resistance. Therefore, ignoring the two resistances, the net current out of an illuminated solar cell is

$$I = I_{sc} - I_0 \, [\exp(\frac{eV}{kT}) - 1] \tag{2.9}$$

2.3.5 Fill-factor, FF

Fill factor is a measure of how well a p-n junction and a series resistance in the solar cell are made [22]. It is the ratio of maximum power (P_m) of solar PV panel to the product of open circuit voltage (V_{oc}) and short circuit current (I_{sc}). In other word, fill factor, FF is the ratio of the maximum power output of the solar panel to the theoretical power input when the current and voltage are at their maximum values (points) [23] and is mathematically expressed as

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} \tag{2.10}$$

The empirical relationship between FF and V_{oc} [3] points out the dependency of FF only on V_{oc}. On the I-V curve (Figure 2.7) the area of rectangle A formed by the intersection of the extended lines from the voltage axis (voltage at maximum power, V_m) and the current axis (current at maximum power, I_m) represents the maximum power of the solar PV panel whereas the area of rectangle B formed by the intersection between the extended lines from the voltage axis (voltage at V_{oc}) and the current axis (current at I_{sc}) represents theoretical power input when the current and voltage are at their maximum values. Dividing the area of rectangle A by the area of rectangle B gives the fill factor of the solar panel [24], such that;

$$FF = \frac{Area\ of\ rectangle\ A}{Area\ of\ rectangle\ B} \tag{2.11}$$

The shape of I-V curve changes with the change in fill factor (FF) of solar cell. The I-V curve with highest value of FF (=1) indicates the maximum value of power.

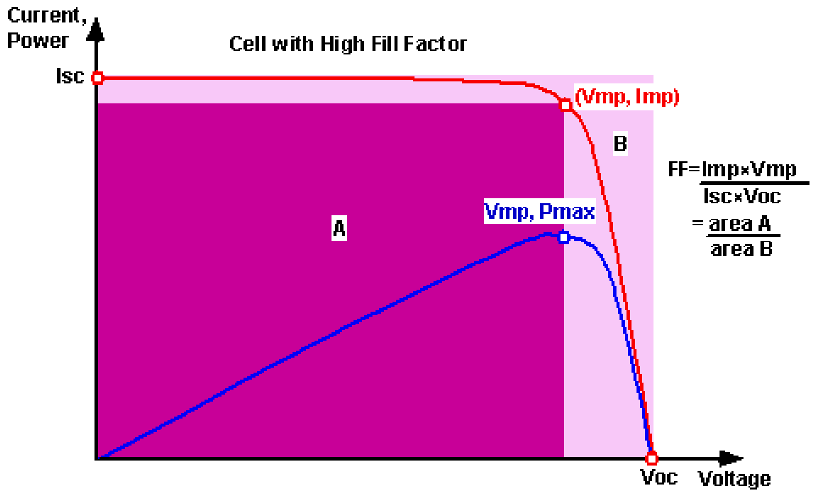


Figure 2.7: Fill factor as a ratio of areas of rectangles [25]

The more squareness of the I-V characteristic curve leads to the optimized value of fill factor of the solar panel and consequently causes the maximized efficiency of solar PV power generating system.

The maximum theoretical FF from a solar cell can be determined by differentiating the power from a solar cell with respect to voltage and finding where this is equal to zero.

$$\frac{d(IV)}{dV} = 0 \tag{2.12}$$

which gives

$$V_m = V_{oc} - \frac{kT}{e}\ln\left(\frac{V_m}{kT/e} + 1\right) \tag{2.13}$$

The above equation is an empirical equation and it converges rapidly with iteration. By starting with $V_m = 0.9 \times V_{oc}$ as the initial condition, there is < 1% error after one iteration and negligible (< 0.01%) after three iterations. By using Lambert functions, substituting the value of V_m back into the diode equation gives I_m and FF. A more commonly used empirical expression for the FF is

$$FF = \frac{V_{oc} - \ln(V_{oc} + 0.72)}{V_{oc} + 1} \tag{2.14}$$

This whole expression is a function of open circuit voltage (V_{oc}). It means that the optimized value of this function will yield to ensure the extraction of maximum power from solar PV system to the load at any instant of time throughout the day.

Equation (2.14) also demonstrates the importance of the ideality factor, also known as the "n-factor" of a solar cell [26]. The ideality factor is a measure of the junction quality and the type of recombination in a solar cell. The n-factor has a value of 1. However, some recombination mechanisms, particularly if they are large, may introduce recombination mechanisms of 2. A high n-value not only degrades the FF, but since it also usually signals high recombination, it gives low open-circuit voltages. A key limitation in the equations described above (eqn 2.13 and eqn 2.14) is that they represent a maximum possible FF, although in practice the FF will be lower due to the presence of parasitic resistive losses.

Series resistance in a solar cell is caused by (1) the movement of current through the emitter and base of the solar cell, (2) the contact resistance between the metal contact and the silicon and (3) 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. The empirical equation for the FF as a function of series resistance is given as

$$FF_s = FF_0(1 - 1.1r_s) + \frac{r_s^2}{5.4} \tag{2.15}$$

This equation is valid for $r_s < 0.4$ and $V_{oc} > 10$.

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 empirical equation as a function of shunt resistance [27] is given as

$$FF_{sh} = FF_0\left(1 - \frac{V_{oc}+0.7}{V_{oc}}\frac{FF_0}{r_{sh}}\right) \tag{2.16}$$

This equation is valid for $r_{sh} > 0.4$ [22]

Combining the effects of both series and shunt resistances the net fill factor becomes;

$$FF = FF_0\left\{(1-1.1r_s)+\frac{r_s^2}{5.4}\right\}\left\{1-\frac{V_{oc}+0.7}{V_{oc}}\frac{FF_0}{r_{sh}}\left[(1-1.1r_s)+\frac{r_s^2}{5.4}\right]\right\} \quad (2.17)$$

This equation is valid for $r_s < 0.4$, $V_{oc} > 10$ and $r_{sh} > 0.4$.

2.3.6 Efficiency, η

Efficiency of a solar PV panel is the most important parameter to consider when buying a solar panel. It is a ratio of the measured power output to the total power incident on the solar panel [28]. Solar PV panel efficiency is denoted by the symbol 'η'.

$$\eta = \frac{Power\ output}{Power\ input} \quad (2.18)$$

If a solar panel could convert light energy perfectly, i.e. 100% efficiency, the power output would be the same as the power available. This is not possible due to several energy losses, some of which are illustrated in Figure 2.8.

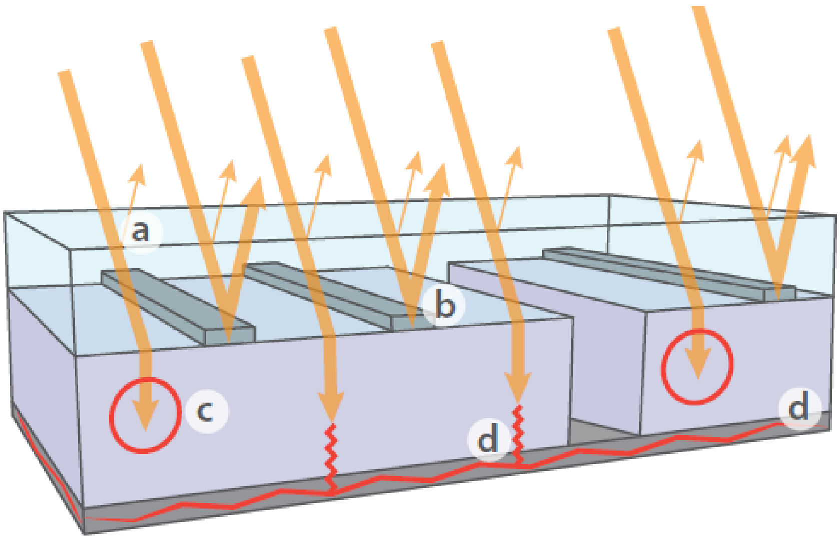


Figure 2.8: Sources of energy loss in a solar panel [29]

a. Solar energy being reflected by the glass cover.

b. Shading from metal conductors which are placed on top of the cells to collect the electrical current generated.
c. Not all of the solar energy converts to electricity via the photovoltaic effect – some wavelengths of light have excess power and some do not have enough to produce electricity.
d. As electricity travels through the cells and cell interconnections, it encounters electrical resistance resulting in heat loss.

Efficiency of the solar panel will always be less than the efficiency of the PV cell. While the PV panels incur losses caused by reflection of light off the glass, shading of the cells caused by connection bars, and the increased electrical resistance from the module's interconnections.

The rated power of a solar panel takes into account its efficiency and a panel with reduced efficiency is typically characterised by an increased physical size relative to a panel of the same rated power but higher efficiency (Figure 2.9 a). Alternatively, if two solar panels have the same physical size, the one with lower panel efficiency will have a lower rated power output (Figure 2.9 b). This is often the case when a manufacturer offers a single panel brand or model for a range of power ratings.

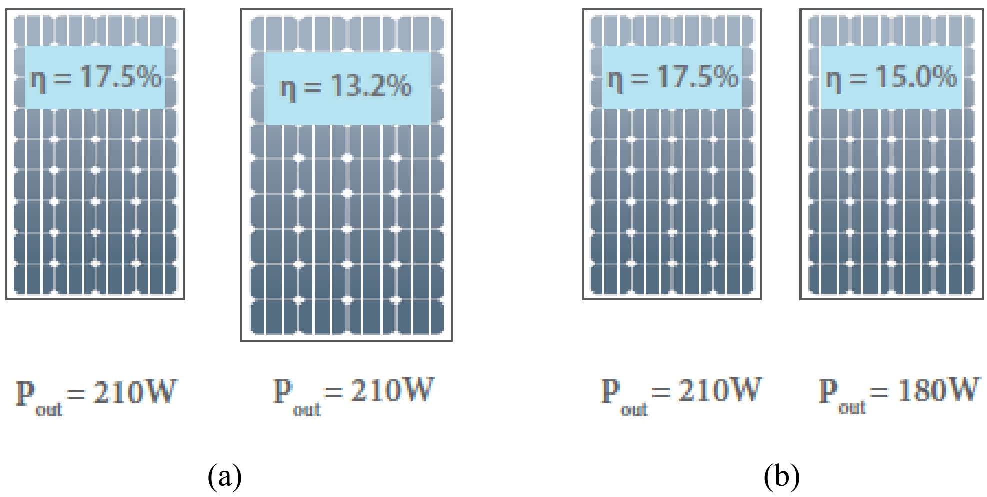


Figure 2.9: a) Effect of efficiency on solar panel size at identical power output. b) Effect of efficiency on power output at identical physical size [30]

In some cases, such as satellite applications or a client having limited installation space, both the available area for the array and the required power output will have been specified: in such situations, the process of choosing a solar panel type may be assisted by a rough efficiency calculation. By dividing the specified rated power by the available area multiplied by 1000 W/m^2, a minimum efficiency can be obtained [31].

$$\eta = \frac{Specified\ rated\ power\ of\ solar\ array}{Available\ installation\ area\ (m^2)\times 1000\ W/m^2} \tag{2.19}$$

In other words efficiency is the ratio of power produced by a photovoltaic device to the total light irradiance falling on its surface under standard conditions. It is proportional to the fill-factor [32]. Thus, the conversion efficiency of a solar cell is given by

$$\eta = \frac{I_{SC}\times V_{OC}\times FF}{Incident\ solar\ Radiation\times Area\ of\ solar\ cell} \tag{2.20}$$

Note that the rated efficiency of panels will always be greater than the calculated value.

When studying the efficiency of solar cells it is important to understand what really occurs inside the solar cell. There are two terms that are important to distinguish between, the semi-empirical limit and the detailed balanced limit. The semi-empirical limit of efficiency (calculated as a function of the energy gap) is based upon empirical values for constants of the system whereas the detailed balanced limit is the theoretically justified limit of efficiency [6]. At the time of Shockley and Queisser, the efficiency of solar cells was based solely on the semi-empirical limit. The walk through, following Shockley and Queisser's steps, finds the maximum possible efficiency by deriving the theoretically justified limit, the detailed balanced limit. Since the detailed balanced limit is significantly higher than the semi-empirical limit, at times up to 50% higher, the difference between the two gave scientists hope that real progress could be made in increasing the efficiency of pre-existing solar cells and bringing the experimentally found semi-empirical limit up to match the newly found theoretical limits [6].

For the efficiency definition used in thermodynamic engines, the maximum efficiency corresponds with zero entropy creation, which then leads to the Carnot efficiency limit. The efficiency definition in solar cells however is different and maximum efficiency operation does not correspond with the reversible operation (zero entropy) but gives rise to appreciable entropy creation [33]. The thermodynamic efficiency limits of Carnot cannot be reached in solar cells; different approaches must be used when it comes to calculating the theoretical efficiency limits of solar cells.

The ultimate efficiency hypothesis states that each photon with energy greater than hv_g produces one electronic charge e at a voltage of $V_g = hv_g/e$ where V_g is the cut off voltage in a device that utilizes a photoelectric process [7, 10]. This theory holds for all types of solar cells. In theory, the efficiency of a solar converter can be brought to the thermodynamical limit $(T_s - T_c)/T_c$ by using reflectors. However, a simple planar solar cell without any method to concentrate the radiation cannot hope to even approach this limit. The limit it can approach depends on:

- its energy gap, E_g
- the angle subtended by the sun
- the angle of incidence of radiation
- absorption coefficient of solar energy and other degrading factors which in principle can be treated as if they approach unity.

The fraction of recombination between holes and electrons result in radiation, and it is this radiative recombination that determines the detailed balance limit for efficiency. Thus efficiency is the ratio of power delivered from the cell to the incident solar power collected. In order to carry out the calculation to determine the limit of efficiency, five processes must be considered: (1) the generation of hole-electron pairs by the incident solar radiation, (2) the radiative recombination of hole-electron pairs with resultant emission of photons, (3) other non-radiative processes which result in a generation, (4) recombination of hole-electron pairs, and (5) removal of holes from the p-type region and electrons from the n-type region in the form of a current I which withdraws hole-electron pairs at a rate I/e [10, 12]. In accordance with the given processes, the ultimate efficiency [34] is

$$u(x_g) = hv_g\, Q/P_{sun} = \frac{x_g \int_{x_g}^{0} x^2 dx/(e^x-1)}{\int_0^{\infty} x^3 dx/(e^x-1)} \tag{2.21}$$

Given the maximum output of the system, which is obtained by using a voltage V that produces a maximum I-V value, the efficiency can be expressed as a function dependent upon four variables,

$$\eta = \eta(x_g, x_c, t_s, f) \tag{2.22}$$

where $x_g = E_g/kT_s$ and $x_c = T_c/T_s$ are both ratios, t_s is the probability that a photon with $hv > E_g$ incident on the surface will produce a hole-electron pair, and f is the quantity which takes into account all other parameters such as those involving transmission of radiative recombination (f_c) and the solid angle subtended by the sun [35].

$$\eta = \eta(x_g, x_c, t_s, f) = \frac{I_{max}V_{max}}{P_{inc}}$$
$$= t_s u(x_g) v(f, x_c, x_g) m(vx_g/x_c) \tag{2.23}$$

where t_s is the probability that a photon will produce an electron-hole pair; $u(x_g)$ is the ultimate efficiency in accordance with the ultimate efficiency hypothesis; $v(f, x_c, x_g)$ is the ratio of the open-circuit voltage to the energy gap of the cell; and $m(vx_g/x_c)$ is the impedance matching factor, which is a function of the ratio of the open-circuit voltage to thermal voltage for the cell. To summarize, the maximum efficiency of a single gap solar cell is the electrical power out of the cell divided by the power of the incident solar energy falling on the cell.

CHAPTER 3

3.0 LITERATURE REVIEW

Research and development efforts in solar photovoltaics have paid off in the form of increasing the fill factors and efficiencies at both solar cell and solar panel levels. For example, cell efficiencies reported in major laboratories for crystalline silicon have increased from 13% in the 1970s to 26% in 2016 [36, 37], almost doubling in the period, and thus approaching the theoretical thermodynamic limit of 34% (Shockley-Queisser limit) [6] for single crystal silicon cell at standard test conditions. Advances in thin-film and multi-junction cell technologies have been even more rapid. The cell-to-panel efficiencies for these cell technologies have also improved to 99% in 2015 and are projected to exceed 103% by 2026 because of improvement in light management techniques [38].

As research laboratories and industry players focus on improving solar-to-electric conversion efficiencies, there is increasing acknowledgement of the need for data on the performance of systems that have already been deployed across the various climates and geographical regions of the world.

A characteristic feature of solar PV is the conversion efficiency of incident radiation to output power. Once installed, the reliable performance and durability of the solar system enable it to generate electricity which represents a benefit to the investor and the system owner. Reliability is understood as the probability that an item, in this case the solar PV panel, will continue to perform its intended function without failure for a specified period under stated conditions [39]. Durability on the other hand has to do with how long the product will last under normal operating conditions [40].

For the solar PV investor, reliable operation of the PV panels and their durability as per warranty conditions, are important for the realization of the expected return on investment. Solar panel manufacturers, similar to other product manufacturers, attempt to assure buyers of their products by providing warranties. The warranties on PV panels have evolved from 5 years in the 1980s through 10 - 20 years in the 1990s to the current industry standard practice of 80% of peak power for 25 years [41]. Some manufacturers provide 2-stage (and other multi-stage) warranties [42]. The Renewable Energy Corporation (REC) Solar [43] for example, provides a 97% performance guarantee on its panels within the first year of exposure and 80.2% of peak power by the end of the 25th year.

For the current standard 25-year warranty (80% of peak power) to hold, solar panels must, on average, degrade at not more than 0.8% per year. However, industry players are seeking to extend warranty periods to 30 years [44], which would imply a maximum average annual performance decline of no more than 0.65%.

Warranties on solar panels entail that the panels will work in the outdoor environment efficiently and effectively for the stipulated period. However, solar PV warranties encounter two major hurdles. First, is the enforceability of the warranties [45]. This is largely attributable to the rapidly evolving landscape that has led to the extinction of many manufacturers, with others filing for bankruptcy. This extinction was most noticeable in the period 2010 - 2013, when, in the US alone, over 50 companies either collapsed or filed for bankruptcy protection [46]. Warranties provided by defunct companies on PV panels sold therefore become difficult to enforce, particularly if the need for warranty claims arise after official liquidation. The second challenge with warranties, is the more fundamental question of physical basis.

The current testing and qualification regimes such as the International Electro-technical Commission (IEC 61215) [47] for crystalline Silicon modules and IEC 61646 [48] for thin film panels employ techniques such as accelerated ageing and stress tests with the view to detecting the presence of known failure or degradation modes in the intended environments [49]. These qualification tests cannot predict or guarantee product life under field conditions. They are not designed for such a purpose [49, 50]. The IEC qualification tests rather seek, among others, to find design and process flaws and have been credited with significantly reducing infant mortality among PV panels [51]. The performance testing of PV panels in outdoor conditions is required to have an accurate estimation of the output of PV panels under specific climatic conditions.

It has been suggested [41] that recent studies based on field exposure is providing some basis for and validation of 25-year warranties; however, mainly an overwhelming majority of panels have hardly lasted 25 years on the field to prove the validity of the warranties. According to Renewable Energy Policy Network for the 21st Century – REN21 [52], over 80% of panels installed today have been installed in the last 5 to 6 years. But still, the validation of fill factors and efficiencies of the panels should be done as soon as the panel is bought from the manufacturer or supplier and installed in the environment.

Monitoring and assessment of fielded solar panels provide useful insight and feedback for panel manufacturers and R&D institutions and reduce uncertainties for solar PV investors. A number of researchers have undertaken, over the years, to study the long-term outdoor performance, degradation and failure of solar PV panels around the world. Degradation of solar panels results in a number of ways. Lorenzo et al [53], Bandou et al [54], Ndiaye et al [55], Jordan and Kurtz [41], Quintana et al [56], Skoczek [57], Skoczek et al [58], Kahoul et al [59] and Ferrara and Philipp [60] identified major causes and modes of solar panel degradation and failure include: degradation of packaging materials, loss of adhesion, degradation of cell/panel interconnects as a result of thermomechanical fatigue, degradation due to moisture intrusion and degradation of the semiconductor device. These defects tend to result in reduced panel output, safety issues and sometimes complete failure.

Nevertheless, as noted by Jordan et al [61], it may be surmised, that, degradation in performance characteristics of solar panels have some dependence on local conditions and climate zone, and there are no reports on degradation rates and failure modes of PV panels in many climate zones [61, 62]. Indeed, as demonstrated by authors such as Jordan et al [61] and Phinekarides et al [62], who compiled globally reported degradation rates and overlaid them on global maps (using the Koppen climate classification), there is very little reported from Africa, with nothing at all in the vast majority of climate classifications.

It should be noted, however, that, whereas the Koppen-Geiger classification scheme is based on temperature and precipitation, for solar PV performance and durability issues additional parameters such as humidity, temperature variation, altitude and air salinity are important as well [60]. The use of solar panels over extended periods also affects the panel performance as the output degrades with the ageing of the solar panels. Different types of solar panels degrade at different rates, for example, amorphous silicon solar panels have a higher rate of photo-degradation than poly-crystalline solar panels as investigated by Midtgard et al [63].

In principle, different types of solar cells display different characteristics under different climates around the world. This is what M. Schweiger, U. Jahn and W. Herrmann et al [64] discovered after evaluating the performance of twelve different types of PV panels: two crystalline solar panels (mono- and poly-crystalline silicon to compare with thin-film specimens), three CI(G)S solar panels (CIS and CIGS), one CdTe solar panels and six amorphous silicon solar panels (a-Si; a-Si/a-Si, a- Si/µ -Si) in Germany/European climates. Their findings were that with respect to the low irradiance behaviour, the CdTe, the c-Si and some of the a-Si specimens showed good performance. The best efficiency curves of tested thin-film solar panels were achieved by CI(G)S.

Carr and Pryor [65] as well evaluated and compared the performance of five different PV panels using an outdoor facility in the climate of Perth for one year. They found that amorphous silicon solar panels had highest performance ratio with maximum energy produced at that site. Akhmad et al [66] equally investigated the outdoor performance of polycrystalline and amorphous silicon solar panels and found that amorphous silicon solar panel had better efficiency and output power in summer. A similar study was conducted by Midtgard et al [63] at the site in Norway to investigate the performance of three PV solar panels (monocrystalline, polycrystalline, and micromorph-silicon). They concluded that monocrystalline solar panel was better in terms of efficiency and overall power production.

The fill factor and efficiency values of PV panels provided by the manufacturers are based on the Standard Test Conditions (i.e., irradiance 1000 W/m^2, panel temperature 25 ^oC and AM 1.5) which may not accurately represent panel's performance under real world outdoor conditions. For example, solar panels output current is directly proportional to the incident solar radiation, which affects the panel efficiency [67]. However, the rise in solar radiation also leads to an increase in the temperature of the photovoltaic cells which can negatively impact the panel's fill factor and efficiency. The speed at which the electrons travel in an electrical circuit is affected by temperature. The increase in temperature increases the resistance. Similarly, decrease in temperature decreases resistance and hence the speed of electron flow is affected [68]. Solar cells are delicate to temperature like all other semiconductor devices. The band gap of a semiconductor material is reduced with an increase in temperature; most of the parameters of semiconductor material are affected by an increase in temperature. By increasing the temperature of the semiconductor material, the electrons in the material have their energy increased, to break the bond lower energy is needed. The reduction in the bond energy also reduces the band gap. Hence, temperature increase reduces the band gap.

Darwish et al [69] studied the relationship between solar radiation and temperature and the resulting effect on the polycrystalline solar panel's output current, voltage, power, and electrical efficiency in Sharja, United Arab Emirates. The results showed that solar radiation had a direct effect on the temperature of the cell; as temperature increased with the increase in solar radiation low current and voltages were recorded and led to a decrease in the resulting power and efficiency. PV panel parameters are sensitive functions of panel temperature [70, 71]. Solar panel temperature can change relatively quickly if the weather conditions change, so it has to be monitored on a continuous basis [72]. Since the actual temperature inside a PV panel cannot be measured, the temperature sensors are usually attached directly to the back surfaces of the panels. The measured temperature is not quite equal to the temperature inside the panel, but it provides a good starting point for good estimates. Agroui [73] using a sun simulator found that an increase in temperature influences the electrical properties of PV panels in a controlled environment.

Nishihata et al [74] recommended that a photovoltaic panel should be installed with a tilt angle equal to the latitude of the site. To harness more incident solar radiation the tilt angle should be varied from time to time. In the Southern Hemisphere, for optimum solar radiation, a solar panel should face north and make an angle with the horizontal equal to the latitude of the location. In the Northern hemisphere, a solar panel should face south and make an angle with the horizontal equal to the latitude of the location. Between 21 March and 21 June the Sun moves further in the North. During this period, for places in southern hemisphere the photovoltaic panels should face north and tilted at an angle between ϕ and ϕ+23.5°. Between September and December, the Sun moves further in the South. During this period all solar panels in southern hemisphere should be oriented towards the south inclined at an angle between ϕ and ϕ-23.5° [75].

Another factor requiring due attention when harnessing solar energy is load matching. Load matching also called maximum point tracking is a way to maximize the total energy output of a solar panel by determining the optimal load at runtime [76]. This requires the solar system owner to be aware of the sunlight condition and the efficiency curves of the solar panel. Solar panels, like batteries and other power sources, have internal resistance R_i. Unlike batteries, whose R_i is around 0.2 - 0.7Ω solar panels have a much larger R_i values ranging from 10 $k\Omega$ to 100 $k\Omega$ [77]. The internal resistance of solar cells is a function of the sunlight intensity, solar output power and current drawn. Because the R_i forms a voltage divider with the load resistance R_L, the effective value of R_L directly determines the efficiency of the solar panel. In other words, if the load R_L is not balanced with R_i, then much of the power can be wasted. If the load is matched then the system can get the maximum benefit from the available power for longer operation [78]. Additionally, it is necessary to account for losses during conversion from the photovoltaic produced direct current (*DC*) to usable alternating current (*AC*).

The flow of wind significantly affects the fill factor and efficiency of solar panels. The direct air around the panels is called the local air temperature. This can vary the voltage of the PV system. As solar cells are below glass they are insulated. Consequently, they have temperatures more than the surroundings. In maximum cases, solar cells operate at temperatures above 25^{o}C more than the immediate air around the panels. The solar cell temperature reduces at higher wind speeds because the air temperature is also reduced [72]. As a result, wind gives a good impact on the solar cell efficiency because the temperature is reduced. But, wind can also affect the PV system physically. For instance, the wind can damage the solar system in case it is not installed properly. It can lose the electrical contact and will be displaced. A 15-20^{o}C cooling effect was stated for wind speeds of more than 10m/s at 1000W/m^2 solar irradiance. The wind cooling effect plays a central part for improved estimation of module temperature of PV system. The cell temperature will reduce as the air speed will rise [72].

The African countries which are more desert are suitable for PV generation due to plenty of sunlight all year. But, the PV panel in these types of countries is greatly affected by the build-up of dust particles [79]. The dust build-up on the surface of the panel depends on different factors like PV panel tilt angle, adjustable or fixed panel and humidity. It is vital to know how frequently the panel will need cleaning and in the event cleaning the panel is not easy the panel will lose its performance. Dust particles cause shading to the solar cells. Shading has a negative effect on the performance of solar panels. Gooijer and Dijk [80] observed that shaded solar cells receive lower irradiance, thus, causing drop in current, power and efficiency.

These studies do not validate the quality of solar panels in terms of outer performance in the field condition. This study seeks to contribute to filling this gap (Outdoor testing of some commercial solar panels found on the Zambian market in terms of fill factors and efficiencies). As noted by Jordan et al [61], degradation in performance characteristics of solar panels have some dependence on local conditions and climate zone. Yet there is no report of validation of performance of solar panels under the Zambian solar conditions.

CHAPTER 4

4.0 METHODOLOGY AND MATERIALS

4.1 Study Design

A survey was carried out to find the types and sizes of solar panels supplied to the market in Lusaka. Areas of Lusaka surveyed included Kalingalinga, Mtendere, Lusaka Central Business Area, Matero, Kanyama, Chilanga, Chawama, Mandevu, George, Zingalume and Linda. This study design ensured that proper attention was given to all shops that were open in the area at the time of the survey as well as to solar panels that were sold on the streets. Samples of panels of the same type and same power ratings were bought. Each category of power ratings such as 3Wp, 15Wp, 40Wp, 50Wp were tested for I_m, V_m, I_{sc}, and V_{oc} from which the fill factors and efficiencies were determined.

4.2 Research Instruments

The systems under study comprised 3Wp, 15Wp, 40Wp and 50Wp solar panels. The panels consisted of tempered glass at the front, ethylene vinyl acetate (EVA) encapsulate, polymer back sheet and aluminium frame [36, 81]. In the study, two methods which were used are visual inspection and I-V characterisation. The visual inspection of the panels was undertaken using the widely applied field visual inspection template by the National Renewable Energy Laboratory or the International Energy Agency (NREL/IEA) [36]. This procedure was used to systematically document any visually observable defects on the various components of the panels such as front glass, back sheets, junction boxes, metallisation, encapsulations, frames and interconnections following intervals of outdoor exposure. The I-V characterization of the panels under study was undertaken using an I-V curve tracer. The measurements of irradiance, panel temperature and panel inclination angle were taken using a Solar Survey 200R. In-plane irradiance and panel temperature are necessary for the translation of the current-voltage measurements to other reference conditions, such as Standard Test Conditions (STC) -i.e., 25°C, 1000 W/m^2 and Air Mass (AM) 1.5.

4.3 Experimental Set up for the Solar Panels

The solar panels were oriented towards the sun with varying angles of inclination to the horizontal, such as 15ºC, 17ºC, 20ºC, 35ºC and 39ºC. The angles were varied on some measurements in order to have an incident solar radiation close or equal to 1000 W/m^2 on the panel. On the measurement days the impact of wind and cloud covers affected the solar insolation falling on the panels such that it was fluctuating between 800 W/m^2 and 1000 W/m^2. In order to record the desired solar insolation (close or equal to 1000 W/m^2) the angles had to be varied. To eliminate impact of dust on the measurement, the panel's surfaces were cleaned with a smooth cloth before measurements were made.

4.3.1 Measurements of the 3Wp solar panels

The four 3Wp solar panels, all poly-crystalline were inclined at 20^o to the horizontal. The set-up for each panel is shown in Figure 4.1 and the electrical specifications are shown in Figure 4.2.

Figure 4.1: Set up for the 3Wp solar panels

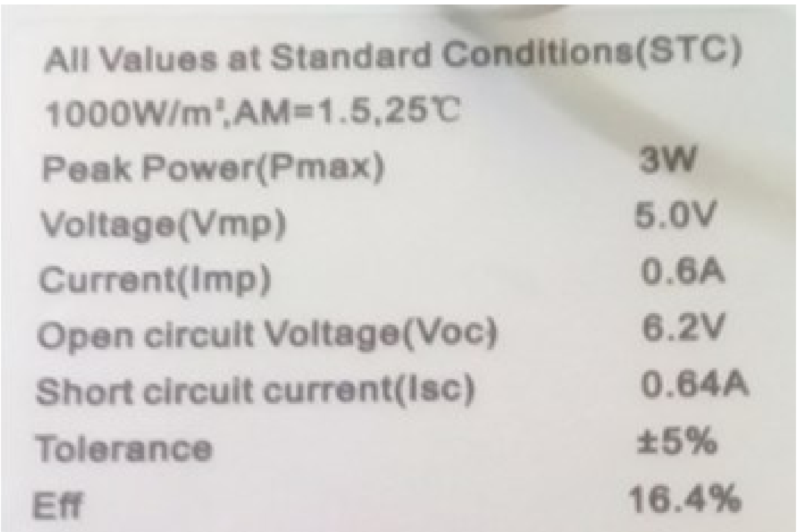


Figure 4.2: Electrical Specifications for the 3Wp solar panels

4.3.2 Measurements of the 15Wp solar panels

The one 15Wp poly-crystalline solar panel was inclined at three different inclinations to the horizontal, i.e. 17^o, 20^o and 39^o for three consecutive I-V measurements. The angles were varied for each measurement in an attempt to record nearly same amount of incident radiation on the panels since due to wind and cloud covers the irradiance was fluctuating below 1000 W/m^2. The set-up for the I-V measurement with desired solar irradiation is shown in Figure 4.3, and the electrical specifications are shown in Figure 4.4.

Figure 4.3: Set up for the 15Wp solar panels

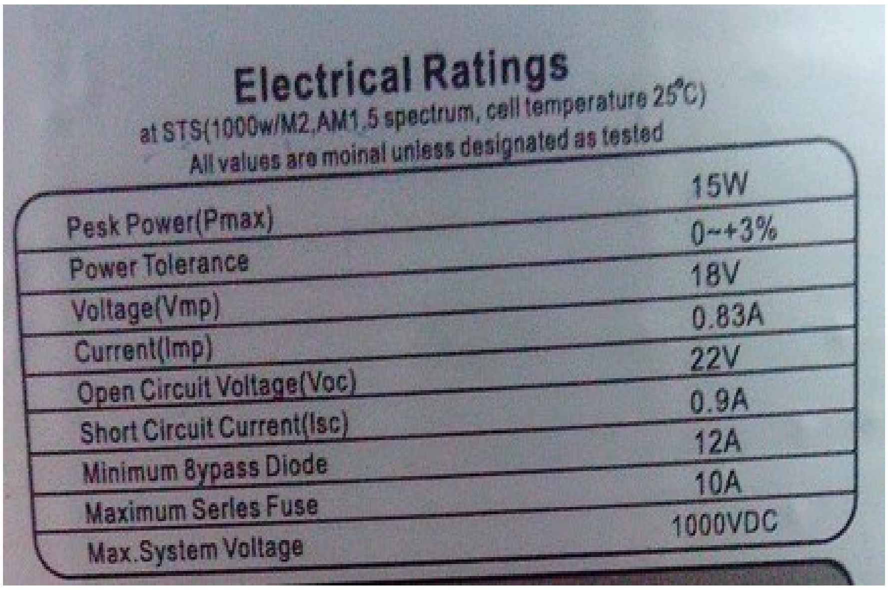


Figure 4.4: Electrical Specifications for the 15Wp solar panels

4.3.3 Measurements of the 40Wp solar panels

The four 40Wp solar panels all poly-crystalline were inclined at 35^{o} to the horizontal. The set up for the panels is shown in Figure 4.5 and the electrical specifications are shown in Figure 4.6.

Figure 4.5: Set up for the 40Wp solar panels

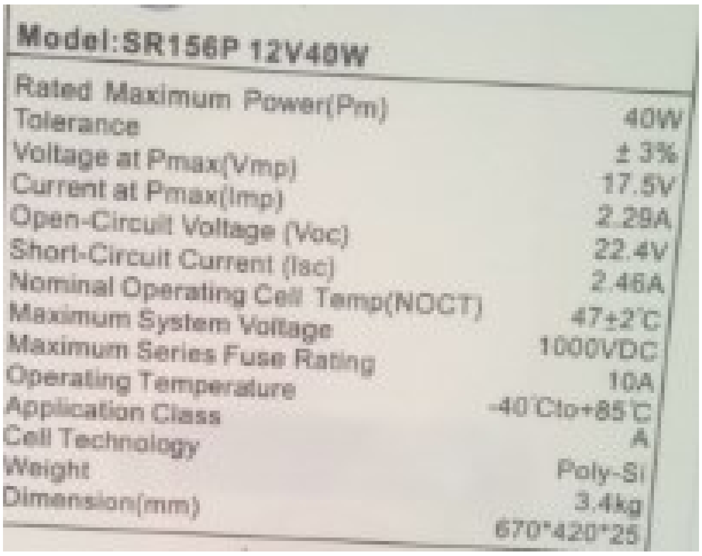


Figure 4.6: Electrical Specifications for the 40Wp solar panels

4.3.4 Measurements of the 50Wp solar panels

The one 50Wp poly-crystalline solar panel was inclined at 15^o, 17^o and 19^o to the horizontal for three consecutive I-V measurements. The angles were varied for each measurement in an attempt to record nearly same amount of incident radiation on the panels since due to wind and cloud covers the irradiance was fluctuating too below 1000 W/m^2. The set up for the I-V measurements is shown in Figure 4.7. The electrical specification is shown in Figure 4.8.

Figure 4.7: Set up for the 50Wp solar panels

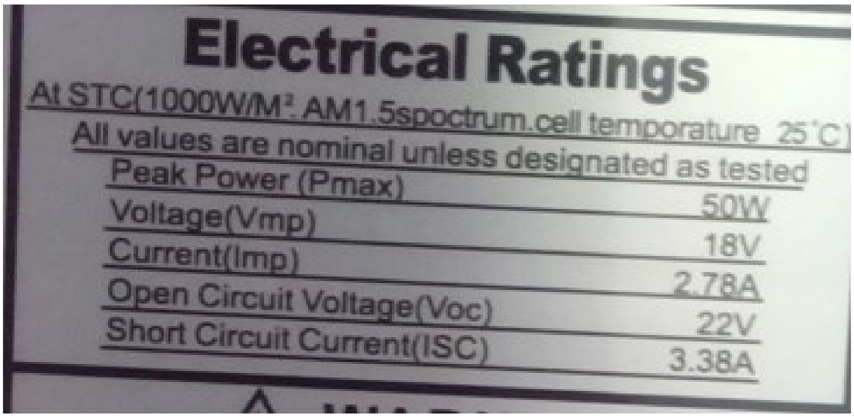


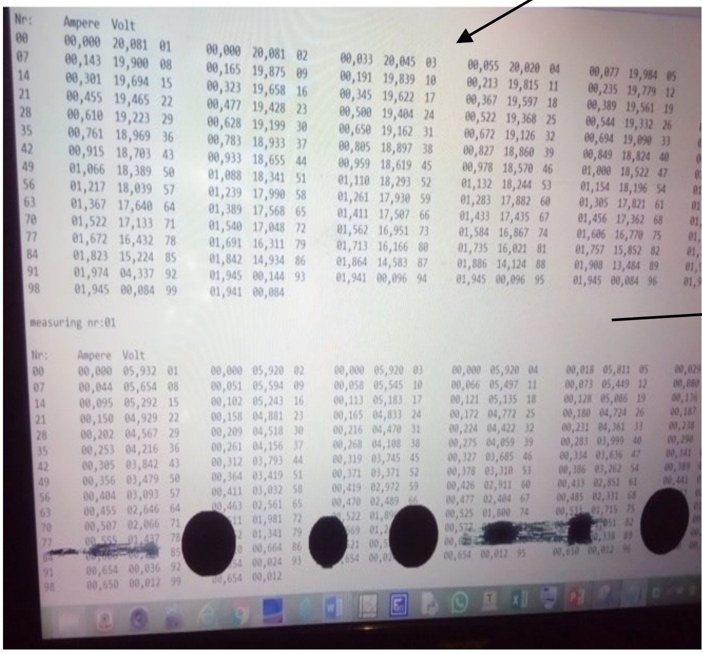
Figure 4.8: Electrical Specification for the 50Wp solar panels

4.4 Data Collection Procedure

Figure 4.9 shows how the I-V curve tracer was interfaced with each solar panel and the computer to obtain the I-V curves. For each measurement, the solar panel was connected to the I-V Curve tracer which was directly connected to the computer. The output of the solar panel was connected to the computer that used the Tera Term software for data collection. The data was manually arranged in vertical columns as an Excel file and the I-V curves were plotted. The excel data was analysed to obtain the required parameters.

Panel Set up with Irradiance meter

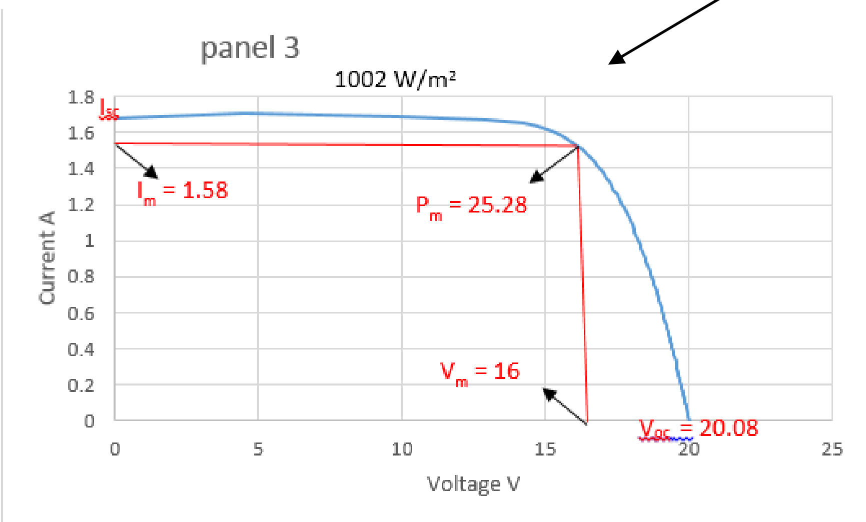
I-V Curve tracer



Nr:	Volt	Ampere
0	20.02	0
1	20.02	0
2	19.996	0.025
3	19.96	0.044
4	19.936	0.066
5	19.912	0.084
6	19.875	0.102
7	19.851	0.121
8	19.827	0.139
9	19.803	0.158
10	19.767	0.18
11	19.742	0.198
12	19.718	0.216
13	19.682	0.235

Computer Display

Data in vertical column



Plotted data

Figure 4.9: Plotted I-V curve data

4.5 Data Analysis

The visual and physical inspection tables and pictures of each type of solar panels have been provided. Further, the current-voltage curves for the solar panels are plotted. The fill factor (FF) and efficiency (η) are calculated using the following equations:

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} \tag{4.1}$$

$$\eta = \frac{I_{sc} \times V_{oc} \times FF}{Incident\ solar\ Radiation \times Area\ of\ solar\ cell} \tag{4.2}$$

CHAPTER 5

5.0 RESULTS AND DISCUSSION

5.1 Measured Solar Panels Parameters versus the Manufacturer's Given Parameters

5.1.1 3Wp solar panels

For the four 3Wp solar panels tested, three measurements were taken for each panel. Only measurements with irradiation above 800 W/m^2 were analysed. Measurements with irradiation less than 800 W/m^2 were considered to be much lower than the standard condition of 1000 W/m^2 and thus were discarded. The curves for the analysed measurements are shown in Figure 5.1. The curve with irradiation close to 1000 W/m^2 was used to record the measured values of the solar panel at local conditions as shown in Table 5.2.

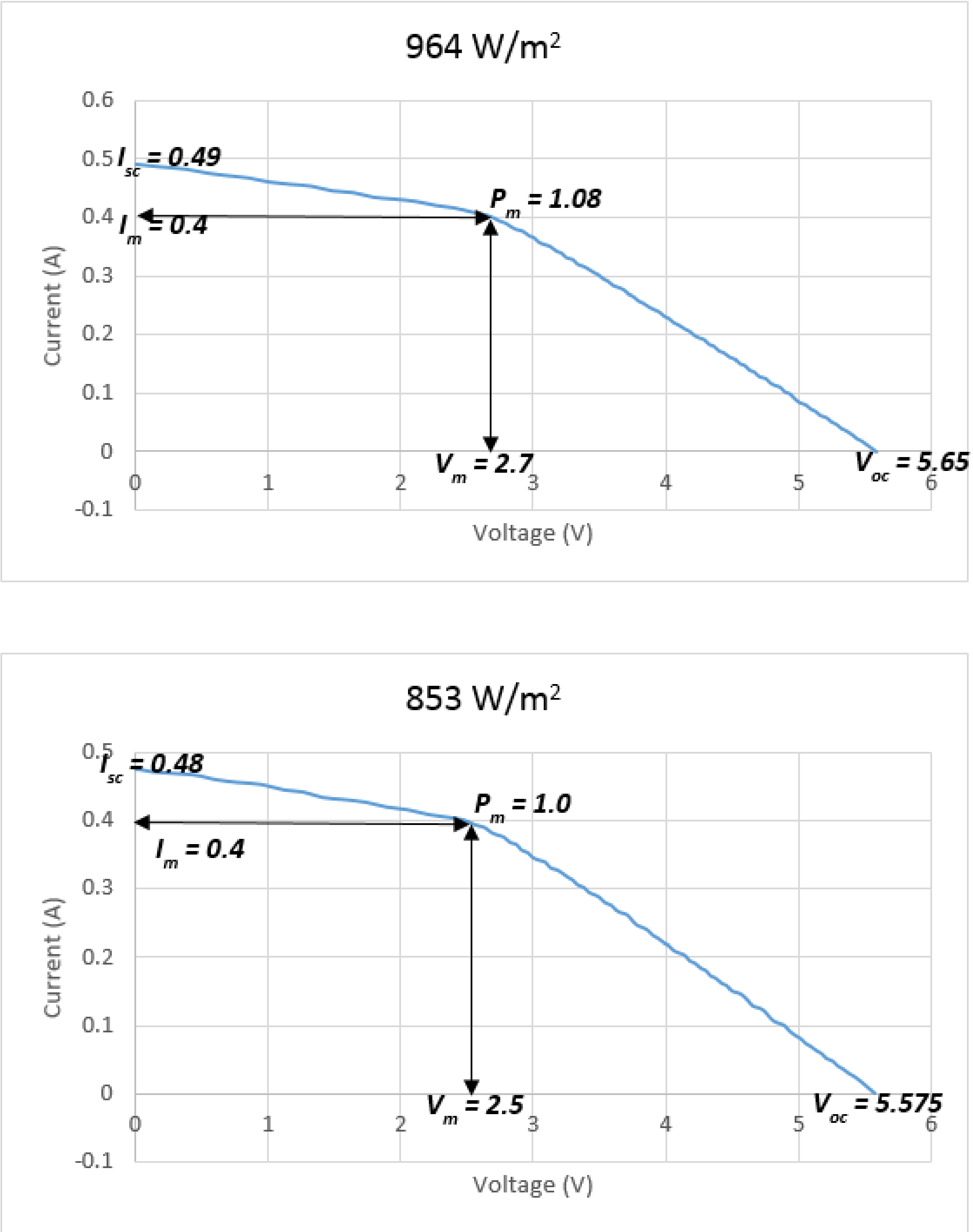


Figure 5.1: I-V Curves for the 3Wp solar panels

5.1.1.1 Visual and physical inspection of the $3W_p$ solar panels

The summary is presented in Table 5.1. Accompanying pictures are shown in Figure 5.2 and Figure 5.3.

Table 5.1: Visual inspection observations of the $3W_p$ solar panels

COMPONENT	OBSERVATION(S)
Front glass	Smooth, no damage or cracks (Figure 5.2)
Back-sheet	No discolouration on the back side of glass.
Wires/ connectors	No embrittlement or burns are observed
Junction box	Completely sealed and well attached, no loss of adhesion is observed (Figure 5.3)
Frame	No discolouration. No corrosion. Frame adhesive is not visible.
Metallisation	Bus-bars and cell interconnects shows no burns, discolouration or corrosion
PV Cell	The cells are observed to be in good condition

Figure 5.2: Smooth, dry and transparent $3W_p$ solar panel

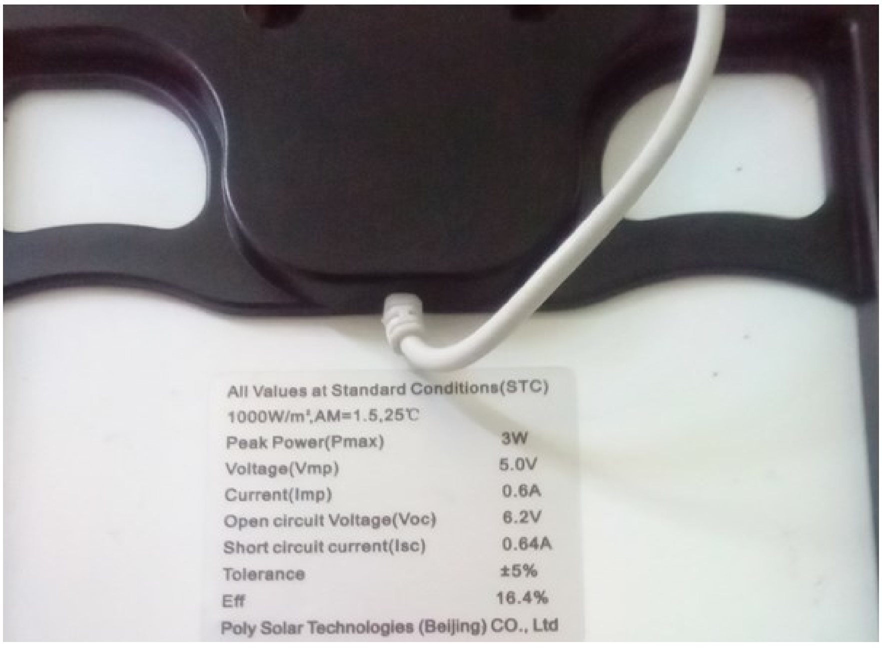


Figure 5.3: Completely sealed $3W_p$ panel junction box

Table 5.2 below compares the manufacturers given values to the measured values of the 3Wp solar panels in this study.

Table 5.2: Table of the 3Wp solar panels parameters for the manufacturer's values versus values measured in the study.

Parameter	**Manufacturer's Values**	**Values measured in the study**
Irradiance	1000 W/m^2	964 W/m^2
Panel Temperature	25^{o}C	38^{o}C
Peak Power, P_m	3Wp	1.08W
Open Circuit Voltage, V_{oc}	6.2V	5.65V
Short Circuit Current, I_{sc}	0.64A	0.49A
Maximum Voltage, V_m	5.0V	2.7V
Maximum Current, I_m	0.60A	0.40A
Tolerance	±5%	-
Fill Factor, FF	0.76	0.39
Efficiency, η	16.4%	6.1%

5.1.1.2 Calculations of fill factor and efficiency on the 3Wp solar panels

Using the manufacturer's given values (Table 5.2) the given fill-factor can be obtained as follow:

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{0.60 \times 5.0}{0.64 \times 6.2} = 0.76 \tag{5.1}$$

Using the formula for efficiency (equation 4.2), the area of exposed surface can be obtained as:

$$\eta = \frac{I_{sc} \times V_{oc} \times FF}{Incident\ solar\ Radiation \times Area\ of\ solar\ cell} \tag{5.2}$$

$$16.4\% = \frac{0.64 \times 6.2 \times 0.756048387}{1000 \times Area\ of\ solar\ cell} \tag{5.3}$$

From which the exposed area is A = 0.018 m^2.

Now, using the values measured in the study, the fill-factor and efficiency at the incident solar radiation of 964 W/m^2 can be obtained as follow:

$$FF = \frac{0.40 \times 2.7}{0.49 \times 5.65} = 0.39 \quad (5.4)$$

$$\eta = \frac{0.49 \times 5.65 \times 0.390102943}{964 \times 0.018292682} = 0.06124481638 = 6.1\% \quad (5.5)$$

5.1.1.3 Peak Power as given by the manufacturer versus the value measured in the study

The labelled peak power was 3Wp and the measured maximum power was 1.08W at 964 W/m^2 (Table 5.2). This represents a power difference of sixty four percent (64%). The solar panel has a power tolerance of ±5% meaning that the experimental value of maximum power determined may increase or decrease by this percentage such that 2.85W to 3.15W will be within the purchase agreement.

5.1.1.4 Short Circuit Current as given by the manufacturer versus the value measured in the study

The manufacturer’s given value of short circuit current of the panels was 0.64A and the short circuit current measured in the study was 0.49A as shown in Table 5.2. This represents a difference of 23%.

5.1.1.5 Open Circuit Voltage as given by the manufacturer versus the value measured in the study

The given open circuit voltage of the panels was 6.2V and the open circuit voltage measured in the study was 5.65V. This represents a difference of 8.87%.

5.1.1.6 Fill Factor as given by the manufacturer versus the value measured in the study

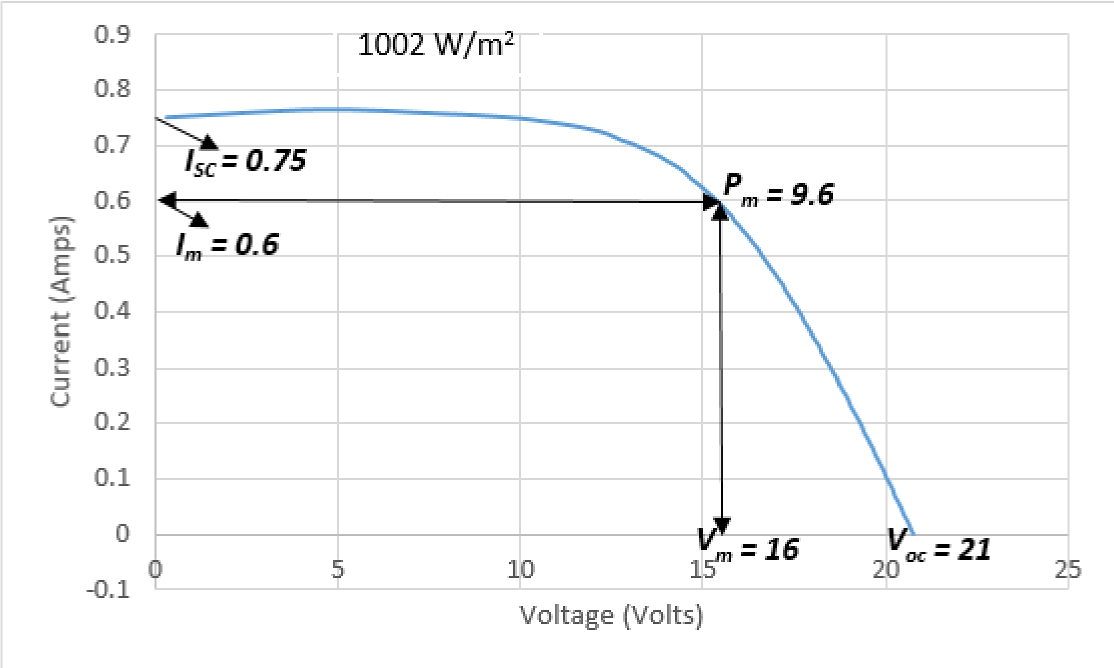
The manufacturer's given value of the fill factor was found to be 0.76 and the fill factor calculated using the parameters measured in the study was 0.39. This represents a difference of 49%.

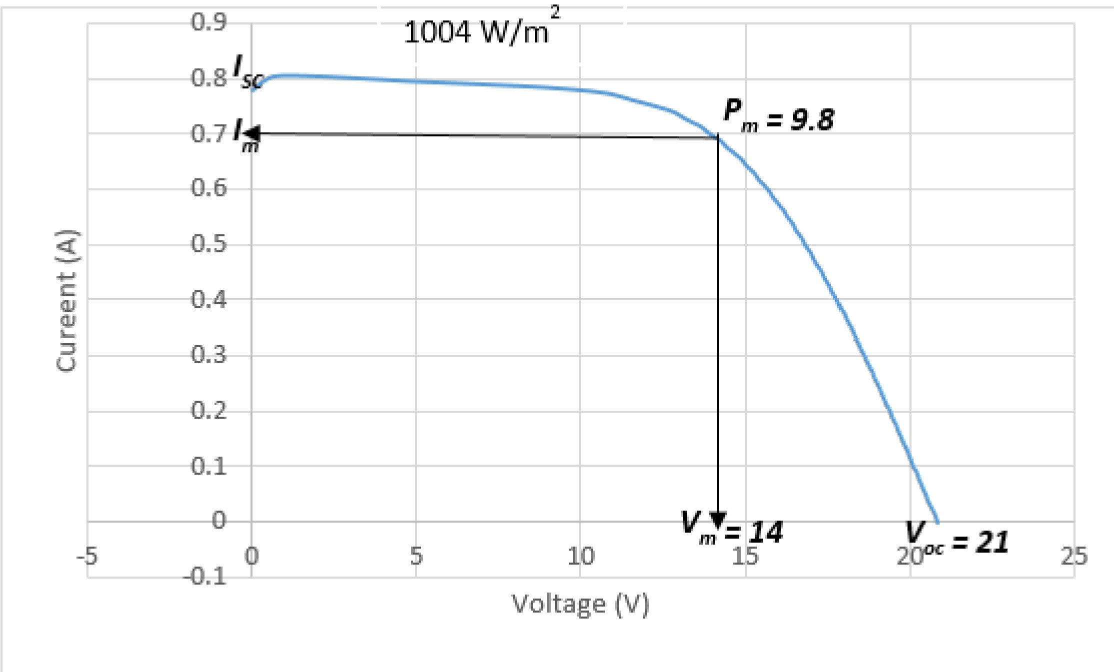
5.1.1.7 Efficiency as given by the manufacturer versus the value measured in the study

The efficiency of the 3Wp panels as given by the manufacturer was 16.4% and the efficiency calculated from the parameters measured in the study was 6.12%. This represents a difference of 63%.

5.1.2 15Wp solar panels

For the one 15Wp solar panel tested three measurements were taken at same inclination from the horizontal. The results are as shown in the curves of Figure 5.4. The curve appearing nearly smooth was used to record the measured values of the solar panel at local conditions as shown in Table 5.4.


1002 W/m²
Current (Amps)
Voltage (Volts)
I_{SC} = 0.75
I_m = 0.6
P_m = 9.6
V_m = 16
V_{oc} = 21
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20
25


1004 W/m²
Cureent (A)
Voltage (V)
I_{SC}
I_m
P_m = 9.8
V_m = 14
V_{oc} = 21
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-5
0
5
10
15
20
25

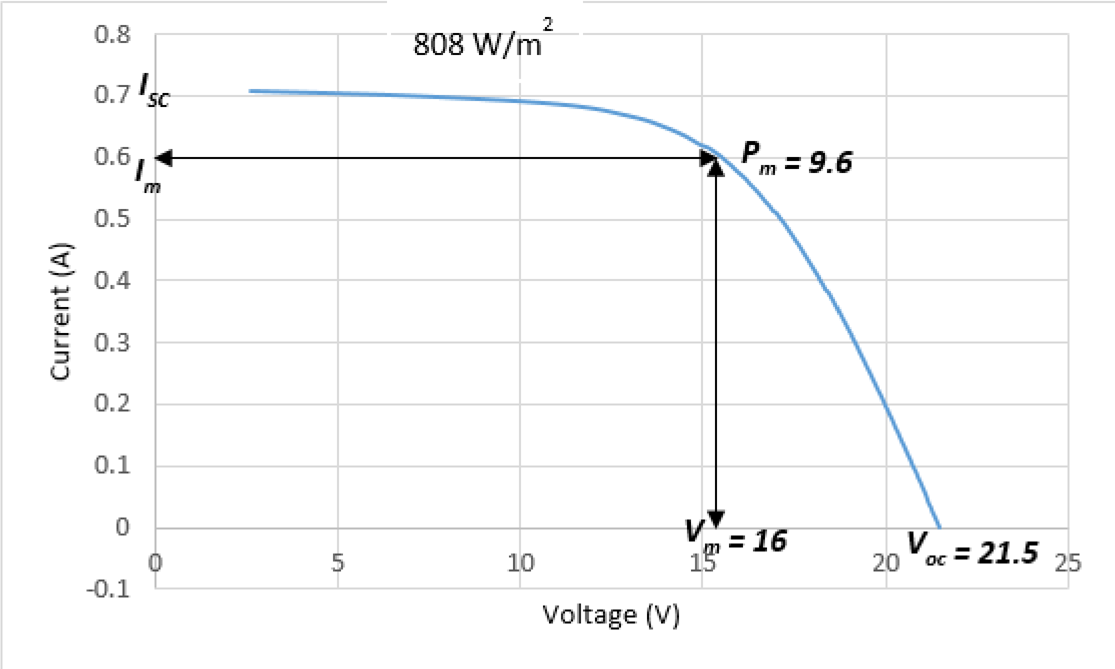


Figure 5.4: I-V Curves for the 15Wp solar panels

5.1.2.1 Visual and physical inspection of the $15W_p$ solar panels

The summary is presented in Table 5.3. Accompanying pictures are shown in Figure 5.5 and Figure 5.6.

Table 5.3: Visual inspection observations of the 15Wp solar panels

COMPONENT	OBSERVATION(S)
Front glass	Smooth, no damage or cracks are observed on the front side of the panels (Figure 5.5)
Back-sheet	No discolouration is observed.
Wires/ connectors	No embrittlement or burns are observed
Junction box	Intact and well attached, no loss of adhesion is observed (Figure 5.6). It was opened by the researcher during study
Frame	No discolouration is observed. No corrosion is found and frame adhesive is not visible.
Metallisation	Bus-bars and cell interconnects show no burns, discolouration or corrosion
PV Cell	The cells are observed to be in good condition

Figure 5.5: Smooth, dry and transparent 15W_p solar panel

Figure 5.6: Opened 15W_p panel junction box

Table 5.4 below compares the manufacturers given values to the locally measured values of the 15Wp solar panels.

Table 5.4: Table of the 15Wp solar panels parameters for the manufacturer's values versus measured values in the study.

Parameter	Manufacturer's Values	Values measured in the study
Irradiance	1000 W/m^2	1002 W/m^2
Panel Temperature	25°C	38°C
Peak Power, P_m	15Wp	9.6W
Open Circuit Voltage, V_{oc}	22V	21V
Short Circuit Current, I_{sc}	0.90A	0.75A
Maximum Voltage, V_m	18V	16V
Maximum Current, I_m	0.83A	0.60A
Tolerance	±3%	-
Fill Factor, FF	0.76	0.62
Efficiency, η	-	9.8%

5.1.2.2 Calculations of fill factor and efficiency on the 15Wp solar panels

Using the given values (Table 5.4), the manufacturer's fill-factor can be found as

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{0.83 \times 18}{0.9 \times 22} = 0.76 \tag{5.6}$$

Total exposed surface area is 0.098 m^2

Now, using the measured values, the fill-factor and efficiency at the measured incident solar radiation of 1002 W/m^2 can be determined as

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{0.6 \times 16}{0.7 \times 22} = 0.62 \tag{5.7}$$

And the efficiency as

$$\eta = \frac{0.7 \times 22 \times 0.623376623}{1002 \times 0.09828} = 9.8\% \qquad (5.8)$$

5.1.2.3 Peak Power as given by the manufacturer versus the value measured in the study

The manufacturer's peak power was 15Wp and the maximum power measured in the study was 9.6W at 1002 W/m^2 as shown in Table 5.4. This represents a power difference of 36%. The solar panel has a power tolerance rating of ±3% which implies that the maximum power less or more than 3% (in this case 14.55W to 15.45W) would still be within the purchase agreement.

5.1.2.4 Short Circuit Current as given by the manufacturer versus the value measured in the study

The given short circuit current of the panel was 0.9A and the short circuit current measured in the study was 0.75A as shown in Table 5.4. This represents a difference of 17%.

5.1.2.5 Open Circuit Voltage as given by the manufacturer versus the value measured in the study

The given value of open circuit voltage was 22V and the measured value was found to 21.5V. This represents a difference of 2.3%.

5.1.2.6 Fill Factor as given by the manufacturer versus the value measured in the study

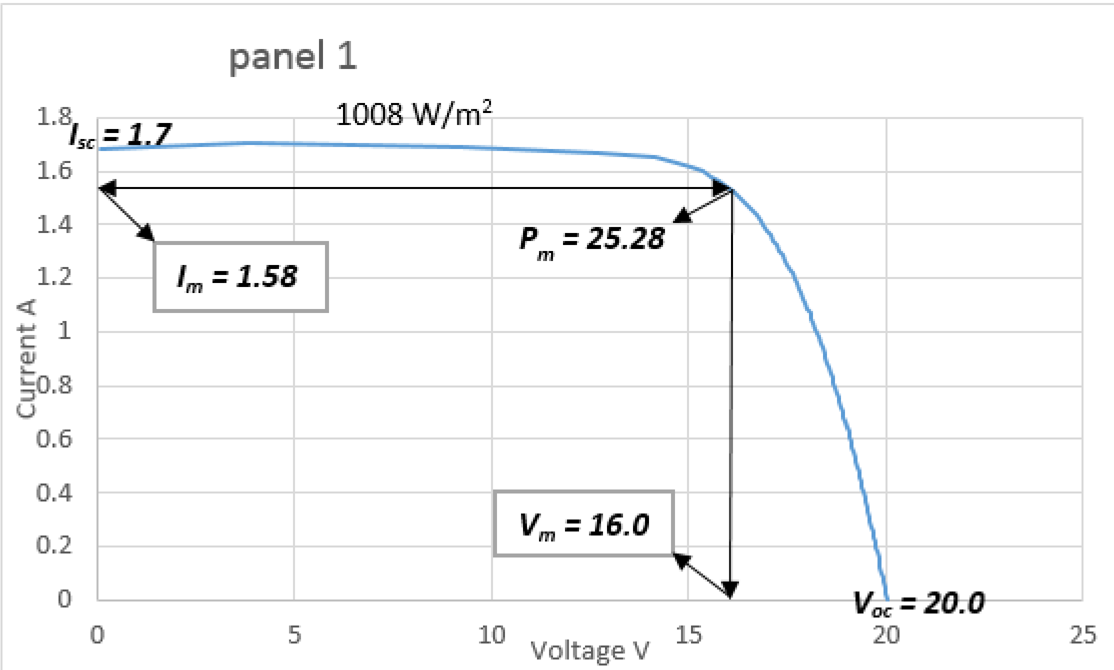
The manufacturer's value of the fill factor was found to be 0.76 while the calculated value was 0.62 as shown in Table 5.4. This represents a difference of 18%.

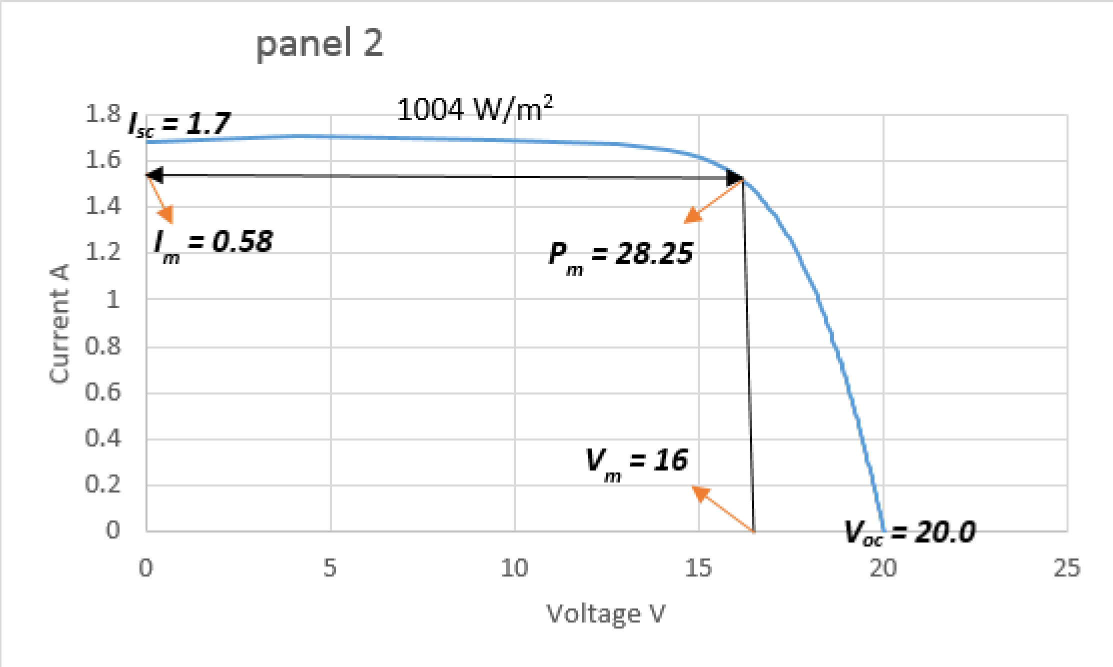
5.1.2.7 Efficiency as given by the manufacturer versus the value measured in the study

The manufacturer did not record the efficiency of the 15Wp solar and the efficiency calculated from the parameters measured in the study was 9.8%. The measured efficiency is too below the expected value of a poly-silicon solar panel.

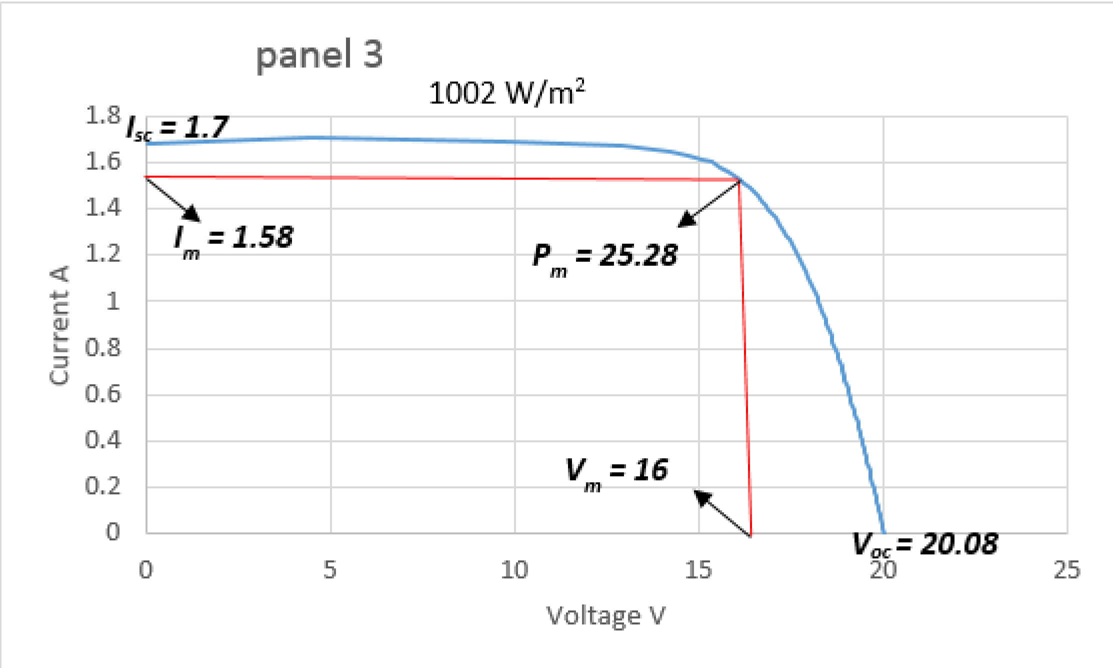
5.1.3 40 Wp solar panels

For the four 40Wp solar panels tested three measurements were taken for each panel and only one I-V Curve for each panel with irradiation of about 1000 W/m^2 were analysed as shown in the curves of Figure 5.7. The curves appear nearly the same, thus, the average was used to record the measured values at local conditions as shown in Table 5.6.





panel 2
1004 W/m²
I_{sc} = 1.7
I_m = 0.58
P_m = 28.25
V_m = 16
V_{oc} = 20.0
Current A
Voltage V
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25



panel 3
1002 W/m²
I_{sc} = 1.7
I_m = 1.58
P_m = 25.28
V_m = 16
V_{oc} = 20.08
Current A
Voltage V
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25

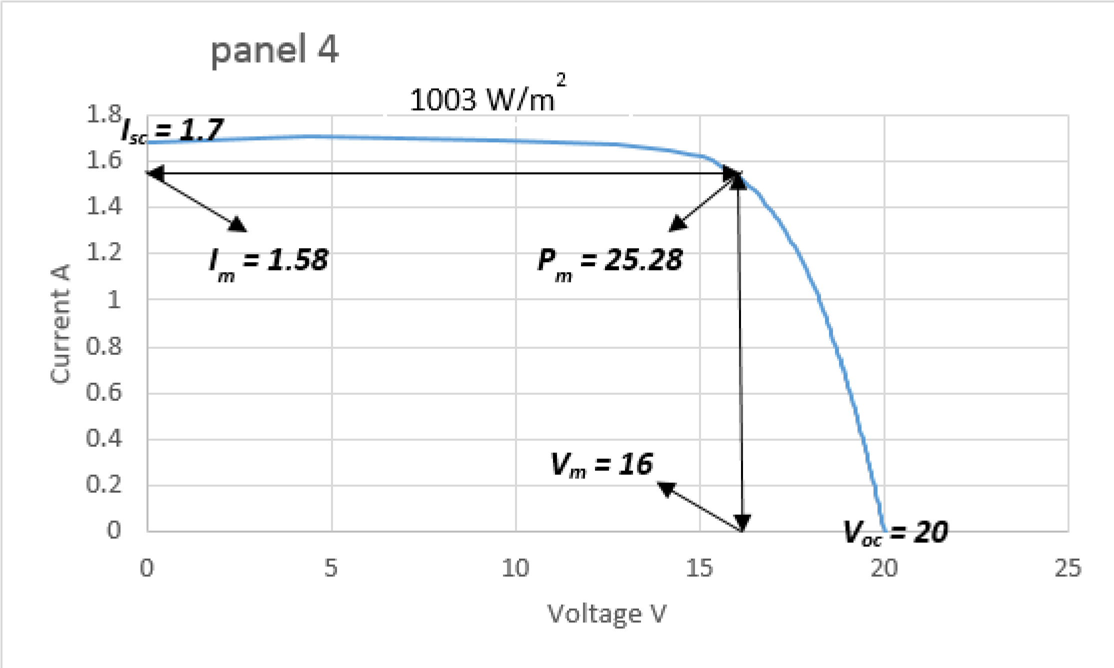


Figure 5.7: I-V Curves for the 40Wp solar panels

5.1.3.1 Visual and physical inspection of the 40W_p solar panels

The summary is presented in Table 5.5. Accompanying pictures are shown in Figure 5.8 and Figure 5.9.

Table 5.5: Visual inspection observations of the 40W_p solar panels

COMPONENT	OBSERVATION(S)
Front glass	Smooth. No damage or cracks are observed. (Figure 5.8)
Back-sheet	No discolouration observable from front glass.
Wires/ connectors	No embrittlement or burns are observed
Junction box	Intact and well attached, no loss of adhesion are observed (Figure 5.9). Opened by the researcher during study
Frame	Minor discolouration and corrosion. Frame adhesive is not visible.
Metallisation	Bus-bars and cell interconnects show no burns, discolouration or corrosion
PV Cell	The cells are observed to be in good condition

Figure 5.8: Smooth, dry and transparent $40W_p$ solar panel

Figure 5.9: Opened $40W_p$ panel junction box

Table 5.6 below compares the manufacturers given values to the locally measured values of the 40Wp solar panel.

Table 5.6: Table of the 40Wp solar panels parameters for the manufacturer's values versus measured values in the study

Parameter	**Manufacturer's Values**	**Values measured in the study**
Irradiance	1000 W/m^2	1008 W/m^2
Panel Temperature	25^{o}C	38^{o}C
Peak Power, P_m	40Wp	25.2W
Open Circuit Voltage, V_{oc}	22.4V	20.0V
Short Circuit Current, I_{sc}	2.46A	1.7A
Maximum Voltage, V_m	17.5V	16.0V
Maximum Current, I_m	2.29A	1.58A
Nominal Operating Cell Temperature (NOCT)	47 ± 2%	-
Tolerance	±3%	-
Maximum Series Fuse Rating	10A	-
Operating Temperature	-40 to +85^{o}C	-
Fill Factor, FF	0.74	0.73
Efficiency, η	-	11.2%

5.1.3.2 Calculations of fill factor and efficiency on the 40Wp solar panels

Using the given values (Table 5.6), the fill-factor can be found as

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{2.29 \times 17.5}{2.46 \times 22.4} = 0.73 \qquad (5.9)$$

Total exposed surface area is 0.22 m^2

Now, using the measured values, the fill-factor and efficiency at the measured incident solar radiation of 1008 W/m^2 can be obtained as

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{1.58 \times 16}{1.7 \times 20} = 0.74 \qquad (5.10)$$

And the efficiency as

$$\eta = \frac{1.70 \times 20.0 \times 0.743529411}{1008 \times 0.22464} = 11.2\% \qquad (2.11)$$

5.1.3.3 Peak Power as given by the manufacturer versus the value measured in the study

The given peak power of these solar panels was 40Wp and the maximum power measured in the study was 25.28W at 1008 W/m^2 as shown in Table 5.6. This represents a power difference of 37%. These panels have a tolerance rating of ±3% which implies that the maximum power less or more than 3% (in this case 38.8W to 41.2W) would still be within the purchase agreement. The panels have a Nominal Operating Cell Temperature (NOCT) of 47^{o}C ± 2^{o}C. Taking 48^{o}C as the temperature of the panel at the measurement site means the output power was recorded at 23^o higher than STC. Dividing the power difference of 3% by 23^o the power coefficient is determined to be 1.6. Further, the power loss due to the temperature rise is found by multiplying the power difference, for this panel, 37% by the manufacturer's peak power, in this case 40Wp. The power loss is 14.8W. This means at 48^{o}C, the 40W solar panel would generate 25.2W. The Operating Temperature recorded on this panel is -40 *to* 85^{o}C. This means these panels are capable of working effectively and efficiently when the panel temperature drops to -40^{o}C or rise to 85^{o}C.

5.1.3.4 Short Circuit Current as given by the manufacturer versus the value measured in the study

The given short circuit current of the panels was 2.44A and the short circuit current measured in the study was 1.7A. This represents a difference of 30%.

5.1.3.5 Open Circuit Voltage as given by the manufacturer versus the value measured in the study

The given open circuit voltage of the panels was 22.4V and the open circuit voltage measured in the study was 20.0V. This represents a difference of 10.7%.

5.1.3.6 Fill Factor as given by the manufacturer versus the value measured in the study

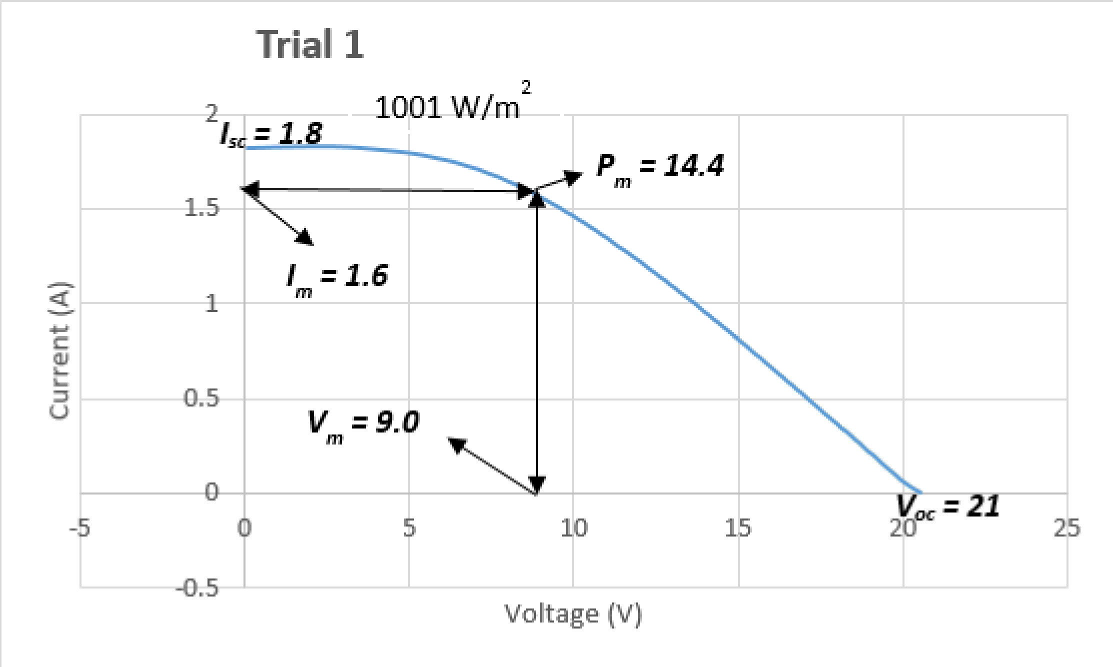
The manufacturer's value of the fill factor was found to be 0.74 the fill factor calculated from the parameters measured in the study was 0.73. This represents a difference of 1.4%.

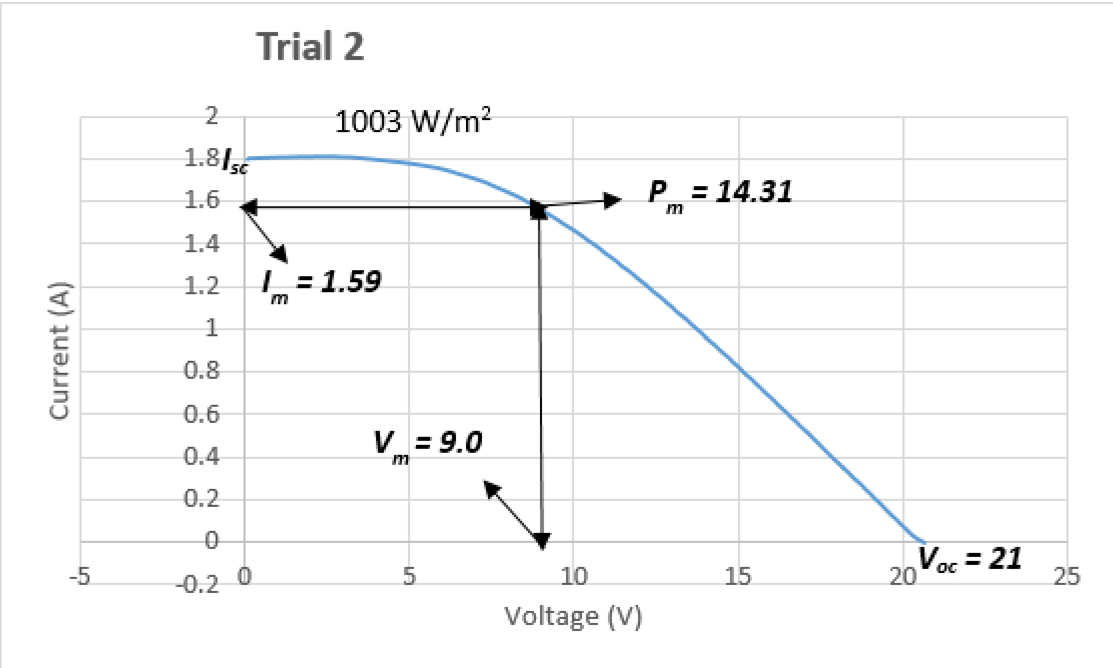
5.1.3.7 Efficiency as given by the manufacturer versus the value measured in the study

The manufacturer did not record the efficiency of the 40Wp solar panels and the efficiency calculated in the study was found to be 11.2%. The measured efficiency is too below the expected value of a poly-silicon solar panel.

5.1.4 50Wp solar panels

For the one 50Wp solar panel tested three measurements were taken at same inclination from the horizontal. The results are as shown in the curves of Figure 5.10. The curves appeared nearly the same thus, the average was used to record the measured values of the solar panel at local conditions as shown in Table 5.8.


Trial 1
1001 W/m^2
I_{sc} = 1.8
P_m = 14.4
I_m = 1.6
V_m = 9.0
V_{oc} = 21
Current (A)
Voltage (V)
2
1.5
1
0.5
0
-0.5
-5
0
5
10
15
20
25


Trial 2
1003 W/m^2
I_{sc}
P_m = 14.31
I_m = 1.59
V_m = 9.0
V_{oc} = 21
Current (A)
Voltage (V)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-5
0
5
10
15
20
25

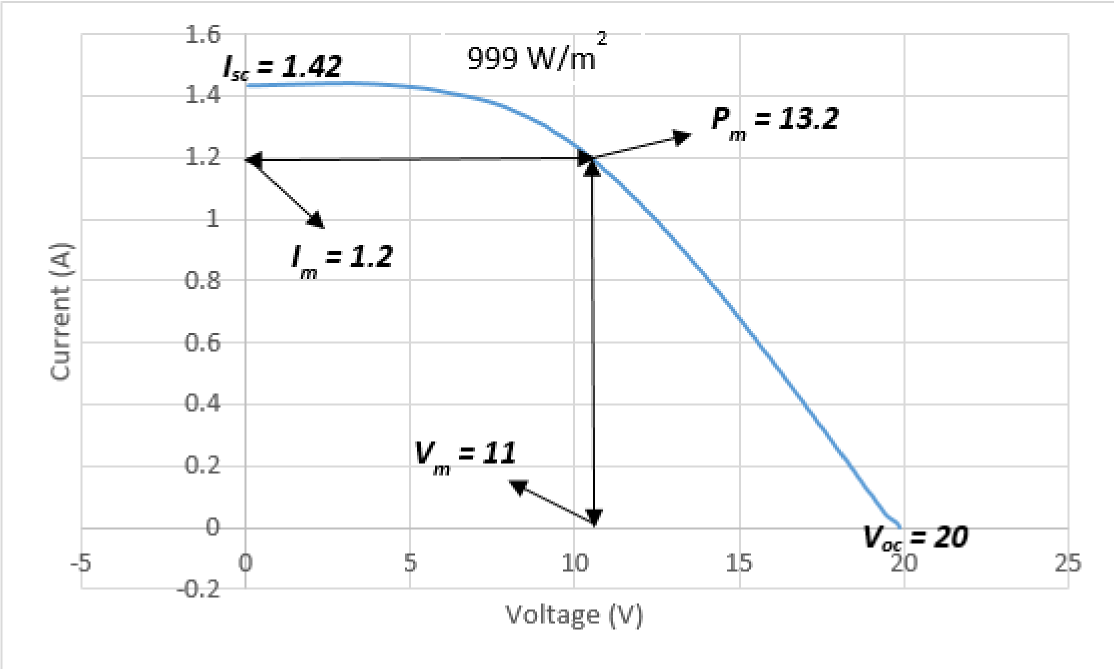


Figure 5.10: I-V Curves for the 50Wp solar panels

5.1.4.1 Visual and physical inspection of the $50W_p$ solar panels

The summary is presented in Table 5.7. Accompanying pictures are shown in Figure 5.11 and Figure 5.12.

Table 5.7: Visual inspection observations of the $50W_p$ solar panels

COMPONENT	OBSERVATION(S)
Front glass	Smooth. No damage or cracks are observed (Figure 5.11).
Back-sheet	No discolouration from front glass.
Wires/ connectors	No embrittlement or burns are observed
Junction box	Intact and well attached, no loss of adhesion (Figure 5.12) and it was opened by the researcher during study
Frame	No discolouration. No corrosion is found; frame adhesive is not visible.
Metallisation	Bus-bars and cell interconnects show no burns, discolouration or corrosion
PV Cell	The cells are observed to be in good condition

Figure 5.11: Smooth, dry and transparent $50W_p$ solar panel

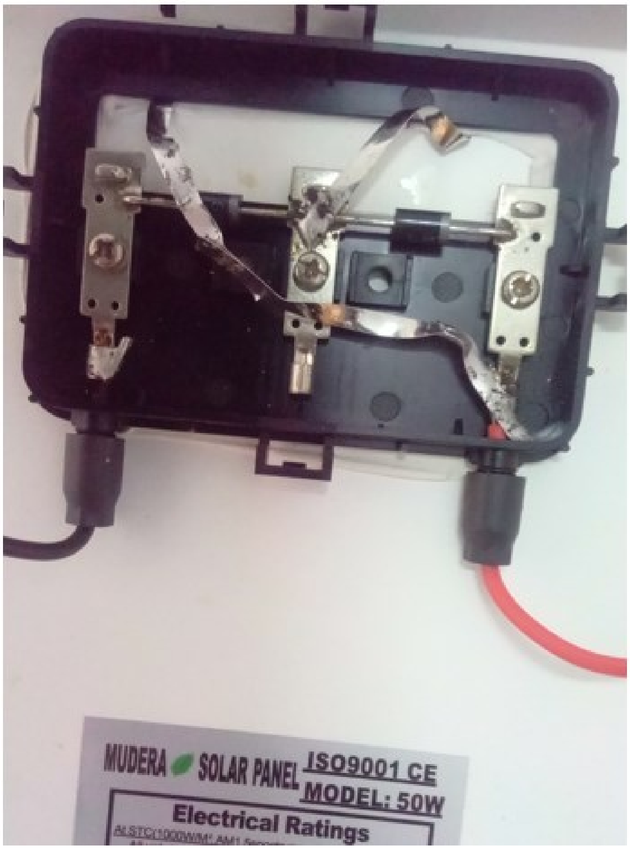


Figure 5.12: Opened $50W_p$ panel junction box

Table 5.8 below compares the manufacturers given values to the locally measured values of the 50Wp solar panels.

Table 5.8: Table of the 50Wp solar panels parameters for the manufacturer's values versus measured values in the study

Parameter	**Manufacturer's Values**	**Values measured in the study**
Irradiance	1000 W/m^2	999 W/m^2
Panel Temperature	25ºC	38ºC
Peak Power, P_m	50Wp	17.6W
Open Circuit Voltage, V_{oc}	22V	21V
Short Circuit Current, I_c	3.38A	1.8A
Maximum Voltage, V_m	18V	11V
Maximum Current, I_m	2.78A	1.6A
Tolerance	±5%	-
Fill Factor, FF	0.67	0.47
Efficiency, η	-	6.0%

5.1.4.2 Calculations of fill factor and efficiency on the 50Wp solar panels

Using the given values (Table 5.8), the fill-factor can be found as

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{2.78 \times 18}{3.38 \times 22} = 0.67 \tag{5.12}$$

Total exposed surface area is 0.29 m^2

Now, using the measured values, the fill-factor and efficiency at the measured incident solar radiation of 999 W/m^2 are determined to as follow:

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} = \frac{1.6 \times 11}{1.8 \times 21} = 0.47 \tag{5.13}$$

And the efficiency as

$$\eta = \frac{1.8 \times 21 \times 0.465608465}{999 \times 0.292032} = 6.0\% \qquad (5.14)$$

5.1.4.3 Peak Power as given by the manufacturer versus the value measured in the study

The given peak power was 50Wp and the measured maximum power was 13.2W at 999 W/m^2 as shown in Table 5.8. This represents a power difference of 74%.

5.1.4.4 Short Circuit Current as given by the manufacturer versus the value measured in the study

The given short circuit current of the panel was 3.38A and the measured peak power was 1.5A. This represents a power difference of 56%.

5.1.4.5 Open Circuit Voltage as given by the manufacturer versus the value measured in the study

The given open circuit voltage was 22V and the measured value was 21.0V. This represents a difference of 4.5%.

5.1.4.6 Fill Factor as given by the manufacturer versus the value measured in the study

The manufacturer's value of the fill factor was found to be 0.67 while the calculated value was 0.47. This represents a difference of 30%.

5.1.4.7 Efficiency as given by the manufacturer versus the value measured in the study

The manufacturer did not record the efficiency of the 50Wp solar while the calculated value was found to be 6.0%.The measured efficiency is too below the expected value of a poly-silicon solar panel.

5.2 Discussion

The difference between the values of peak power measured in the study and those given by the manufacturers is mainly due to an increase in temperature of the solar panels when exposed to the sun in the real outdoor environment in which the panels' temperature was as high as 38°C. The panels tested had no given peak power values at Nominal Operating Cell Temperature (NOCT) and the Negative Temperature Coefficient. Thus, the power loss at the outdoor panel temperature could not be determined. The NOCT [82] is a more realistic measure of the temperature the solar panel could operate at in the environment. Nominal Operating Cell Temperature (NOCT) is a testing standard geared to the operational conditions of solar cells, defined as temperature reached by open circuited cells in a panel assuming 800 W/m^2 irradiance, 20°C ambient temperature and wind speed of 1 m/s with the PV panel at a tilt angle of 45° and its back open to the breeze (as opposed to conditions where the panels are mounted on roofs and heat builds up under the panels) [82]. NOCT conditions are an approach to mirror real-world conditions. It is applied to calculate real available wattage on an average day and is a comparably more strict parameter that is required by a range of energy rating and output performance standards. It is the major testing condition alternative to Standard Testing Conditions (STC) and also used for solar panel performance quality testing during mass production. The NOCT is also used to estimate the temperature of the panel at different irradiance and different ambient temperature conditions. NOCT depends on thermo-optical properties such as absorptance and hemispherical emittance of the panel package materials [83].

Materials used for solar panels as well as packing density may have major impacts on the NOCT and results in distorted ratings [84]. For example, a rear surface with a lower packing density and reduced thermal resistance can result in temperature difference of over 5^{o}C.

All solar panels reduce the power as they heat up. The temperature coefficient of peak power tells how much power the panel loses for every degree celsius the panel is hotter than 25^{o}C [39]. Solar panels begin to generate less power once the temperature rises above 25^{o}C. Since the temperature during measurement was 38^o the output power was recorded at 13^o higher than STC. In most cases solar panels are installed in sunny hot environment to generate more solar energy, but the panels lose some performance when the sunshine is accompanied by excessive heat. To express how well a solar panel will perform in hot temperatures, panel manufacturers use a measurement called the Temperature Coefficient [85]. The lower the temperature coefficient the better the solar panel will perform on hot days. Thus, temperature coefficient is a very important parameter when buying a solar panel. The average operating temperature for Silicon panels is about 50°C, meaning 25°C more than the reference conditions. The temperature coefficient is the parameter needed to calculate the power loss, and it usually ranges between -0.29 and -0.5 %/°C [86]. This means that every 10°C in excess results in a decrease in power of the panel ranging between 2.9% and 5%. This parameter must be taken into account when choosing a panel to optimise the annual yield.

Besides the temperature coefficient of P_m there are also other temperature coefficient ratings for solar PV panels [85, 86]. These are: temperature coefficient of the open circuit voltage (V_{oc}), which measures the changing open circuit voltage values of the PV panels when the temperature increases or decreases and temperature coefficient of the short circuit current (I_{sc}), which measures the changing short circuit current values of the PV panels when the solar cell temperature increases or decreases [69]. Each solar cell type has its own temperature coefficient. These coefficients are applicable at the same irradiance level at which the measurements are made.

The difference between the measured short-circuit current values and those given by the manufacturer is attributed to internal resistances of the solar cells. Though the series resistance and the shunt resistance of this panel were not given, from the literature, shunt resistance contributes largely to the loss of short circuit current [68]. A part of the light-generated current flows through the shunt resistance, this current will not be collected at the external terminals of the solar cells (panel). Further, for the short circuit current to be equal to the light generated current, the thickness of the solar cells should be equal or less than the width of depletion layer. Lager than this makes unnecessary resistance which drops the short circuit current [71, 72]. The short circuit current has a strong dependence on irradiance and hence a decline in short-circuit is due to optical absorption/transmission problems caused by factors such as panel soiling, browning/yellowing of encapsulant and delamination which causes optical decoupling (mismatch of refractive indices). All solar panels have the temperature coefficient of the short circuit current which measures the changing short circuit current values of the PV panels when the solar cell temperature increases or decreases. The temperature coefficient of short circuit current for this panel was not given, thus, the percentage loss in short circuit current could not be determined. Since short circuit current increases slightly with increase in temperature, it was expected that with the 13^{o}C temperature above STC, short circuit current would increase approximately 13 times the temperature coefficient of short circuit current.

The difference between the measured values of open circuit voltage and those given by the manufacturer is mainly attributed to degradation of the cells due to overheating when the panel temperatures are too high and also to shunting problems [72]. All solar panels have the temperature coefficient of the open circuit voltage (V_{oc}), which measures the changing open circuit voltage values of the PV panels when the temperature increases or decreases. The temperature coefficients of open circuit voltage for the panels in this study were not given. Since open circuit voltage decreases linearly with increase in temperature, it expected that with the 13^{o}C temperature above STC, open circuit voltage would decrease 13 times the temperature coefficient of open circuit voltage.

This difference in the fill factor values is due to the increase in series resistance, arising from such factors as corrosion and thermo-mechanical fatigue of the solder bonds and interconnections. The series resistance and shunt resistance which are collectively known as parasitic resistance cause losses in short circuit current and open circuit voltage. 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. 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. The current levels in the solar cell have a major impact on the losses on the *FF* due to series resistance.

Furthermore, losses caused by the presence of a shunt resistance 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 [72]. 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 on the fill factor. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large [87]. The impact of the shunt resistance on the fill factor can be determined from the slope of the IV curve at the short circuit current point.

This difference between efficiency values measured in the study and those given by the manufacture (for $3W_p$ solar panel) is due to losses in fill factor and peak power which also depends on the short circuit current and open circuit voltage. As efficiency is directly proportional to the short circuit current, the series resistance and the shunt resistance which contributes largely to the loss of short circuit current by blocking part of the light-generated current reduces the solar panel efficiency [72]. The short circuit current having a strong dependence on irradiance and hence a decline in short-circuit current due to optical absorptance and transmission problems leads to loss of panel efficiency. Additionally, efficiency depends on the open circuit voltage which is sensitive to temperature changes. As temperature of the panel increase above 25^{o}C the cells begin to degrade thus reducing its efficiency.

Further, efficiency of solar panels is directly proportional to the fill factor which is highly affected by series resistance, arising from such factors as corrosion and thermos-mechanical fatigue of the solder bonds and interconnections.

In addition, loss of efficiency is as a result of significant power losses caused by the presence of a shunt resistance typically due to manufacturing defects in a solar panel. Some solar panels are poorly designed and made, as such shunt resistance significantly reduce the conversion efficiency of the panel. 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 on the fill factor and efficiency [87].

CHAPTER 6

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The study sought to determine outdoor performance and validate fill-factor and efficiency of some commercial solar panels found on the Zambian market with focus on three objectives: 1. Record and ascertain whether all the information pertaining to the fill-factor and efficiency of some selected solar panels on the Zambian market are given. 2. Carry out measurements and calculate the fill-factor and efficiency of these solar panels. 3. Compare the given values of the fill-factor and efficiency on the solar panels to the values measured in the study.

6.1.1 Objective 1: Record and ascertain whether all information pertaining to the fill-factor and efficiency of some selected solar panels on the Zambian market are given.

The findings are that the manufacturers of the solar panels tested in the study did not provide all the information required for consumer's knowledge. Figure 4.2, Figure 4.4, Figure 4.6 and Figure 4.8 show the values given by the manufacturers. The most important features to look for when buying a solar panel are the maximum power at Standard Test Condition (STC), panel efficiency, tolerance, power coefficient and maximum power at Nominal Operating Cell Temperature (NOCT).

6.1.2 Objective 2: Carry out measurements and calculate the fill-factor and efficiency of these solar panels.

The study revealed that for the 3Wp solar panel (Table 5.2) the maximum power dropped from $3W_p$ to 1.08W indicating a power difference of 67%. The short circuit current dropped by 23% (from 0.64A to 0.49A). The open circuit voltage dropped by 8.87% (from 6.2V to 5.65V). The fill factor dropped by 49% (from 0.76 to 0.39). The efficiency dropped by 63% (from 16.4% to 6.12%). For the 15Wp solar panel (Table 5.4) it is found that the maximum power dropped by 36%

(from 15Wp to 9.6W). The short circuit current dropped by 17% (from 0.9A to 0.75A). The open circuit voltage dropped by 2.3% (from 22V to 21.5V). The fill factor dropped by 18% (from 0.76 to 0.62). The manufacturer did not give the efficiency of the 15Wp solar panel while efficiency calculated in the study was 9.75%. The study also shows that for the 40Wp solar panel (Table 5.6) the maximum power dropped by 37% (from 40Wp to 25.28W). The short circuit current dropped by 30% (from 2.44A to 1.7A). The open circuit voltage dropped by 11% (from 22.4V to 20.0V). The fill factor dropped by 1.4% (from 0.74 to 0.73). The manufacturer did not give the efficiency of the 40Wp solar panel while efficiency calculated in the study was 11.16%. Furthermore, the study reveals that for the 50Wp solar panel (Table 5.8) the maximum power dropped by 74% (from 50Wp to 13.2W). The short circuit current dropped by 56% (from 3.38A to 1.5A). The open circuit voltage dropped by 5% (from 22V to 21V). The fill factor dropped by 37% (from 0.67 to 0.42). The manufacturer did not give the efficiency of the 50Wp solar panel while efficiency calculated in the study was 6.0%.

6.1.3 Objective 3: Compare the given values of the fill-factor and efficiency on the solar panels to the values measured in the study.

This study established that the manufacturers did not give all the information required by the consumers. For example, the efficiencies for the 15Wp, 40Wp and 50Wp solar panels were not given. As such it's difficult to compare the efficiencies measured in the study to that of the manufacturers. In addition, the study revealed that the manufacturers did not give the panels ratings at Nominal Operating Cell Temperature (NOCT). NOCT [82] is a condition to validate and compare manufacturer's values to those measured in the harsh outdoor weather conditions. The manufacturers only gave the values at STC and it's not possible to compare and conclude between the values measured in this study to the STC values. STC is an indoor process and can only be compared to another indoor process. On the other hand NOCT is an outdoor process and is used to validate outdoor measurements.

Furthermore, the study reveals that manufacturers did not give the temperature coefficients of peak powers of the solar panels, as a result loss in power of the panels could not be determined and compared to the NOCT values. Power coefficient tells how much power the panel loses for every degree Celsius the panel is hotter than 25^{o}C [85, 86]. Thus, temperature coefficient is a very important parameter to consider when buying a solar panel.

Therefore, a solar panel that does not show all the parameters on its rating specifications at STC, and does not include some or all parameters at NOCT indicates that the manufacturer is not genuine and the solar panel is of low or poor quality or notably a substandard solar panel.

As argued above, the solar panels examined in this study show that most important solar parameters such as efficiency, power coefficient and maximum power at NOCT are not given. It is also determined that the power differences are exceedingly higher than the recommended power drop of 16.5%. Therefore it is concluded that the solar panels studied herein are substandard and the manufacturers of these solar panels are not genuine.

6.2 RECOMMENDATIONS

The following recommendations were made:

(i) Further research with more solar panels from various suppliers is needed.

(ii) Government should consider setting and enforcing standards and policies aimed at regulating the claims of the manufacturers of photovoltaic panels.

(iii) Consumers should buy solar panels and related components only from reputable shops.

(iv) Government through relevant institutions and professionals should educate the citizens how to identify genuine/ reputable shops that supply solar panels.

(v) Zambia Bureau of Standards should set up an independent testing and certification lab in the country, e.g. at University of Zambia Solar Energy Centre.

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