UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

ANALYSIS OF SHADING EFFECTS IN SOLAR PV SYSTEM

Project number: ACEESD/PSE/20/14

by

Bernadette Dushengere
Reference number: 215025765

A dissertation submitted to the African Center of Excellence in Energy Studies for Sustainable Development (ACE-ESD)
College of Science and Technology, University of Rwanda

In Partial Fulfillment of the Requirement
for the Degree of Masters of Science
in
Electrical Power Systems

Supervisor: Dr.ir. Mulugeta Gebrehiwot Gebremichael

October, 2020
Kigali-Rwanda

DECLARATION

I, the undersigned declare that this thesis work is my original work and has not been presented or submitted for a degree in University of Rwanda or any other universities. All sources of materials which are used for the thesis work have been fully acknowledged.

Names: Bernadette DUSHENGERE Signature:

APPROVAL

Date of Submission: 31/10/2020

This thesis work has been submitted for examination with my approval as a university advisor.

Dr.ir. Mulugeta Gebrehiwot Gebremichael

Thesis Supervisor Signature

ACKNOWLEDGEMENTS

The realization of this project would not have been possible without contributions, encouragement and supports from so many people in various corners of my life. First and foremost, my thanks are due to almighty God who protected me during the whole period of my life. I would like to thank my beloved family with their encouragement, moral support and guidance for carrying out this research project. My special thanks also go to my classmates whose constant collaboration and encouragements have been my source of strength and inspiration throughout these years.

My sincere appreciation to my supervisor Dr.ir. Mulugeta Gebrehiwot Gebremichael for his advice, and guidance during my work on this research project. Finally, my gratitude goes to all lecturers who provided to me a helpful package of knowledge and skills, your help is warmly acknowledged.

Abstract

Due to its advantages, use of clean energy in general and especially solar PV systems offer great solution of problems that people face in their everyday life. Generation of energy using solar PV system technology is cheaper and clean technology compared to the one of fossil fuels. Aside from its advantages, this technology still has some drawbacks that affect its performance where the ones caused by shadows is considered as one of the big problems. This thesis work shows laboratory experiments and simulations in order to see how the system is affected by shading where a 1.5 kWp PV system has been used for the study. The system has been simulated with PVsyst (7.0.6 version) and experimented in UR/ACE-ESD High E-Tech Smart Grid Laboratory. Laboratory experiments showed that whatever shade is applied to the system, the dc voltage and current change (increases or decrease) and dc power decreases. In simulation, it has been notified that the irradiances losses are dependent on time of a day, sun position and the rate of created shadow. From the simulated results, annual energy produced and near shading losses in non-shaded system is 2373 kWh and 0% respectively while in shaded system, the annual energy produced was 2055 kWh and 2.1% of near shading losses. This undoubtedly disturbs the performance of the power system as well as other related works.

Keywords: PV systems**,** shading effect**,** Performance of PV module, PVsyst simulation

Contents

List of figures

List of tables

List of abbreviations

PV	Photovoltaic
T Amb	Ambient temperature
Isc	Short Circuit Current
Vmp	Maximum Power Voltage
Voc	Open Circuit Voltage
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
E Grid	Energy injected into grid
PR	Performance ratio in percentage
Si-Mono	Silicon mono crystalline
STC	Standard Testing Condition

CHAPTER 1. INTRODUCTION

1.1 General introduction

Electrical energy has great impact in the economic development of every country around the globe as it plays a vital role in performing many activities in our communities. Like water, need of electricity is increasing as population all over the world is increasing. This population's grow lead to the increase in energy demand and more energy resources are needed to meet that demand. Apart from being depleted, utilization of conventional energy resources is not environmentally friendly thus affect human being, the use of renewable energy resources will contribute to meet the demand as it does not affect environment.

Among renewable energy technologies, solar energy is an alternative and green energy which can be used as a solution to those problems facing by the world. Availability of the sun in numerous places around the globe makes the usage of solar energy based on photovoltaic to be more feasible compared to other renewable energy technologies [1]. They are many reasons that are making energy production based on solar PV to be more attractive [2] .

- It is quick to install.
- It is renewable, the natural resource does not deplete.
- The systems do not produce noise, there are no moving parts.
- The power density (power/kg) is high.
- It is clean, it produces no emissions.
- It is reliable and requires very little maintenance.
- It is highly portable.
- It is easily scalable, can be implemented in a wide range of sizes depending on need.

At the same time, solar power generation still count some problems like low solar PV conversion efficiency [3] and due to the fact that output power of a PV module depends on many things include solar irradiance, wind speed, cell temperature, geographical location, module orientation, weather conditions, etc., it strongly compromised by reduction of solar radiation intensity [1], [4]. Disregarding on such mentioned problems, shading effect is a very crucial problem in PV system industry. Some conditions of shading in this field is preventable whereas others are not including those ones caused by whether conditions. Those shades cause the PV module to receive less intensity of sunlight and they vary from one factor to another like environmental conditions which not constant during the year, the climate change or even shadows from neighboring objects [5]. Figure 1.1. shows some shading conditions due to different causes.

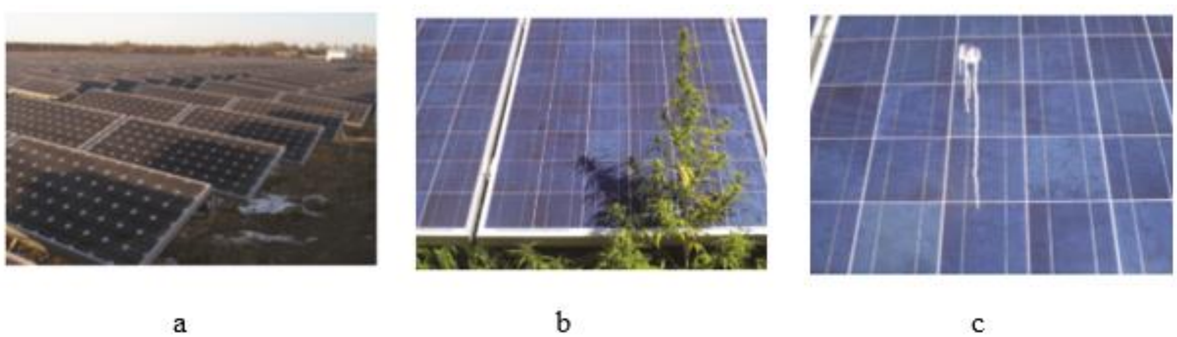


Figure 1.1. Different shading condition (a) nearby module shading in tracking PV system, (b) plant shading and (c) bird dropping shading

1.2 Background

In solar photovoltaic systems, the irradiation of the sun at high frequency is captured by array of semiconductors PV cells which convert that solar radiation directly into direct current electricity where it can be used directly or stored for later use [6]. In the world, one of the quickest growing enterprises is PV and it has changed significantly in the course of the most previous couple of years. The competitiveness of this field is increasing, in 2013 for the first time in more than a decade, solar was over all other renewable energy technologies in the sense of new generating capacity installed with an increase of 29 percent compared with 2012 [7]. Worldwide total PV installations represented 1.8 GW in 2000 and 71.1 GW in 2011 with a growth rate of 44% [8]. The rate of increase in production based on PV in the past 15 years has been shown with a yearly rate growth of over 40% [9]. By the end of 2018, global cumulative installed PV reached to 480 GW of which about 180 GW were utility scaled plants and the reports forecasted that solar PV will reach a cumulative capacity of 2 840 GW globally by 2030 [10].

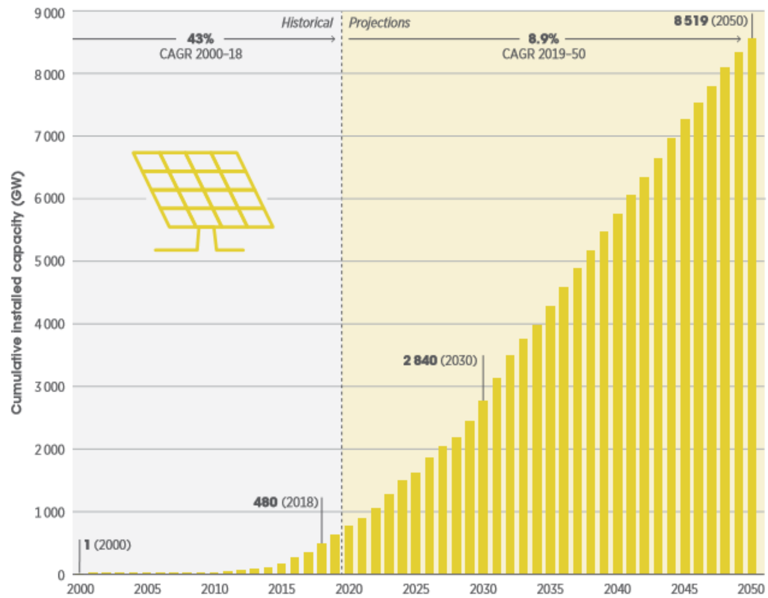


Figure 1.2. Historical and projections cumulative solar PV capacity [11].

Taking a look on figure 2.1, it illustrates the improvement in PV industry as years go on. This development led many researchers to emphasize on many problems related to this industry and they argued the significant impact of shading on PV system.

1.3 Problem statement

As energy demand is increasing all over the world, many energy resources are needed to meet the demand and looking among those resources which are not harmful to the users as well as environment. Many developing countries are suffering due the use of conventional energy resources, it is why governments and other institutions are promoting the use of energy based on renewable resources. Even if the importance of solar energy has seen, there are still some effects that compromise its use due to different situations where some of them are inevitable.

As it has been discussed by many authors , the PV system can be used as standalone or utility interactive system [11], whether used as standalone or utility connected, shading affects the energy production of the system. Apart from reduction on the output power in PV system that can be caused by shade, also shade causes the thermal stress on the module. When a PV cell is shaded, the insolation is reduced by shading and result in reduction of photo current. Because of the series connection of all the cells, the current for all the cells is reduced and according to the level of shading then the thermal stress causes the degradation in the area affected by high temperature [12]. Therefore, analysis of shading effect will positively affect the development of PV related projects in future by taking into consideration on how to deal with those effects.

1.4 Objective

1.4.1 General objective

The main objective of this research is to analyse the shading effects in PV system

1.4.2 Specific objective

- To simulate both non shaded and shaded PV systems and see their results.
- To compare the two systems in terms of performances.
- To perform the analysis of both systems in terms of efficiency, durability and performance.

1.5 Scope of the study

This research will look on the analysis of simulated results for shaded and non-shaded PV systems. Both performances will be analysed, compared and then the results will be discussed in order to choose the ways to deal with the problem.

1.6 Limitation of Study

Like many researches, facing deficiency and limitations are sometimes inevitable. So as this research was conducted by use of software, it was strongly limited by how the software is structured. This include limited data, component's problems like efficiency and other performance characteristics related to manufacturing.

1.7 Hypothesis and Significance of the study

1.7.1 Hypothesis

This study is aimed to analyse the effects of shading in PV system in which after getting results, the study will be used by users before installing their systems and the result of this study will also serve as baseline for future research.

1.7.2 Significance of the study

Due to the grow in PV industry, having profound knowledge of Solar PV performance in normal condition as well as abnormal situation serve a great importance in part of system optimization. This thesis aims to deeply understand shading effects and will lead on how to reduce the power losses due to different causes especially ones which can be caused by shading where it is applicable.

1.8 Thesis outline

The outline of this project consists of six chapters.

- Chapter 1 is Introduction which provides a brief overview of the background and motivation for the study, problem statement, objectives, limitations, expected outcomes and outline of the project.
- Chapter 2 is the literature review which contains the related work done by other researchers on this topic, including theoretical concepts and fundamental definitions used in this research project.
- Chapter 3 is the research methodology that describes methods, tools used in the implementation of this project.
- Chapter 4 is the simulation that represents and explains simulation parameters and scenarios.
- Chapter 5 is the results and analysis that represents the results of the project research in relation to the project objectives.
- Chapter 6 is the conclusion and recommendation based on the research results.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

In PV industry, shading has been paid more attention by many researchers as it has been shown with big negative impact on the performance of PV systems. Looking at its causes, its effects and how it can be minimized will boost the PV system efficiency and reduction of power losses due to mismatch as well as well avoiding unexpected degradation of system's devices. The basics concept needed to understand this study is going to be presented in this part and more information has been read from different literatures.

2.2 Description of PV system

2.2.1 PV system overview

PV systems convert sunlight energy into electrical energy using power electronic devices. SPV are becoming more useful in our daily lives because they are being deployed in many basic needs devices such as calculators, wristwatches, water pumping systems, transport systems and street lighting systems, etc. Also, there are small and large solar power plants generating electricity. Depending on where they are used, a typical PV system contains more than one of the following devices: PV module, battery, power conditioning device, load and balance of the system. PV cells are combined together to build up PV modules which can also be connected together to build up PV panels or PV arrays, for the purpose of producing electrical power reliably and conveniently for any electrical demand requirement, no matter how large or small it is [13].

2.2.2 Main components of PV system

Solar PV system can have different elements according to the type of the system, location and applications. More than one component can be wired together to form a system that can supply power to a typical load, the mains components are panel/module, battery, charge controller, inverter and load.

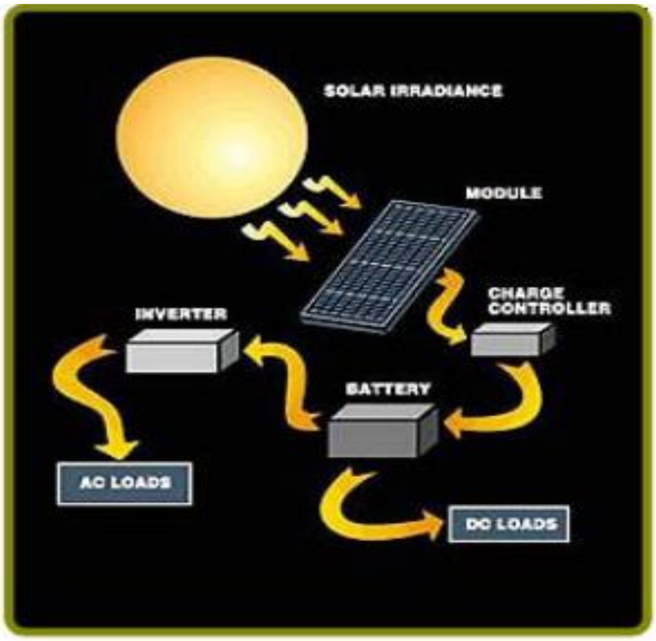


Figure 2.1. Schematic diagram of Photovoltaic System with storage unit [6].

Those components are for a standalone (simple SPV system). For others system like hybrid, grid connected systems, additional elements like transformer, protective equipment, metering equipment power conditioner unit, etc. are required.

- PV cell, panel/module and array

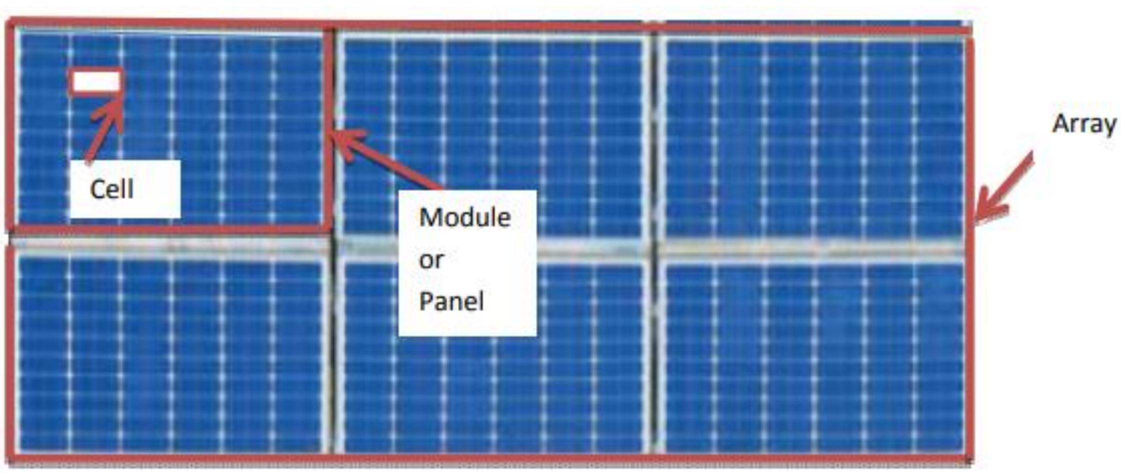


Figure 2.2. Basic elements of PV system [14].

A PV cell is the main and fundamental unit in solar PV system which serves the role of converting directly the solar radiation into electricity (DC). A module is made by a combination of more PV cell. A number of PV modules are connected together either in series or/and in parallel to form an array and its number and connections depend on the required output power [11].

- Battery

Its use is to store the surplus energy that is not going to be used directly. Batteries have the ability to resist on their charging and discharging to a rated value according to their capacities.

- Charge controller

The charge controller's purpose in the system is to regulate the charging and discharging of the battery so that it cannot be destroyed. It also acts as the link between others units of the system by maintaining the voltage and current flow in permissible limit. Its role in the system is very important because the cost of energy produced strongly depend on its quality [15].

- Inverter

It is also called power conditioner because it changes the form of the electric power [11]. In SPV system, this device converts DC electricity produced by PV panel into AC electricity so that AC loads can be easily connected to the system. For grid connected systems, inverters can be used to perform additional functions for output maximization. Those functions include protection and isolation in case of irregularities in the grid or with the PV modules. They are categorised into 3 types named central where multiple strings get connected in a combiner box that runs DC power to the central inverter, string where multiple strings get connected to one inverter and micro inverters an inverter gets attached to each module individually [16].

- Load

Electrical devices to be powered by electricity in order to function. It can be an AC or DC load.

2.2.3 Classification of PV System

According to the system's purpose and configuration, PV Systems are classified into two main types which are standalone and utility connected systems. There others like hybrid systems, independent system which does not require an inverter for DC to AC conversion and other system without storage system and are considered in standalone Solar PV system [15]. Those systems types are designed to power AC and/or DC loads. Figure 2.3. illustrates main types and components of PV system.

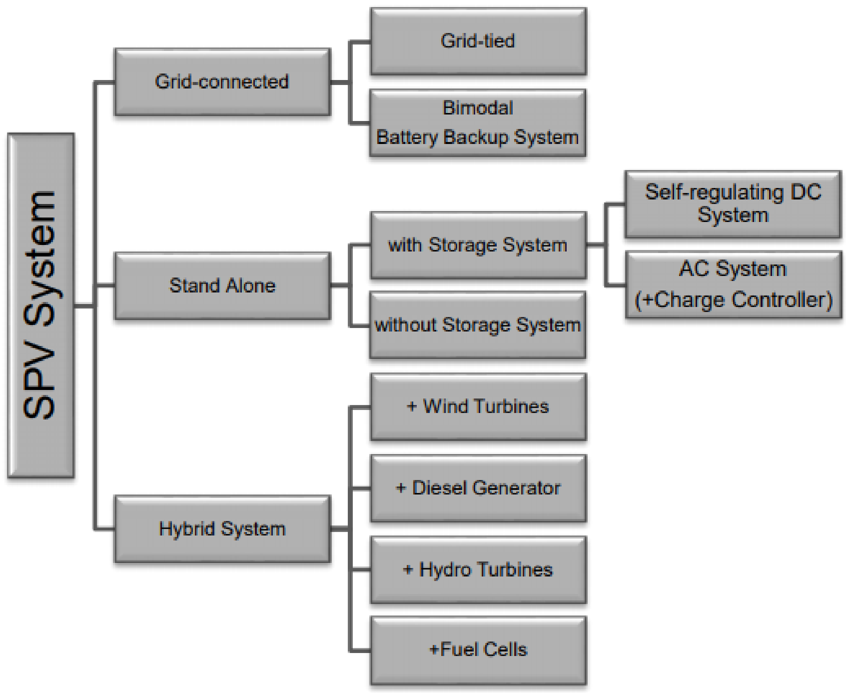


Figure 2.3. PV system classification [16].

2.3 A PV cell model characteristic

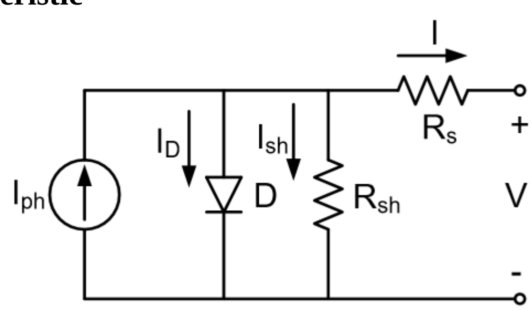


Figure 2.4. Equivalent circuit of PV cell [18].

Figure 2.4. represents a PV cell. The three parallel parameters, source current I_{ph}, diode D and shunt resistance R_{sh} are connected to the series resistance Rs and the amount of flowing current depends on solar radiation that strike the cell as well as present temperature in the location.

The circuit model formed by one diode and two resistors is defined by the following equation:

$$I = I_{PV} - I_O \left[\exp\left(\frac{V + IR_S}{\alpha V_T}\right) - 1\right] - \frac{V + IR_S}{R_{Sh}} \tag{2.1}$$

Where,

$\boldsymbol{I_{PV}}$: the photocurrent delivered by the constant current source;

$\boldsymbol{I_O}$: The reverse saturation current corresponding to the diode;

$\boldsymbol{R_S}$: series resistor that takes into account losses in cell solder bonds, interconnection, etc

$\boldsymbol{R_{Sh}}$: shunt resistor that takes into account the current leakage through the high conductivity shunts across the p-n junction;

α: Ideality factor,

n: the number of cells in series,

T: The cell temperature in Kelvin,
$\boldsymbol{V_T}$: Thermal voltage of the diode and depends on the charge of the electron,

q: is charge of an electron (1.6×10^{19}C),

k: The Boltzmann's constant (1.38×10^{23}j/K)

$$V_T = n\,\frac{KT}{q} \tag{2.2}$$

2.4 Types of PV modules technology

They are 2 basically types of solar PV modules. Silicon is the main material used in making PV cells/modules. Figure 2.5. shows various PV cells manufactured from silicon materials.

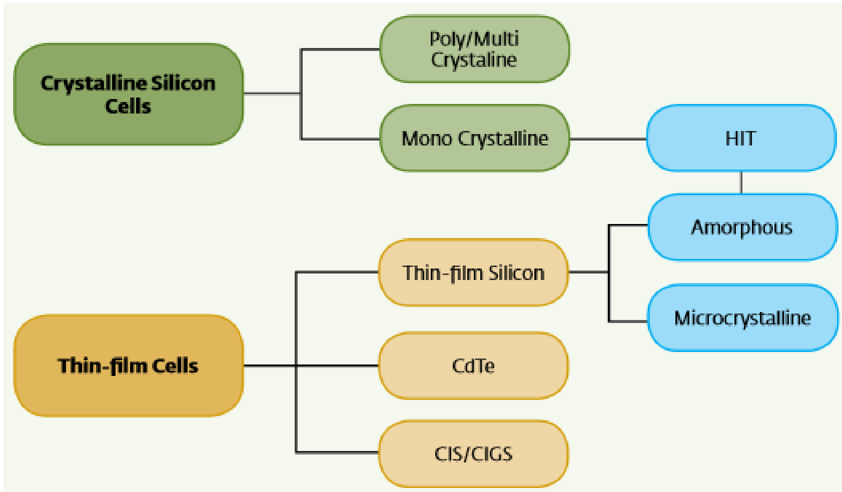


Figure 2.5. PV technology classes [20].

2.4.1 Crystalline Silicon (c-Si)

Modules are made from cells of either mono-crystalline or multi/polly-crystalline silicon.

a. Monocrystalline silicon panel

It is the most effective and commonly utilized commercial solar PV cells because of its powerful conversion efficiency of 15% to 20%. It requires a small area to produce much power when compared to other cells. Its power production magnitude is four times that of thin film cell having the same cell area and under same weather conditions. Also, it has a longer life span above 25 years [16].

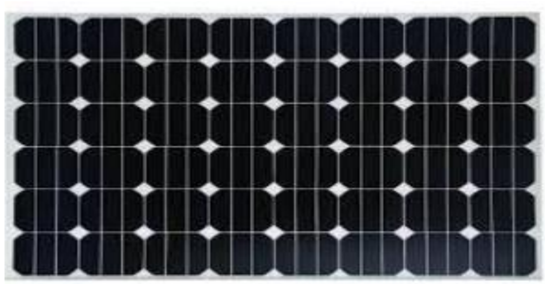


Figure 2.6. Monocrystalline silicon type

b. Polycrystalline silicon Panel

Polycrystalline silicon cells have other names such as poly-Si or polysilicon, multicrystalline. It has a lower efficiency between 13% – 16%, low cost to manufacture when compared to monocrystalline. It requires more space for less power production (not space efficient). Polycrystalline silicon cell produces 130W of electric power using an area of m^2 and 1000W/m^2 of solar irradiance. It has a shorter life cycle of 20 – 25 years [16].

Figure 2.7. Polycrystalline silicon type

2.4.1 Thin film silicon

The thin film silicon cells are considered to be the subsequent batch of PV cells. It requires less material for its production and consumes less power. Thin film cells are cheaper when liken to crystalline cells. Typical efficiency is about 9% – 12% making it the least efficient. It can function perfectly well at lower irradiance, thin film silicon are made from non-crystalline silicon [16].

Figure 2.8.Thin film type

The main important positivities and negativities factors are of key advantages and disadvantages, potential issues of each stated PV technology are summarised in table 2.1.

Table 2.1. Difference between PV cells technologies [16],[19].

PV Technology	Strengths	Weaknesses
Crystalline Silicon	For (mono-Si) -efficiency: 15-20 % (21.5 % most extreme current) -lastingness up to 25 years -space-efficient	-expensive -sensibility to ambient temperature - sensibility to shading issues, snow and dirt -wasteful manufacturing process
Crystalline Silicon	For (p-Si) - nor complex, cost-productive and not inefficient manufacturing process -insignificant intolerance to high surrounding temperature	expensive -sensibility to ambient temperature - sensibility to shading issues, snow and dirt -wasteful manufacturing process
Thin-film (TFSC)	-cost- productive and simple manufacturing process -flexible configurations applicable different installations - high resistance to shading issues and ambient temperature variation	-low productivity: 9-12% -low space efficiency -high degradation

2.5 Maximum power point and PV array tilt

When a PV panel receives uniform irradiation during normal condition, its I-V characteristics show a single maximum power point where it is able to produce the power which is maximum. Devices called maximum power point trackers (MPPT) are used so that arrays keep their ability to generate power at the maximum and there are numerous control algorithms trough them that MPPT can be applied and the common algorithm is known as perturbation and observation (P&O) [21]. The condition for an array to deliver the maximum power is when the angle between the sun's radiation and the receiving surface is right angle. In order to reach this condition, the modules' mounting structure can travel behind the sun's motion, trackers were designed to adjust for azimuth and elevation [22].

2.6 Output characteristic of a PV cell

One of the crucial characteristics of SPV system is the I-V and curves of a photovoltaic cell, module or array. This curve shows how a PV cell or module can generate energy according to the module's inputs like solar irradiation, cell temperature, orientation of the module, etc. This curve also draws the possibilities of couple of voltage and current at which the module can operate for the constant inputs condition. Mostly those parameters illustrated on the curve come out on the module's nameplate so that the users consider them before its installation as well as use.

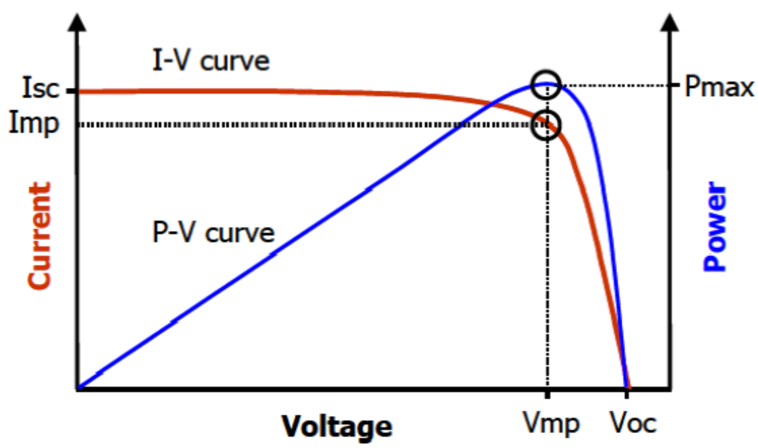


Figure 2.9. I-V and PV characteristics of PV cell [23].

I-V and P-V curves of a PV cell with their main parameters is represented in the figure 2.9.

- I_{sc} represents the cell current when it is shorted means its maximum corresponds to zero voltage and the circuit impedance is low

$$I_{SC}=I_{PV}-I_O\left[\exp\left(\frac{I_{SC}R_S}{\alpha V_T}\right)-1\right]-\frac{I_{SC}R_S}{R_{Sh}} \quad (2.1)$$

- Voc (open circuit voltage) is the voltage across the cell when the circuit is open, its maximum corresponds to zero current.

$$0=I_{PV}-I_O\left[\exp\left(\frac{V_{oc}}{\alpha V_T}\right)-1\right]-\frac{V_{OC}}{R_{Sh}} \quad (2.2)$$

- The point (Imp, Vmp) on the I-V curve is the maximum point at which the maximum DC power can be generated by the module/array.

$$I_{mp}=I_{PV}-I_O\left[\exp\left(\frac{V_{mp}+I_{mp}R_S}{\alpha V_T}\right)-1\right]-\frac{V_{mp}+I_{mp}R_S}{R_{sh}} \quad (2.3)$$

DC output power to be produced in the system strongly depends on irradiance intensity, the more it increases the more output power generated, in other hand the module's temperature is inversely proportional to the output power [24].

Another important parameter is fill factor (FF) that help to measure the cell capability by showing both maximum powers practically and ideally and is calculation is shown in equation 2.4.

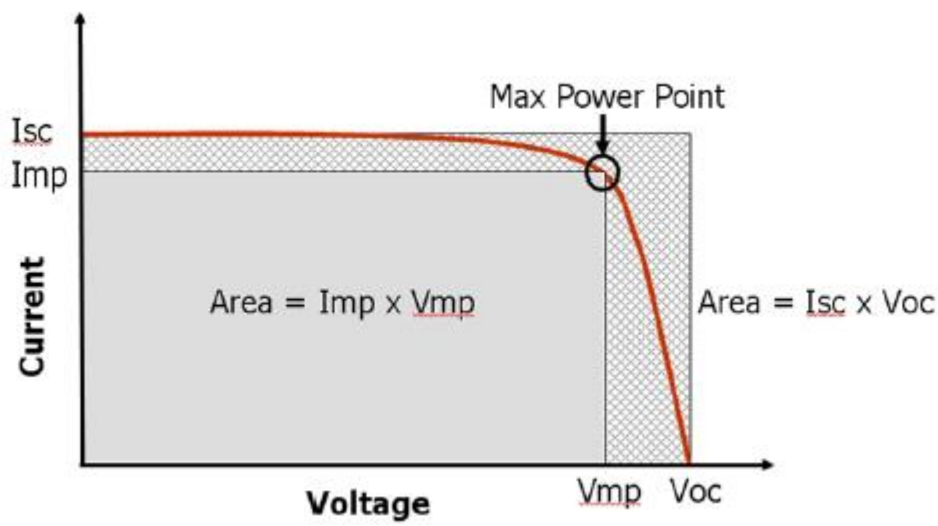


Figure 2.10. The Fill Factor, defined as the gray area divided by the cross-hatched area [23].

$$FF = \frac{\text{Imp x Vmp}}{\text{Isc x Voc}} \quad (2.4)$$

Where,

Imp: Maximum power current
Isc: Short circuit current
Vmp: Maximum power voltage
Voc: Open circuit voltage

The real fill factor magnitude strongly depends on manufacturer as well as module technology. Additionally, any factor which decreases the fill factor will in turn decreases the output power by reducing its maximum power point, figure below represent some factors that reduce where among them different losses have been shown on the I-V curve [23].

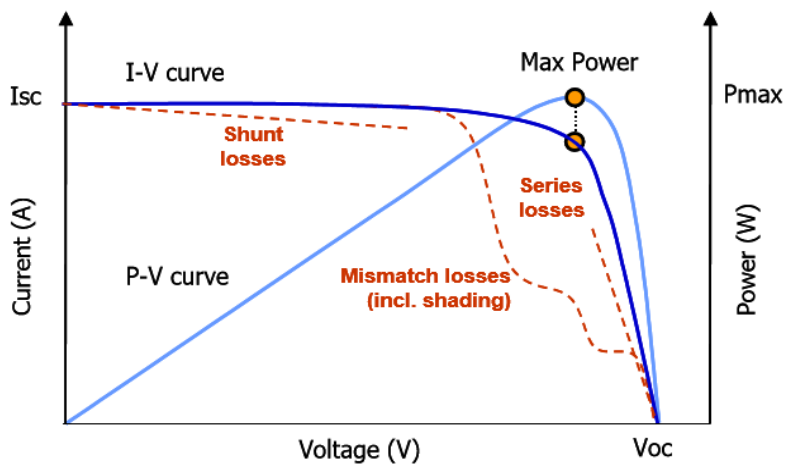


Figure 2.11. Several categories of losses that can reduce PV array output [23].

So as to utilize solar energy for practical devices which need specific voltage or current for their activity, various cells must be associated together to make a panel/module. Photovoltaic panels are the system's core elements and are generally called the power generators. For large PV system, panels are connected in series and/or parallel to form an array. So, the maximum power point of an array can be found in terms of building blocks which can represented by cell, module or a string. As shown in figure below, each building block has a maximum power point in its upper right corner. In case these blocks are structured together, their upper right corner represents the max power point of the array.

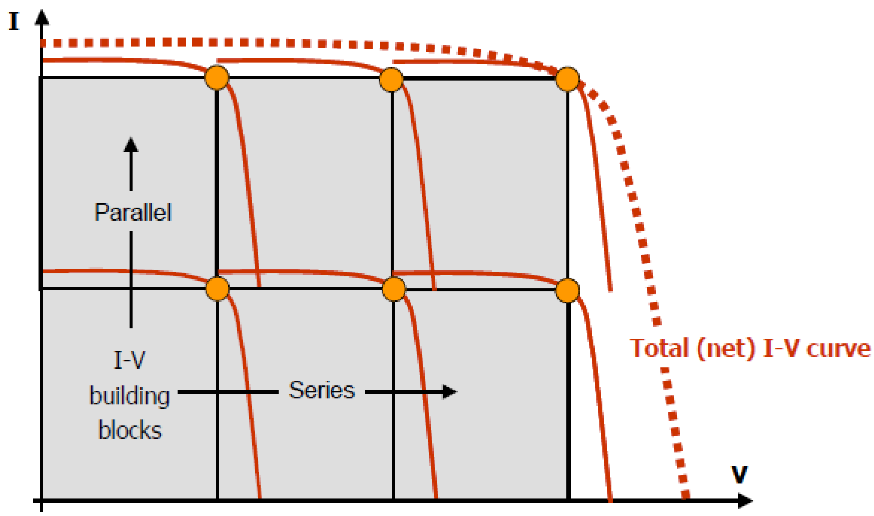


Figure 2.12. Scaling the I-V curve from a PV cell to a PV array [23]

Efficiency is the ratio of the electrical power output Pout, compared to the solar power input, Pin, into the PV cell. Pout can be taken to be PMAX since the solar cell can be operated up to its maximum power output to get the maximum efficiency.

$$\eta = \frac{P_{out}}{P_{in}} \longrightarrow \eta_{max} = \frac{P_{max}}{p_{in}}$$

2.7 Performance factors of PV system

Many factors play a big role during energy production based on solar photovoltaic. Apart from types and structures of solar panels which vary the panels capabilities, there are other external parameters which considered as major factors on PV performance.

- **Insolation/sun's irradiance:** Is the most essential element in PV energy production is irradiance. As the solar cells receive more irradiation from the sun, the more energy is produced. It varies by day to day.

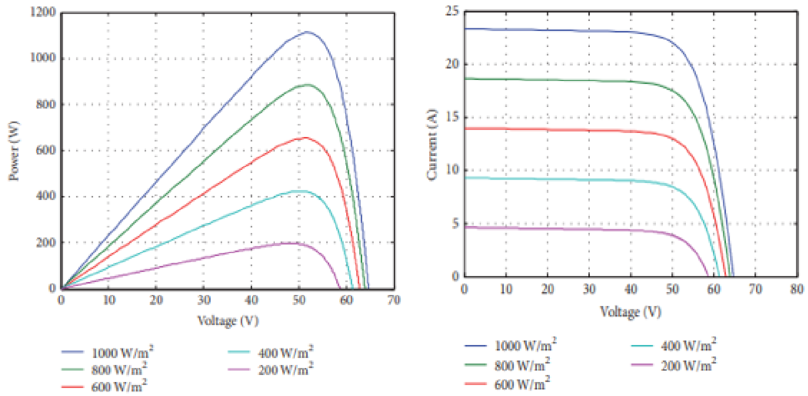


Figure 2.13. Effect of irradiance on PV module

- **Temperature:** The Power produced from solar panel is inversely proportional to the ambient temperature. Means that the cells performance is better in cold climate compared to the hot one.
- **Shading:** In ideal conditions, a PV system should be installed in a place where there will be no shadow on solar panels. Due to non-linearity of shading effects, a small shaded area can strongly reduce the output power of the system to a value nearby zero. For series connected cells inside the panel, a flow of current in the shaded cell affects the whole module. So, for those conditions where shading is inevitable, it is better to consider shading during planning to avoid its influence.
- **Soiling:** Things like dirt, dust or other material which is deposited on the surface of panel and blocks the incoming solar irradiation thus the energy to be produced reduce.
- **Orientation:** Another important aspect is to know the correspondence of solar irradiation to the solar path in the place at the different times of the year. The situation of the sun at any time is determined by the height and azimuth of the sun. The orientation of the photovoltaic module is the angle of deviation from the geographical south of a surface or north in the southern hemisphere, the orientation angle of the solar panel is based on one angle only: the orientation (or the azimuth) of the panel [25].
- **Inclination:** Solar PV performance also influenced by panel's inclination. The amount of energy produced depends on the panel's inclination in the fact that its maximum will be when the position of the plate is perpendicular to the irradiation. The solar panel inclination depends on factors like climatic condition and geographical location. Due to the fact that the optimal Sun's position varies over time, for the installation of fixed modules, an inclination value is usually chosen for the maximum average power received annually [25].

2.8 Shading on PV solar cells

2.8.1 Shading classification

Practically some shading is inevitable in PV systems due to environmental condition whether others can be evitable in practical condition by varying some parameters. When shading occurs on PV system, it can partially or completely cover a single or multiple of a cell, module, array and string and some can vary and others cannot not vary according to its cause. Among categories, there are two main groups of shading named as objective and subjective shadings.

Subjective type is classified into dynamic and static shadings. Objective shadings are those which caused by weather condition like heavy cloud and haze, this kind of shading in unavoidable to the system. In other hand subjective shading, are the one caused by shading objects according to sun's angle like nearby buildings and trees in case of dynamic shading whereas in static type, close proximity obstructions like bird droppings or other objects that can cause dirt on the module's surface. Subjective shading can be avoided by periodic cleaning, better design and instalment [26].

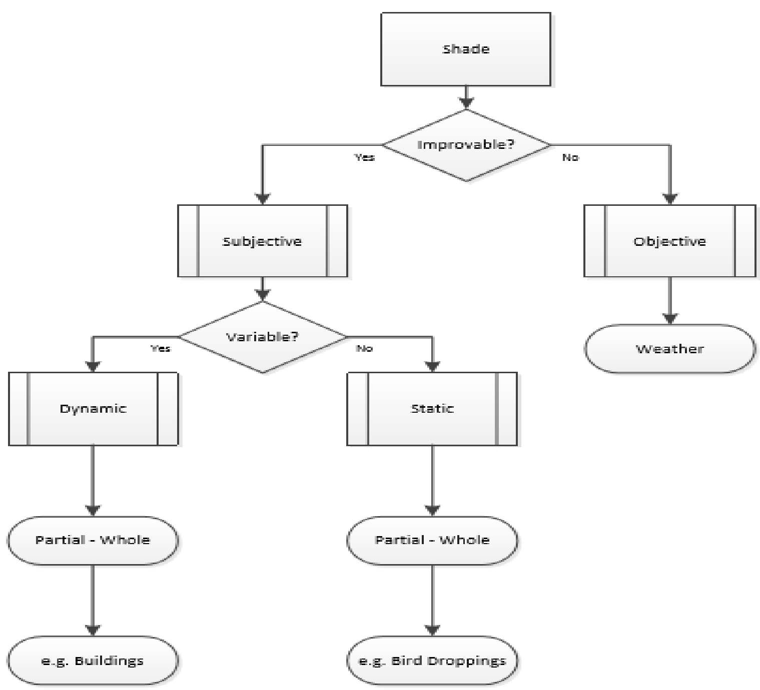


Figure 2.14. Shading classification [26].

2.8.2 Mismatch losses

Even if PV has seen as renewable energy which has many advantages, it still has some disadvantages where one of them is a mismatch loss that can occur during energy production. Really, the actual output is not equal to the expected one due to different causes include defects due to manufacturing, PV cell ageing or other degradation, cell temperature, shading etc. So, the difference between the two values (the expected and actual power outputs) is known as mismatch losses. They can come from external or internal factors and they can be temporary or permanent sources. Like modules configuration, environmental stresses, shading is also a main of the external sources of mismatch whereas internal causes are related to manufacturing and sometimes are due to ageing [27], [28].

2.8.3 Effect of shading on PV system

Output power of a SPV system strongly depends on the irradiation received by solar panel and one of the factors that can lessen the intensity of solar irradiation is shade that can occur on the panel's surface. Environmental condition, location and structure of the system have taken as the main agents that cause the variation of solar irradiation.

For any PV system composed by a series and parallel connected modules, some modules will be will affected during energy production in case shading occurs and the rate at which it was affected will depend on many factors like shaded area, modules interconnections and rate of that shade on the cell. This degree will be determined by how much radiations are obstructed by shadow [29]**.** Some studies assumed that for a single cell, the effect of shading on the output power is proportionally related to the shaded area and the decrease of irradiation, submodule's layout and the bypass diodes is an added factor on the level of array [30]. Another aspect is that shadow can be caused by a nearby module, the more the module is too closer to another the more it can cause additional power losses in cases of shading [13].

During normal condition, the P-V characteristics exhibit one peak as shown in figure 18 of photovoltaic cell characteristics where that peak corresponds to the maximum power that a PV string can produce. Contrary when partial shading occurs, more than one peaks are produced include the local peaks and global peak that indicates the strings maximum power capacity. Some MPPT are not enough sensible to distinguish the global to local peaks [31].

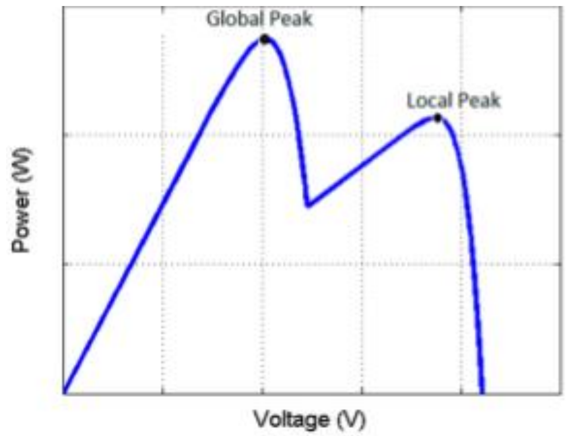


Figure 2.15.P-V characteristics under partial shading [31].

Practically lost power due to shading are high compared to the array shaded surface. For array of few parallel connections, a small shaded area can cause the system output to drop to a fraction of rated power which lead to the failure of the system. When a shade occurs, the series shaded module will not be able to produce the normal output power due to the inability of voltage production and this will lead to power dissipation due to generated heat. In this case the normal modules (unshaded modules) will need to compensate the voltage losses entire the system, then make less current and more power losses**.** Those shaded modules will be no longer generators but they behave as load. Partial shading and module mismatch are also responsible of the creation of hot spots in cells of a module which reduce not only energy production but also the lifespan of the module [29], [32],[33].

2.9 Related works

Yunlin et al [29] on their research on "Analysis on the Effect of Shading on the Characteristics of Large-scale on-grid PV System in China," were interested in shading analysis for grid tied photovoltaic system, they took a case study of a plant located in Northwest China. Their aims were also to show the shading effects on photovoltaic module's properties (electrically affected). During their research, shadings were classified according to the specific circumstances where different regions were taken into account and they have seen that power distribution nearby rooms for distributing power, closer vegetations, or at some unstated time the front row arrays or are common cause on shades. According to the past research regarding grid tied plants, they have categorized shading phenomenon into three types that are: the front row shading phenomenon, closer vegetation, the nearby power distribution room and shade due wires and supports. Based on PV module interconnections whether series or parallel, they saw that there will be no voltage on shaded module when it is in a long series during shading conditions and it cannot produce normal power without voltage even if there is current flowing through it. The said, cause the module to behave as load and dissipates power due to heat generated. After this, the unshaded modules will perform at higher potential to keep the potential of the entire series and this will lessen their current and lead to increase in output power losses and the utilization of bypass diodes has shown as technique to reduce that power losses caused by shading. In order to analyse the effects of nearby building, they conducted some experiments. They used a poly-Si module each of 60 series connected series cells and some nominal parameters and there were three bypass diodes in one module where one diode had a purpose of protecting 20 PV cells. During their experiment, 6 modules were analysed where only 2 modules were not shaded. Looking on IV curve, they have seen that the characteristics on non-shaded modules were maintained while the one of shaded modules were changed. In conclusion of their research, they have mentioned that the electrical properties of PV modules can be affected by shading and that the effects of shading can be not the same on identical PV module when the same area is shaded on different shading positions.

Samuel et al [13] in their research on “Shading Effects in Photovoltaic Modules - Simulation and Experimental Results”, showed advantages of electrical energy based on PV include having no moving parts, no air pollution and with less maintenance compared to other renewable energy technologies. Soft and hard shades classifications have also shown. During their research, some reviews were carried out, some experimentation and matlab Simulation were used to compare the shading effects on PV systems. During experimentation, card board as hard shading was applied on 50% 0f PV module and the results (voltage and current) recorded by the help of two mustimeters on two cases (during no shade and when modules are 50% shaded) showed that the power losses on Si PV module was minimum compared to the power losses on others modules. The simulation was done in matlab on three Silicon PV types of some nominal parameters per each. The standard radiation (non shade), and others two cases of radiations (soft shades) were applied on three types of modules and the results were recorded and show that amorphous Si PV module was not much affected by partial shading compared to monocrystalline and polycrystalline Si PV module types because the difference between the global maximum power point and the expected power at maximum for amorphous Si PV type was minimum compared to others modules. They concluded that shading leads to deterioration of the electricity conversion and photovoltaic system's generation capacity. The effects can vary due to many factors like module types, material's structure, severity of shades on the system and structure of the. They also show that the module with much better adaptation to partial shading should be used in the situations where shading impacts are both dangerous as well as unavoidable.

Amardeep et al [18] in their research named "Effect of Partial Shading on Characteristics of PV panel using Simscape" present a PV characteristic when it receives uniform irradiation and when irradiations become non uniform due to many factors as stated below. They have seen parameters like shading, variability of atmospheric condition, of clouds creation and changes of sun position on daily basis. The possibility of always having uniform irradiation on panel is impossible. It is through that non uniformity of illumination a PV characteristic face changes. Some of those changes were mentioned like mismatched current and voltage in series parallel strings respectively. Their aim was the illustration of shades effects on structure of array and they did so by simulation done in matlab. By comparing the array characteristics in two different conditions (when it has no shade and when it is partially shaded), they observed that the PV characteristics have changed. Finally, they have found that apart from dip in voltage and power caused by partial shades, also the system produces multiple peaks of maximum power point rather than having one MPP and this make a PV characteristic to be more complex. The effects of bypass diode under shading conditions have been also investigated in this research where the simulation results validated the system performance during shaded condition conditions in presence of anti-parallel diode as well as without its presence.
Ekpenyong et al [34] in their research on "effect of shading on photovoltaic cells", have shown the advantages of PV system such as electricity production without noise, air pollution and fuel. After stating that produced electricity is proportional to insolation that received by panel, means increase as radiations increase and also showed that the output degrades gradually as sunlight decreases. The main purpose was to clarify the shading effects on photovoltaic cells. They have shown that primary cause of losses during power production in PV system is partial shading and that effect depend on system interconnections (series or parallel) and investigated how a single module behaves as well as array formed with many modules connected to an inverter with shadows in both cases. It has done with a help of solar energy system of a known capacity, the output current and voltage were recorded 10

hours per day in total time of 3days and the solar illumination were changing. The experimental results demonstrated that there is a substantial power loss due to non-uniform illumination of a series string. The power generated by highly illuminated cells is wasted as a heat in the poorly illuminated cells. They observed that even if the use of by-pass diodes for each PV module may mitigate the negative effect from partial shading, this method alone may still face severe energy efficiency degradation caused by the energy loss due to parasitic effects in the ESS under variable incoming power from the PV modules.

Sathyanarayana et al [35] on their research named ‘‘Effect of Shading on the Performance of Solar PV Panel’’ started by showing why several renewable energy resources are being exploited nowadays. After describing solar PV system in short, cell efficiency and fill factor (FF) have also shown as the parameters that can be affected by shading condition. In their experimentation a rectangular PV panel (450 mm x 280 mm x 30 mm) mounted on an adjustable stand was utilized for exploring shading effects and two types of experiment named uniform and non-uniform shading were conducted. On uniform shading, all cells receive the same radiation whereas in non-uniform shading they receive different irradiation. On uniform shading butter papers were used and in other case various areas were selected for shading where each experiment was repeated three times for consistently reads and determination of power output, fill factor and conversion efficiency. They observed that apart from output power reduction, there is no other effects of uniform shading on panel performance. On non-uniform shading, two cases were considered. First case was when one cell was completely shaded and second was when a cell was partially shaded. In first case they have observed that the output power has completely vanished whereas in the other case they have seen that the decrease in the output power was proportionally related to shaded surface. They have also noticed that during non-uniform extremely affect the fill factor and efficiency depending on the shaded portion of cell. They presented that during non-uniform shading condition, panels with less insolation behaves like loads and conduct as in reverse biased status resulting with hot spots production. They concluded that it is very essential to avoid this this situation so that the PV panels can work on their maximum efficient as well as avoiding the permanent damage of the cell.

2.10 Literature gaps

Like many places in world, renewable energy utilization and SPV system particularly is fastly growing in Rwanda. Therefore, people need to have enough knowledge in order to positively affect its use as well as development of future related projects while taking into consideration the related problems. Regarding to related literatures, shading effects have been discussed by different researchers. Such studies were done throughout the world, unfortunately many Rwandans have not yet effectively informed so that they can deal with those conditions.

This research work will contribute in terms of helping Rwandans to be aware of effects of shading on their systems. Being informed on this will help them to avoid those effects where applicable and apply the technical mitigations techniques for those which are inevitable.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Introduction

After having some basic concept of PV which is helpful for better understanding, this section is going to show used method and some followed steps in order to get results. This method is composed by two part, one for experimentation in UR/ACE-ESD High E-Tech Smart Grid Laboratory and other of PVsyst simulation. After getting final results, those results were analysed and discussed.

3.2 Laboratory experiment

Assembly of various equipments which described here were used to conduct experiment named Maximum tracking with and without shading.

- Solar panel emulator (1.5kW): It consists of a DC power supply source which can be controlled. It provides the required DC voltage, current and power to the inverter analog to PV-modules. The solar panel emulator can be remotely operated using the "Solar Panel" virtual instrument, which allows the simulation of the behavior of a photovoltaic system. Via the user panel, the irradiance, shading of modules and number of shaded modules can be adjusted.
- Mains power supply: It power DC, AC devices and three-phase machines.
- The three-phase power quality meter: It permits measurement and display of all relevant grid parameters. It is able to carry out single, two-phase or three-phase measurements. The “Smart Meter” acts as a digital electricity meter at the end points of the electricity grid to measure electricity consumption and can be used to turn consumers on or off depending on circumstances.
- 3-phase industrial photovoltaic converter: This PV-inverter is designed especially for three-phase power supply. The device has a graphical display for visualizing energy yield values, current power and operating parameters of the photovoltaic system.

The said devices are linked in some cases via different interfaces (ethernet or USB) to the PC.

3.3 PVSYST software

The simulation for this study was done by use of PVsyst software (PVsyst 7.0.6 version. André Mermoud, a graduate (1971) is one who created its package at University of Geneva. This software is known as a trustful solar PV software due to its working capability. It can be used by variety of people include researchers, architects, engineers etc. around the world in sizing and study of photovoltaic system performance. In its four main sections it manages the grid tied systems, isolated/independent systems, Dc grid and pumping photovoltaic systems components databases, as well as general solar energy tools. It is incorporated with a 3D CAD displaying climate and deals with the impacts brought about by the obstructions due to environment [36][37].

PVsyst has four parts where different studies have to be performed, they are shortly described below

- Preliminary design

The Pre-sized level: In this step a quick evaluation of the planed system's dimension and components is made. Assessment of system's production is also made in this level.

- Project design

The Design level is where a detailed study can be done with diverse meteorological data. This level deal with System design, economic evaluation, determination of detailed losses, analysis of shading and economic studies.

- Database

Database level: Is where radiation data from various locations can be found. It deals with the management of meteorological data and system components.

- Tools

The Tools level: It contain an advanced feature. Is where analysis of really measured data on existing systems can be done.

However, the purpose of this study is not a design, there are necessary requirements to be defined in the software and are illustrated below. Geographical data

- Meteorological data (imported from Meteonorm)
- Technical data (tilt and azimuth)

- 3D model scene for near shadings
- PV modules configuration based on accessible rooftop region
- PV framework segments looked over the PVsyst database include module, inverter and strings

After defining the above parameters in the program for a chosen system size, different system simulations were performed and compared for better understanding.

3.4 Description of methods

Followed steps for the analysis of shading effects in PV systems is shown below.

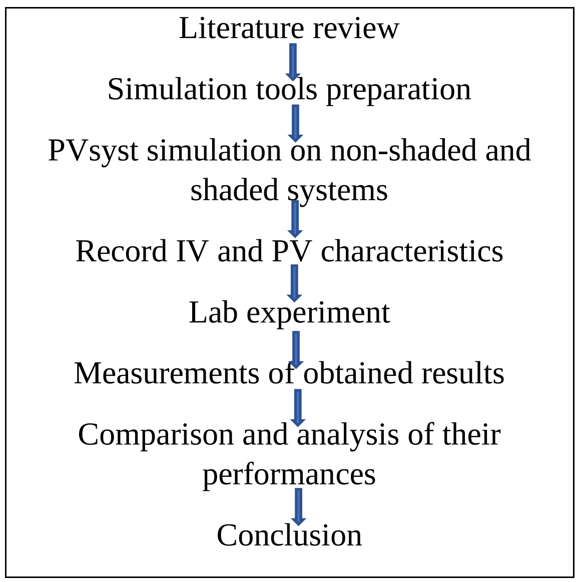


Figure 3.1. Research steps

In this work, a studied system was simulated within PVsyst software (7.0.6 version) under two conditions, one without shading and others with it. In this study, general working principle of PVsyst is explained where different steps to follow have shown in detail.

CHAPTER 4. SYSTEM ANALYSIS

4.1 Characteristics of the used module

In the simulation, a 50Wp monocrystalline module with 36 cells of generic type has been used. Below is a table that shows the important parameters of the above stated module with its specifications in STC conditions, means at (1000 W/m^2. 25 °C).

Table 4.1. Electrical Characteristics

Parameters	Specification
Nominal Power [W_p]	50W
Short circuit current [I_{sc}]	2.930A
Open Circuit Voltage [V_{oc}]	22.10V
Maximum Power Current [I_{mp}]	2.760A
Maximum Power Voltage [V_{mp}]	22.10V
Number of Cells in series	36
Number of cells in parallel	1
Number of bypass diode	2
Efficiency	34.69

Table 4.2. Mechanical Characteristics

Parameter	**Specification**
Type	Monocrystalline silicon
Frame	Aluminium
Length	540 mm
Width	670 mm
Thickness	30.00 mm
Module area	0.144 m^2
Weight	4.20 kg
Connections	JBox

For better understanding on the basic of PV module/array characteristics, the IV characteristics which are generally found from manufacturing data sheets have been viewed. According to various manufactures, the PV characteristics are different due to used solar cell as well as their qualities. A I-V and P-V relations of a single cell are expanded form a PV module as well as to an array. There are various models for any operation of typical solar cell where the five main parameters are considered as they use for the above stated relations for a single solar cell [1].

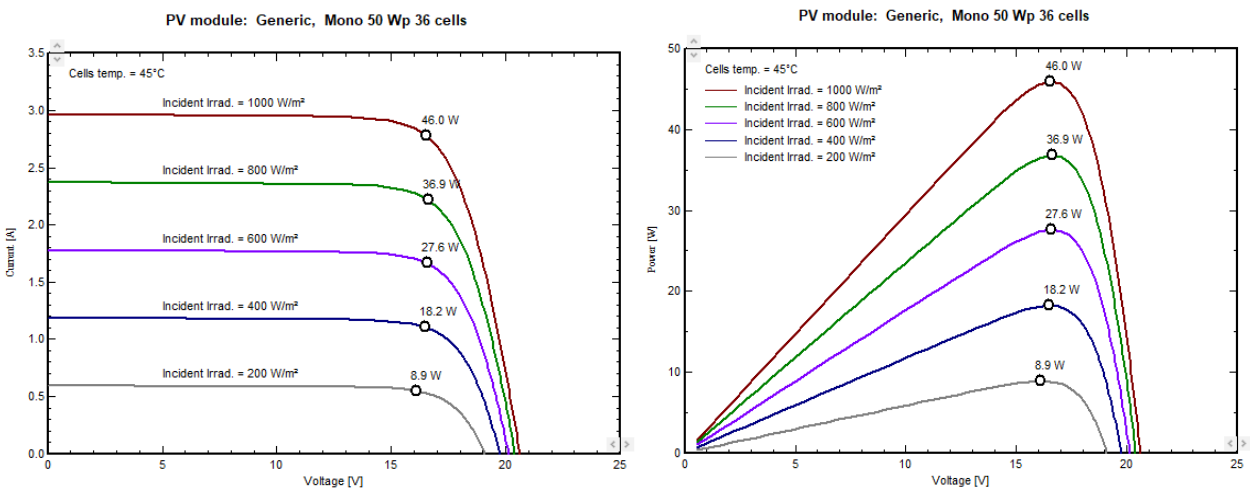


Figure 4.1. I-V and P-V curves of the selected module based on incident irradiance

4.2 Analysis of electrical behaviour of shaded modules

Before going to simulation, it is better to see how PV modules behaves during shading conditions in different configurations. This was done within PVsyst tool box.

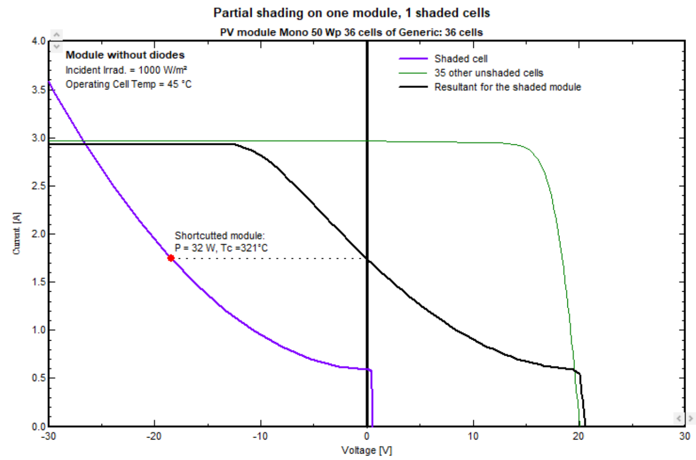


Figure 4.2. PV module with one shaded cell, without protection

The shaded cell is no longer a power producer but absorbs power produced by other unshaded cells and its temperature increases. In the figure 4.2. its power has reduced and temperature raised up to 321°C. This mostly lead to the cell destruction due to preventive powers within the cell. When the cell/module is connected in an array, the array's MPP may push a much current than the one at normal module's short circuit point. The fact is that when a cell is shaded, its current raises and exceeds its rated Isc (short circuit current) and then no longer be forward biased, so absorbed power becomes very large (results to the hot spot creation). In order to limit the shaded cell's power consumption, a bypass diode (anti parallel) is added to each submodule [38].

4.3 Laboratory experiment

According to the nature of experiment and laboratory structure, set of equipment stated in table 4.1 were used to see how shadow affect the characteristics of PV systems where following conditions were studied and the same processes were followed in each case:

- Case 1: when irradiance is 100% (1000 W/m^2), number of shaded modules = 0 and shadow of 0%)
- Case 2: when irradiance is 100%, number of shaded modules = 2 and shadow ratio = 20%
- Case 3: when irradiance is 100%, number of shaded modules = 5 and shadow ratio of 50%
- Case 4: when irradiance is 100%, number of shaded modules = 5 at shadow ratio of 100%

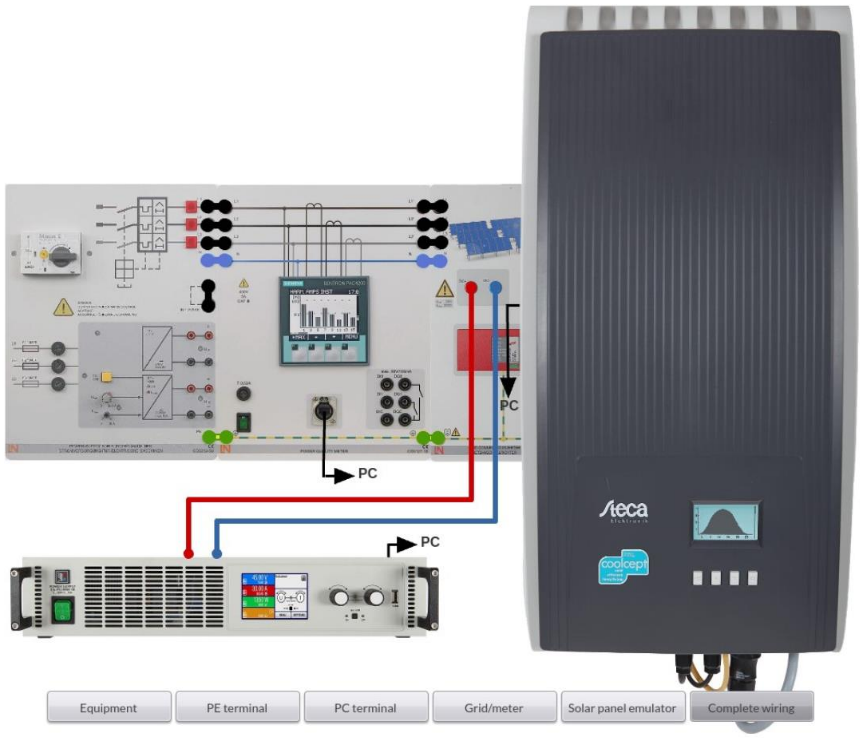


Figure 4.3. Experimental set up

4.4 PVsyst simulation

4.4.1 Introduction

After having all sizes of the necessary equipments and other required concepts for this thesis work, it is time for simulation to see the shading effects for chosen conditions. In this study, a simulation is implemented by using PVsyst software to found the effects of shadow for a selected system. Based on the problem statement, the results from this simulation have been explained in the next chapter.

4.4.2 Location and Geographical

For this software, location means a study area and geographical is about coordinates. The studied system was assumed to be located in Rwanda, Migera cell in Kayonza District.

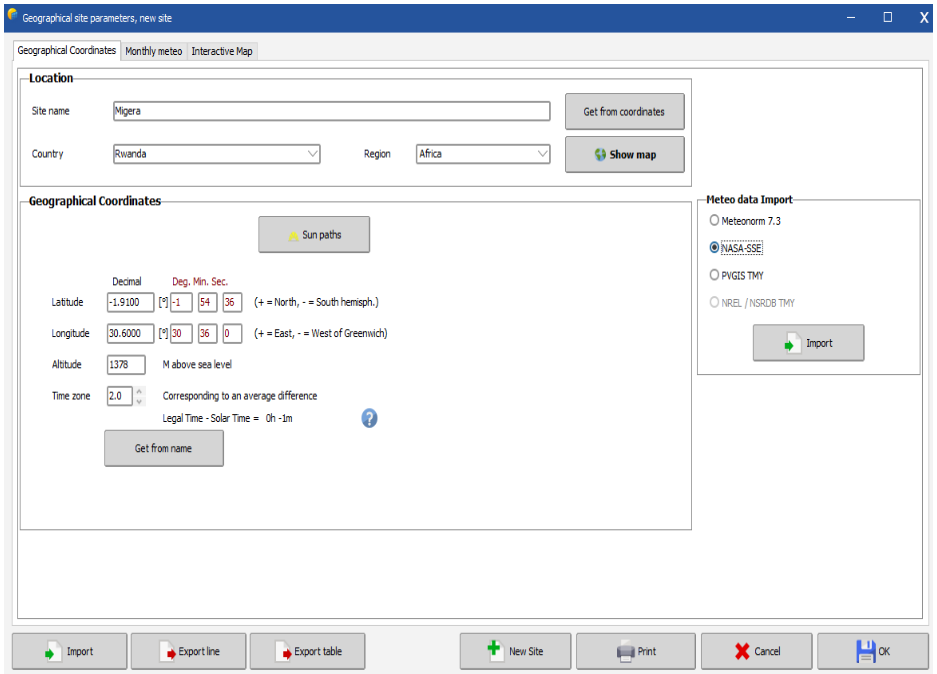


Figure 4.4. Site location and geographical coordinates

The place's geographical coordinates are so important to start the study. With the help of geographical coordinates, the meteorological data of the selected place was imported in the program database. Based on Meteonorm 7.3, the location's solar insolation is 4.98 kWh /m^2 /day, wind speed is 2.8 m/s, annual temperature on average basis is 20.8°C and relative humidity of 68.8% per year at latitude of -1.91°S, longitude30.60°E or -1°54'37"S and 30°35'56"E and altitude of 1378m above sea level.

Because minimum meteorological data for the place is required for simulation, here the program allow user to choose which data can be calculated where at least two of them is required. Those data include:

- Global horizontal irradiation
- Horizontal diffuse irradiation
- Horizontal beam
- Normal beam
- Relative humidity
- Wind Velocity
- Ambient Temperature

- Global tilted plane

Table 4. 3.Monthly values of meteo data [Source: PVsyst]

	Global horizontal irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity	Linke turbidity	Relative humidity
	kWh/m²/day	kWh/m²/day	°C	m/s	[-]	%
January	4.92	2.38	21.5	3.20	4.105	64.6
February	4.85	2.72	22.4	3.41	4.220	57.1
March	5.02	2.42	22.3	3.29	3.762	63.6
April	4.90	2.49	21.0	2.59	3.147	74.4
May	5.09	2.35	20.7	2.39	3.205	74.8
June	5.19	2.00	19.6	2.40	3.620	72.9
July	5.31	2.01	19.0	2.40	4.010	72.8
August	5.15	2.13	19.7	2.50	3.957	70.7
September	4.99	2.37	20.3	2.70	3.523	67.7
October	4.97	2.63	21.4	2.90	3.346	66.1
November	4.66	2.50	20.7	2.89	3.206	73.3
December	4.74	2.13	21.4	3.19	3.577	67.6
Year	**4.98**	**2.34**	**20.8**	**2.8**	**3.640**	**68.8**

4.4.3 Process description

After seeing how the program consider the effect of shaded cell in system configuration, the next step is to see the effect of shading in the yearly system output. The processes followed in simulation have been shown step by step until the production of IV and PV curves. In order to perform the study accurately, firstly the project design option has been chosen among other options and the study was performed as a grid connected. This option contains necessary features desired for the study with the aim of a project analysis.

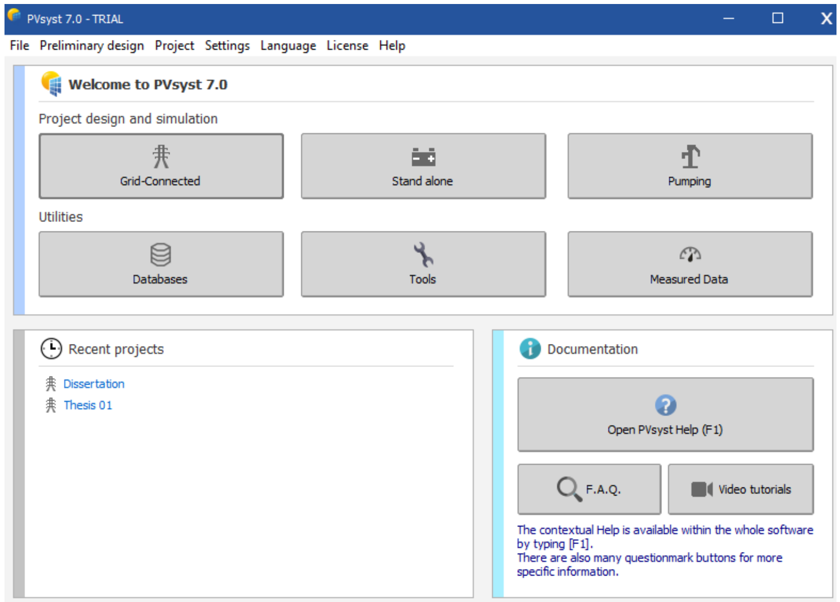


Figure 4.5. Program's main contents

The second step allows user to name the project and after that, the file of the metrological data for the selected location is imported from the database of the program. Also, the named project can be saved to the program working place.

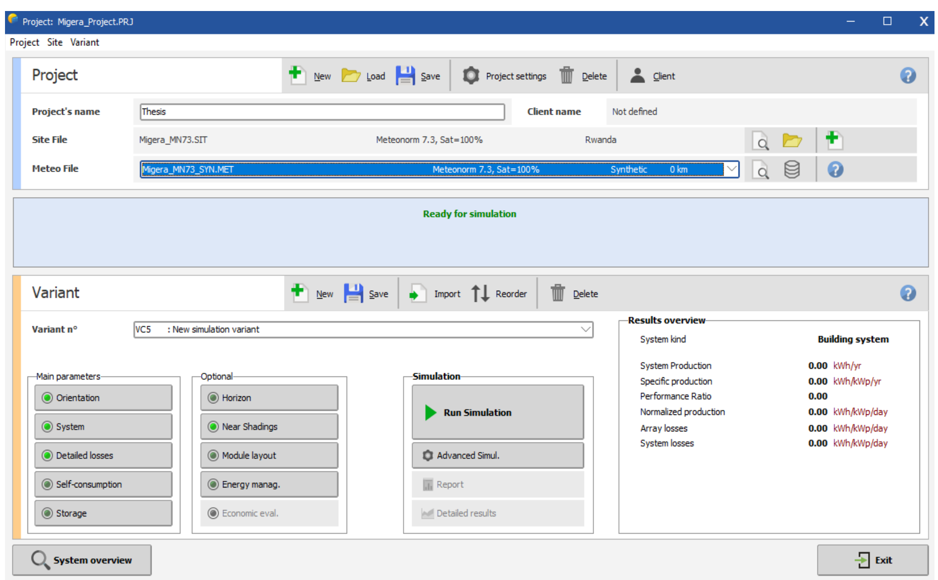


Figure 4.6. Project's identification

After identification of the project and importing the required metrological data for the selected location, the next step is to define how the system will be oriented. Here the system is a fixed tilted plane, inclined at 10 º to south. Those angles were taken by considering the maximum yearly meteo yield. This step is necessary to determine the amount of daylight that strikes the surface of the panels. Always, the panel is oriented according to the sun's direction.

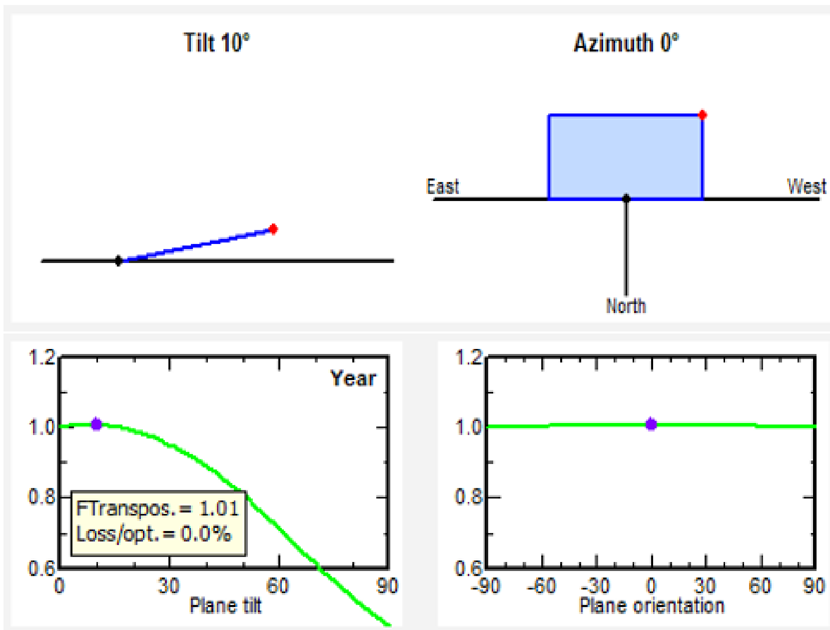


Figure 4. 7. Tilting and orientation of photovoltaic module

According to the above figure, it is possible that both tilt and azimuth angles can be varied for maximum energy production by considering those three factors like transportation factor, loss which correspond to optimum and the global incident on collector plane. And with those angles, various solar irradiation on the system's panels can be easily observed.

The next figure shows the sun path and horizon profile for selected place (Migera). It represents the sun's height with respect to the azimuth angle and it shows a statistical relation between the azimuth angle and the sun's height at specific time (hours) of the day

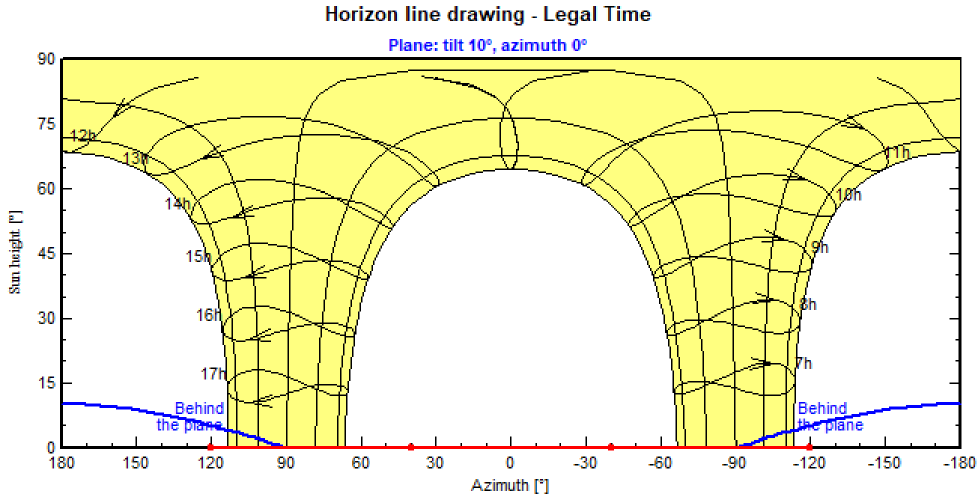


Figure 4.8. Sun path and horizon profile for Migera

The above figure shows the sun's movement and is related to the values of tilt and azimuth angles in solar insolation falling on the module.

The system characteristics in PVsyst allows you to size your system according to available technologies and corresponding manufacturer's specifications. Point by point data of wanted power at the output, inverter and module to be used based on manufacturer and available size; technology and output power (Wp), effect of shading, etc. are needed to input the system. It is in this section where you define the number of modules and string of the system. Here you can also determine what number of modules will be parallel or series connected. In this simulation, a monocrystalline 50 Wp generic module and a 1.5kW inverter were chosen. The system is made of 2 strings of 15 modules per each. Based on the operating conditions of the selected components (modules and inverter), the program allows the user to select the system which doesn't violate the electrical properties of the components (it should be adequately sized, not oversized or undersized).

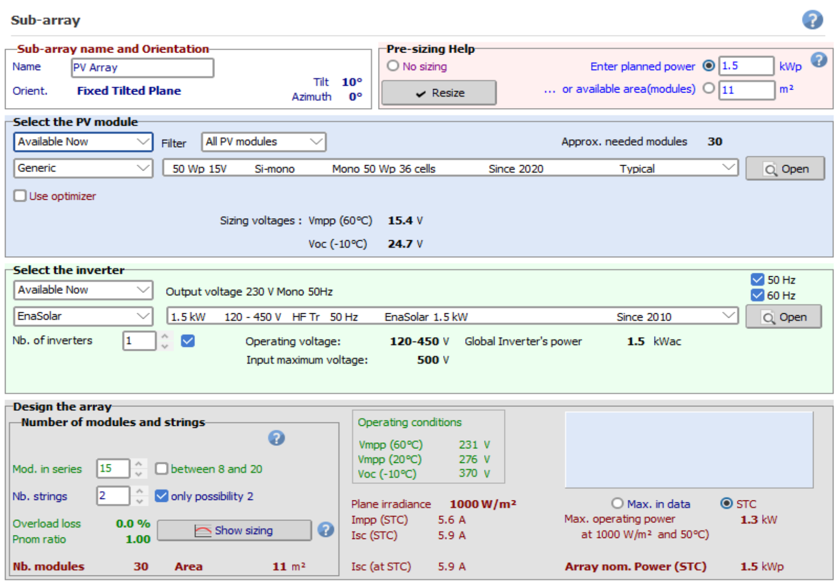


Figure 4.9. System definition

In the next step, a shading scene is required so that it can be applied to evaluate its effect on the system. Here the scene is constructed in three-dimensional plane enclosed in the program. The proposed scene for this study is shown in 3D tool.

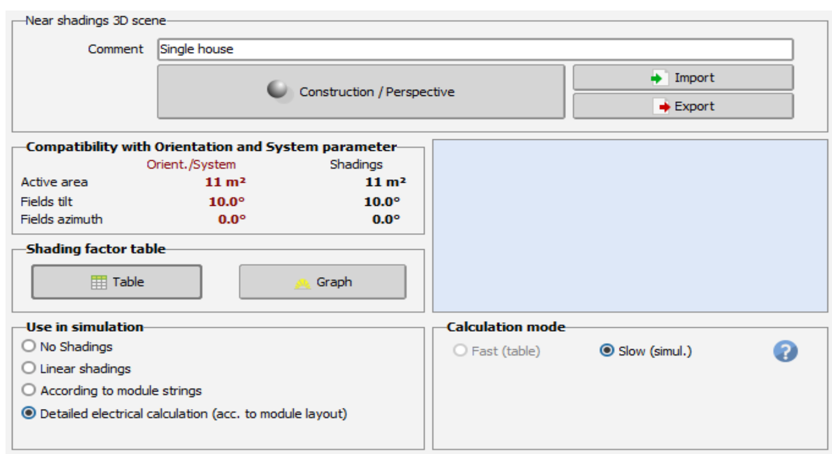


Figure 4.10. Near shading definition

After near shading construction scene, it is better to see how shading effects will be calculated. In this work, calculation according to the module layout has been chosen as it considers all detailed electrical losses calculations. Below are drawings in PVsyst 3D for the studied system.

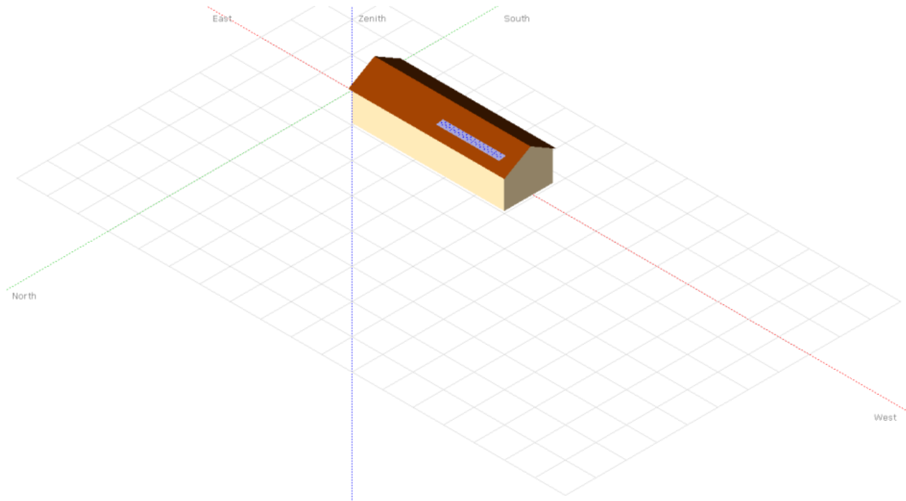


Figure 4. 11.System without near shading in 3D

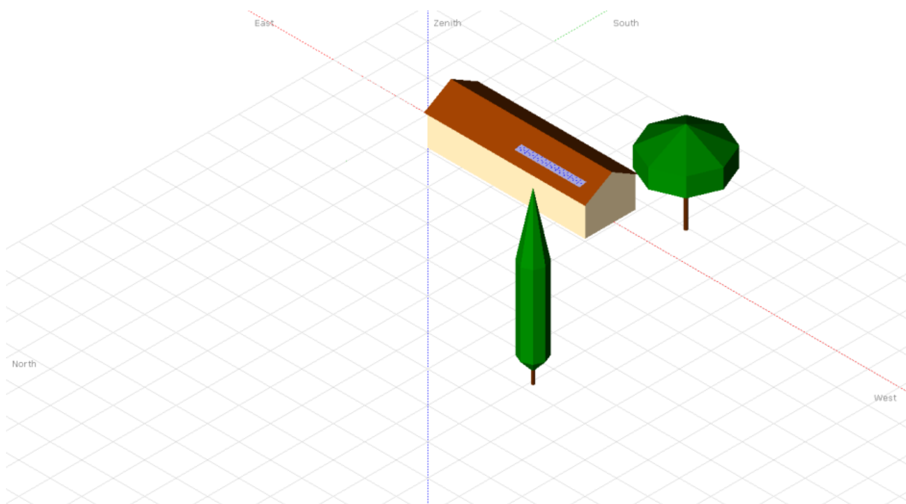


Figure 4. 12.System with near shading (surrounding) in 3D

In this study, various shading conditions were simulated to see their respective P-V and I-V curves. During this process, various near shading objects were applied to the system and it has shown that their effects can vary differently in specific time of a day. In order to see their effects, a roof with 10° tilt without shadow and a roof with 10° tilt with shadow in different situations were used for the study.

Another important simulation step for this study is module layout where the system is detail simulated for a chosen day of a year. The main parts for this step (module layout) are mechanical, electrical, shading 3D and IV & PV curves.

- Mechanical: Here is a mechanical arrangement of modules on elementary sub field areas as defined in 3D scene.
- Electrical: Here each module of the system should be attributed to an electrical string defined in the second step of the simulation processes (system definition).
- Shading 3D: After attribution of each module in the system, the next step is to choose a date of a year where you want to evaluate shading effects on the system.
- IV & PV curves: After electrical shading calculations, here the results are displayed.

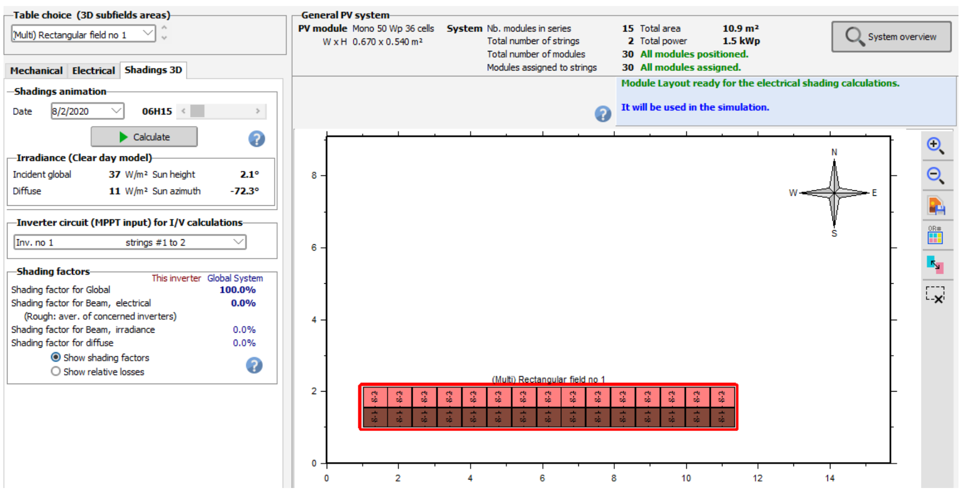


Figure 4.13. Definition of module layout

During 3D shading calculation, there is identification of by the program of how each module/ sub-module's is shaded where it expresses their states in terms of corners. One shaded corner of Sub-module represents 25% shaded, two shaded corners represent 50% shaded, three shaded corners represent 75% shaded and four shaded corners represent 100% shaded.

Each module in the system is composed by 2 submodules and a whole array is formed by 36 modules has a total number of 60 submodules. During simulation, various shading objects have been applied to the system to vary the shading conditions and below are performed conditions to see how shade affects the system.

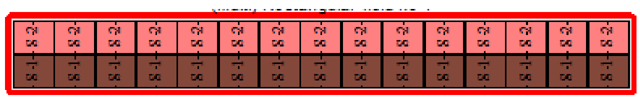


Figure 4.14. Condition 1: No shade on the system

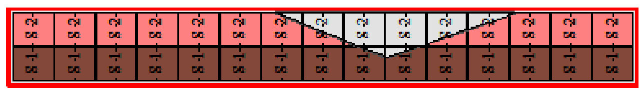


Figure 4.15. Condition 2: Shaded system

Figure 4.15 and 4.16 represent two simulated conditions. Condition 1 is when the array was not shaded and condition 2 is when the array is shaded. In condition 2, the grey triangle indicates the shadow.

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Introduction

Within this part, study results are shown as well as discussed in accordance to the study's aim that was to analyse the shading effects in PV systems. Based on specific objectives, simulation and validation of both non shaded and shaded PV systems have been done and then their comparison based on performances.

5.2 Experimental results

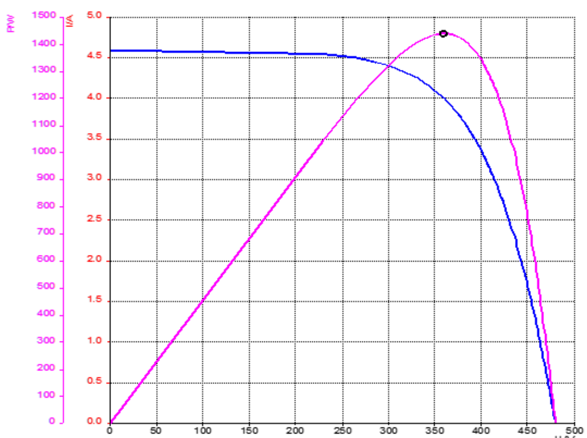


Figure 5.1. 100% of irradiance and no shadow

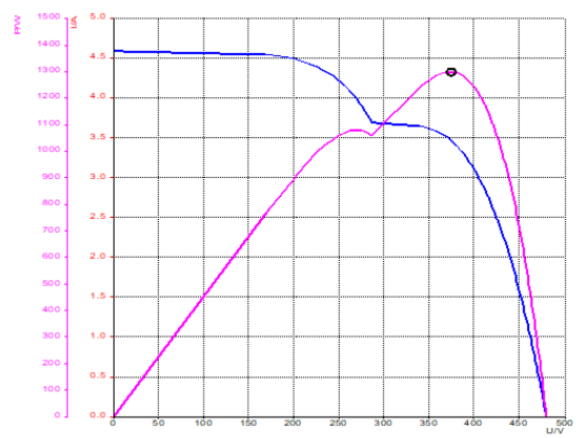


Figure 5.2. 100% of irradiance at 20% of shading ratio

Figure 5.1: I-V and P-V curve for condition 1 when irradiance is 100% (1000 W/m^2), number of shaded modules = 0 and shadow of 0%). The measured quantities on DC side were: Power (P_{dc}) = 1440 W, I = 3.95 A and V = 364 Volts and figure 5.2 shows IV and PV curves for condition 2 when irradiance is 100%, number of shaded modules = 2 and shadow ratio = 20% .The measured quantities on DC side were: Power (P_{dc}) = 1301 W, I = 3.48 A and V = 374 Volts

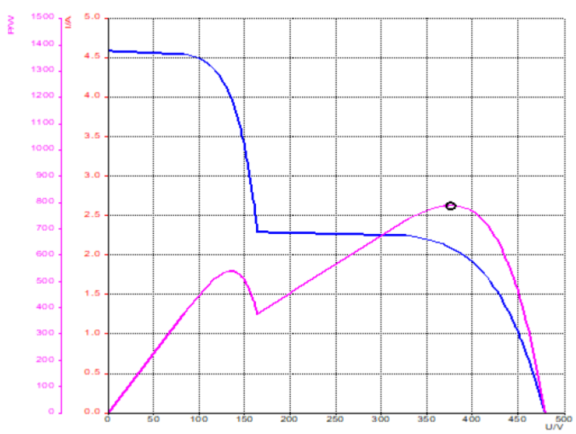


Figure 5.3. shaded modules =5 at 50% of shading

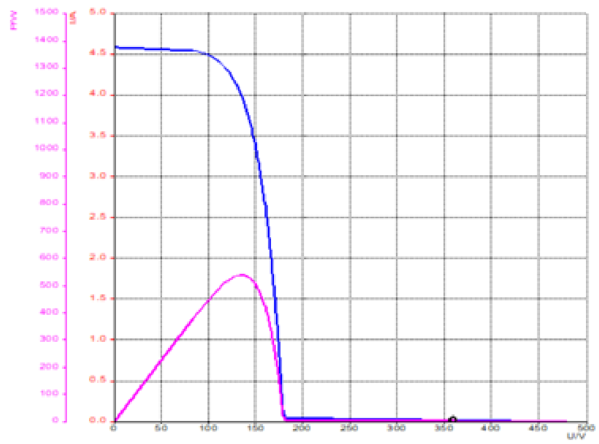


Figure 5.4. Shaded modules = 5 at 100% of shading

Figure 5.3: I-V and P-V curves for condition when irradiance is 100%, number of shaded modules = 5 and shadow of 50%) the measured quantities on DC side were: Power (P_{dc}) = 800W, I = 2.6 A and V = 370 Volts and figure 5.4 shows I-V and P-V curves for condition when irradiance is 100%, number of shaded modules = 5 at shadow ratio of 100%), no measured quantities was found.

From the experiment, it was observed that whatever shade is applied to the system, the dc voltage and current change (increases or decrease) while dc power decreases. However, the maximum power points were obtained. It was also noted that by increasing number of shaded modules, direct voltage increases while the direct current and power drop accordingly. Another observation is when a maximum shading ratio (100%) applied to the system where the resulted characteristics are out inverter MPP voltage range, the algorithm became unable to find the MPP of the system (referred to 5.4).

5.3 Simulated IV and PV curves for studied conditions

Because the program values hourly incident global irradiations, shading effects have been calculated according to the insolation that stroked the panels during the evaluation time. August 2nd, 2020 has been chosen for the study, generally the irradiation varies during specific times of a day as well as day of a year. In each situation, shading can be taken into account due to sun's position,

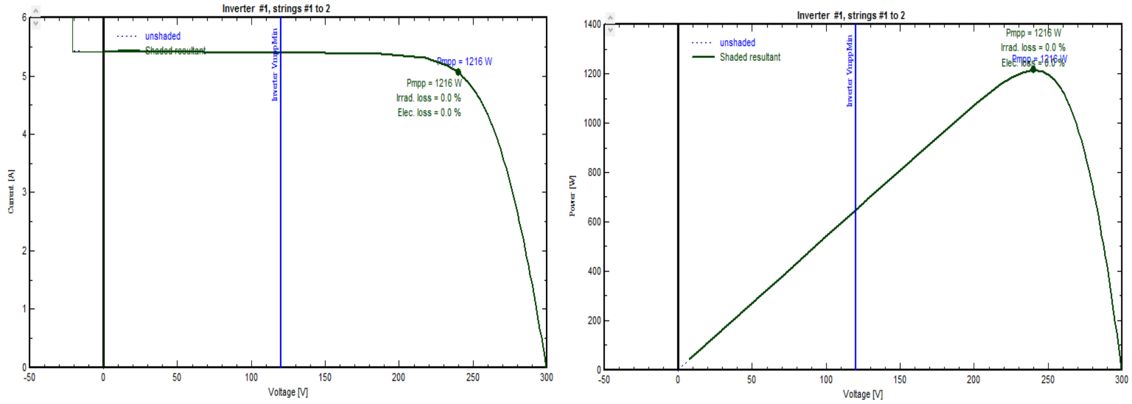


Figure 5.5. I-V and P-V curves when no shadow considered

Based on figure 5.5 when the panels were receiving 910 W/m^2, insolation that have been received by panels were completely converted into expected power with no electrical and irradiance losses and one MPP has been exhibited as per PV characteristics.

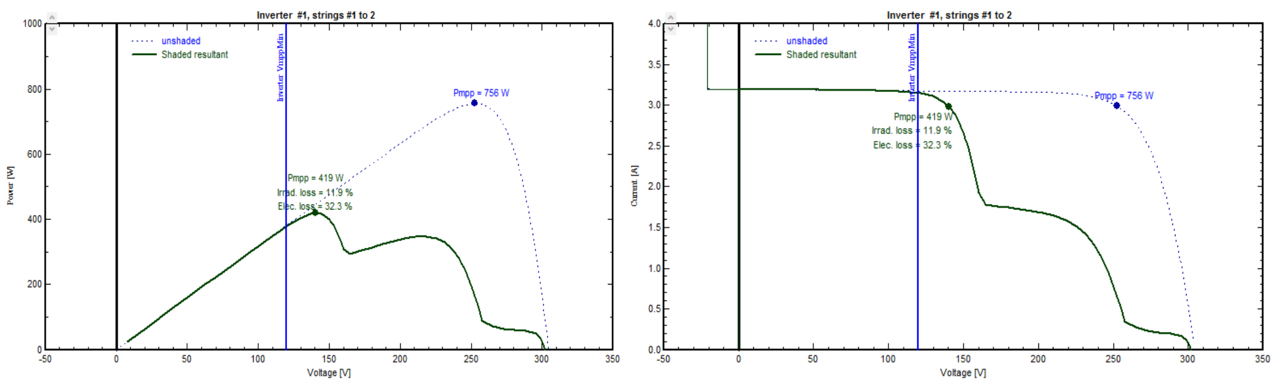


Figure 5.6. P-V and I-V curves for shading condition

Regarding on figure 5.6 when the panels were receiving 540 W/m^2, the panels were expected to generate 756 W but 419W of maximum power was generated with mismatch of 337W. It has noted that around 90W (11.9%) has been lost due to irradiance losses resulted from shading and electrical losses which includes inverter losses etc. It has also noted that the system exhibits more than one maximum power point that can be complicated for some inverters to distinguish the real peak.

5.4 Main simulation results

The main results for detailed simulation are system production (produced energy), specific production, performance ratio, normalised production, array losses and losses of the system.

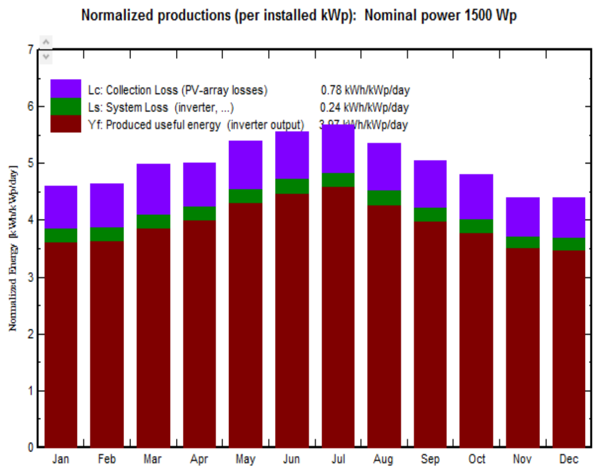
Table 5. 1. Annual energy produced in different cases

Months and their respective energy production	Produced energy by a system with shadow in kWh	Produced energy by a system without shadow in kWh
January	163.2	168.6
February	148.4	153.3
March	163.3	179.7
April	164.2	180.6
May	191.7	200.4
June	193.6	201.7
July	206,0	213.5
August	185.2	199.2
September	161.7	179.7
October	169.6	176.3
November	152.2	158.2
December	156.4	161.7
Annual energy produced in kWh	2055	2172.8
Annual reduced energy in %	5.4	

Table 5.1 illustrates annual energy production for studied conditions, it has seen that energy production in non-shading condition is 2172.8 kWh and 2055 kWh in case of shaded condition. Based on this result, the effects of shading in terms of energy is represented by 5.4 % of reduced energy.

5.4.1 Normalized production

Normalised production represents three different variables; losses of the system, assortment (collection) losses and delivered valuable (useful) energy. Those factors determine the system performance terms of energy production which are which are helpful in determination of system's performance in relation to produced energy.



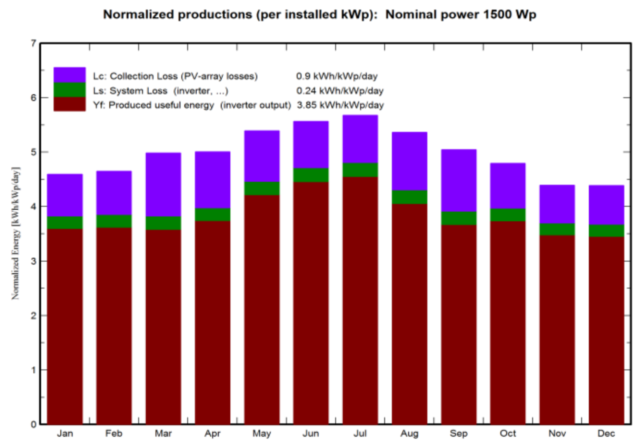


Figure 5.7. Normalised production for unshaded **Figure 5 8.Normalised production for shaded**

Based on figure 5.7 and figure 5.8, normalized production shaded sub module, the losses are equal to system losses + PV array losses = 0.24 + 0.78 = 1.02 kWh/kWp/day, useful energy produced is 3.97, this represents percentage difference between losses and useful energy of 25%. For both conditions, the highest useful energy was produced in Jun and July as it is in sunny season. Meanwhile normalized production in case of shaded condition (Figure 5.8), system losses+ collection losses = 0.24+ 0.9 = 1.14 for useful energy produced of 3.85; and this represents percentage difference between losses and useful energy of 29 %.

5.4.2 Performance ratio

Performance ratio is taken as the efficiency of the system globally due to nominal power installed as well as the incident energy.

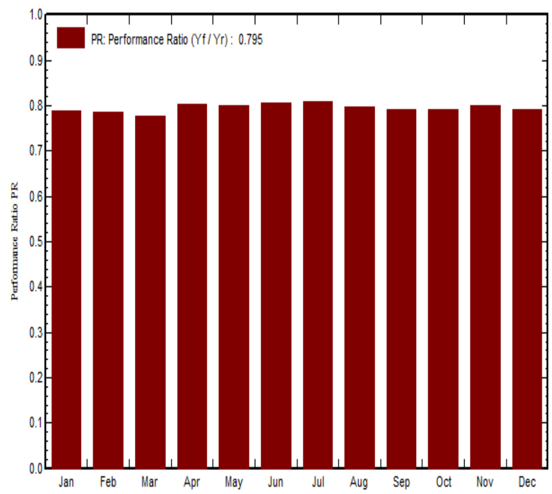


Figure 5.9. Performance ratio for unshaded

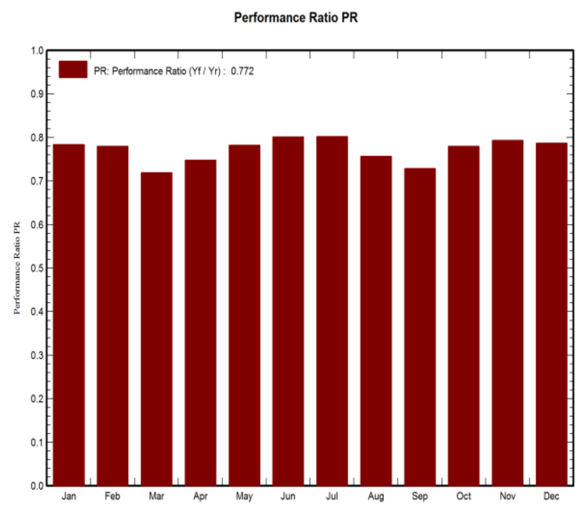
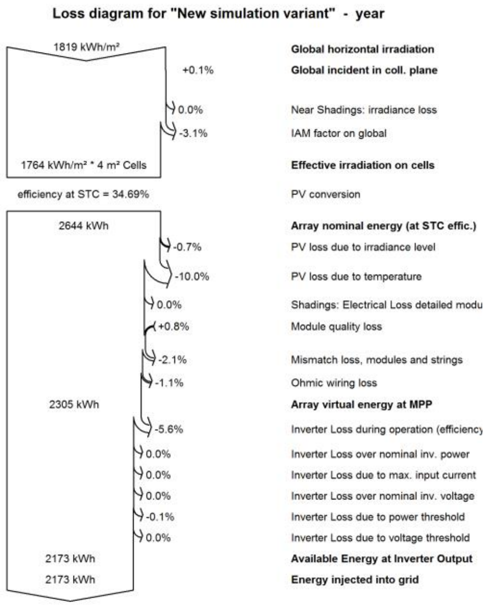


Figure 5.10. Performance ratio for shaded

Figure 5.9 and figure 5.10 showed a small difference between both performance ratios of 0.795 and 0.772 (for non-shaded and shaded condition respectively) because the system was lessly affected. For a grid connected system PR = (E_Grid*PnomPV). Where E Grid is the available energy at inverter output and PnomPV is STC installed power (manufacturer's nameplate value). It includes optical losses (shading effects, soiling, IAM), array losses (wiring, mismatch, module quality, ageing, photovoltaic, etc) and system losses (inverter efficiency) [39].

5.4.3 Detailed system losses

During system output calculation, the detailed losses diagram represents various losses which occur during energy production, means from irradiance conversion to the available energy at the inverter output and injected energy to the grid (for grid connected system). The diagram of losses gives a clean cut into the system's quality as it identifies where those losses come from. This always present on the simulation report for the whole year.



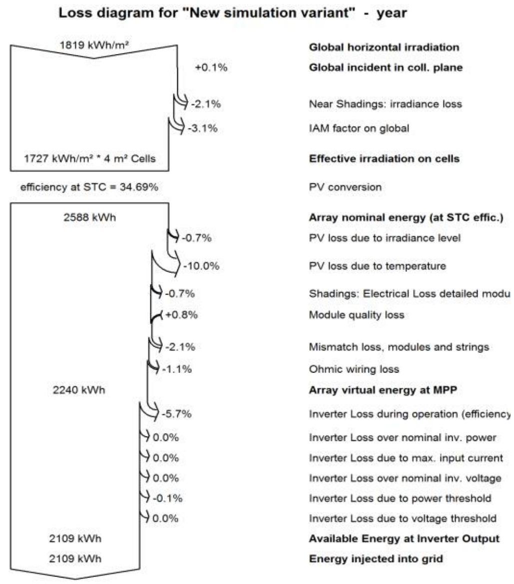


Figure 5.11. Loss diagram for unshaded

Figure 5.12. Loss diagram for shaded

From figure 5.11 and 5.12 the produced energy in the yearly basics at STC is 2173 kWh and 2109 kWh for shaded and non-shaded systems respectively. Another special point to be noted on these graphs (Figure 5.11 and 5.12) is that there are no irradiance losses caused by near shading in case of non-shaded system whereas in shaded case, 2.1% of irradiation losses has been found.

CHAPTER 6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Due to its affordability, scalability and cleanliness, solar photovoltaic has been promised as the most dominant energy resources among other renewable energy technologies. The use of Solar PV systems is a solution to many countries around the world especially for low- and middle-income countries which are still struggling in providing electricity to their citizens. Leading improvement in photovoltaic sector drove governments to raise investment in this field while researchers concentrating on numerous issues with this industry. Based on the result for this work, shadow affects the performance of PV systems and the rate at which PV system is affected depends on the shaded area, position and the how much radiation reach that shaded area. Shadows decrease the expected power from the shaded system as well as the system output power. Also, shadow changes electrical characteristics of the module/array by creating various MPP where this is contrary in case of unshaded condition where only one peak is obtained. This increase the system's instability as it can lose its ability to generate power at the maximum due to the used control algorithm as well as degradation of the output that a PV panel can produce.

6.2 Recommendation

Furthermore, investigations need to be carried out to modify this work, the following recommendations are given by the author of this thesis:

- To PV plant's operators, they are encouraged to remove plantations and other things that are in vicinity of installed modules to reduce the shadow effects on their systems.
- To engineers and technicians who install PV plants, they have to choose a proper orientation of PV panels for receiving maximum solar irradiation for efficient operation of the plant even in case of shading.
- To the public and private institutions which provide energy based on solar systems, sensitization regarding on shading issues is needed towards their beneficiaries and make follow up to installed systems so that users can give special attention on shading issues while they operate their system.

- To new researchers, they are recommended to continue this research within Rwandan Solar power plants consideration as case study.

Reference

[1] A. Sayigh, "Mediterranean green buildings & renewable energy: Selected papers from the world renewable energy network's med green forum," *Mediterr. Green Build. Renew. Energy Sel. Pap. from World Renew. Energy Network's Med Green Forum*, pp. 1–963, 2017.

[2] M. P. Kazmierkowski, *Power Electronics for Renewable and Distributed Energy Systems [Book News]*, vol. 8, no. 2. 2014.

[3] T. Zhou and W. Sun, "Study on maximum power point tracking of photovoltaic array in irregular shadow," *Int. J. Electr. Power Energy Syst.*, vol. 66, pp. 227–234, 2015.

[4] A. Ahmad, M. A. Khattak, M. Zeeshan, M. Salman, and K. Alam, "Techniques to Mitigate Problem of Partial Shading and Soiling on PV Module: A Review," *Int. J. Eng.*, vol. 6, no. 05, pp. 148–152, 2019.

[5] A. Mohammedi, N. Mezzai, D. Rekioua, and T. Rekioua, "Impact of shadow on the performances of a domestic photovoltaic pumping system incorporating an MPPT control: A case study in Bejaia, North Algeria," *Energy Convers. Manag.*, vol. 84, pp. 20–29, 2014.

[6] A. Ansari and A. Rafique, "Generation Of Electricity through Solar cell and Thermocouples with selling power back to Grid," no. May 2014, 2011.

[7] T. Haukkala, "Does the sun shine in the High North? Vested interests as a barrier to solar energy deployment in Finland," *Energy Res. Soc. Sci.*, vol. 6, no. 2015, pp. 50–58, 2015.

[8] G. Najafi, B. Ghobadian, R. Mamat, T. Yusaf, and W. H. Azmi, "Solar energy in Iran: Current state and outlook," *Renew. Sustain. Energy Rev.*, vol. 49, pp. 931–942, 2015.

[9] "New solar power plants added almost 35% to the world-wide new power generating capacity in 2017tle." .

[10] I. International and R. Energy, *FUTURE OF Deployment , investment , technology , grid integration and socio-economic aspects*. .

[11] A. N. Al-shamani, M. Yusof, H. Othman, S. Mat, M. H. Ruslan, and A. M. Abed, "Design &

Sizing of Stand-alone Solar Power Systems A house Iraq," no. April 2015, 2017.

[12] R. E. Hanitsch, D. Schulz, and U. Siegfried, "Shading Effects on Output Power of Grid Connected Photovoltaic Generator Systems," *Renew. Energy*, pp. 93–99, 2001.

[13] S. Bimenyimana, G. N. O. Asemota, M. C. Kemunto, and L. Li, "Shading effects in photovoltaic modules: Simulation and experimental results," *2017 2nd Int. Conf. Power Renew. Energy, ICPRE 2017*, pp. 904–909, 2018.

[14] A. Nasir, "Design , Simulation and Analysis of Photovoltaic Water Pumping System for Irrigation of a Potato Farm at Gerenbo," 2016.

[15] A. Labouret and M. Villoz, *Solar Photovoltaic Energy Solar Photovoltaic Energy*. .

[16] M. W. G. Pv, "Study , Design and Performance Analysis of a Grid-Connected Photovoltaic System," no. November, 2017.

[17] J. Qin, "Solar Micro Inverter Modeling and Reliability," no. October, 2015.

[18] G. Varshney, "Effect of Partial Shading on Characteristics of PV panel using Simscape Effect of Partial Shading on Characteristics of PV panel using Simscape Amardeep Chaudhary *, Shriya Gupta **, Dhriti Pande **, Fazal Mahfooz **, Gunjan Varshney **," no. October, 2015.

[19] P. Shoemaker, "Basics of Photovoltaic (PV) Systems for Grid-Tied Applications Basics of Photovoltaic (PV) Systems," 2012.

[20] I. F. Corporation, "Utility-Scale Solar Photovoltaic Power Plants."

[21] Y. S. Kim and R. Winston, "Power conversion in concentrating photovoltaic systems: central, string, and micro-inverters," no. January 2013, pp. 984–992, 2014.

[22] R. Energy, *SOLAR*. .

[23] A. N. Pva-, "Guide To Interpreting I-V Curve Measurements of PV Arrays," 2011.

[24] A. Al Bashir, M. Al-dweri, A. Al Ghandoor, B. Hammad, and W. Al Kouz, "Analysis of Effects of Solar Irradiance , Cell Temperature and Wind Speed on Photovoltaic Systems Performance,"

no. November 2019, 2020.

[25] "https://www.trace-software.com/blog/which-factors-shall-you-consider-for-the-installation-of-photovoltaic-panels/." .

[26] P. Bulanyi and R. Zhang, "Shading Analysis & Improvement for Distributed Residential Grid-Connected Photovoltaics Systems 2 . Shading Types," *Sol. 2014The 52nd Annu. Conf. Aust. Sol. Counc.*, no. 02, pp. 1–12, 2014.

[27] L. Fernando, L. Villa, T. Ho, J. Crebier, and B. Raison, "A Power Electronics Equalizer Application for Partially Shaded Photovoltaic Modules," vol. 60, no. 3, pp. 1179–1190, 2013.

[28] S. Pedrazzi, G. Zini, and A. Dalla, "ScienceDirect Mismatch losses in PV power plants," vol. 100, pp. 42–49, 2014.

[29] Y. Sun, X. Li, R. Hong, and H. Shen, "Analysis on the Effect of Shading on the Characteristics of Large-scale on-grid PV System in China," *Energy Power Eng.*, vol. 05, no. 04, pp. 215–218, 2013.

[30] D. Sera, Y. Baghzouz, and L. Vegas, "On the Impact of Partial Shading on PV Output Power Institute of Energy Technology," no. January 2008, 2014.

[31] J. C. Teo, R. H. G. Tan, V. H. Mok, V. K. Ramachandaramurthy, and C. Tan, "Impact of partial shading on the P-V characteristics and the maximum power of a photovoltaic string," *Energies*, vol. 11, no. 7, 2018.

[32] N. D. Kaushika, A. Mishra, and A. K. Rai, *Solar Photovoltaics*. .

[33] K. Abu-Rub, Haitham, Malinowski, Mariusz (Electrical engineer), Al-Haddad, *POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS, TRANSPORTATION AND INDUSTRIAL APPLICATIONS*. .

[34] "Effect of Shading on Photovoltaic Cell," *IOSR J. Electr. Electron. Eng.*, vol. 8, no. 2, pp. 01–06, 2013.

[35] P. Sathyanarayana, R. Ballal, L. S. P. S, and G. Kumar, "Effect of Shading on the Performance

of Solar PV Panel," vol. 5, pp. 1–4, 2015.

[36] O. Vargas, G. Pinilla, and J. Vasquez, "Sizing and Study of the Energy Production of a Grid - tied Photovoltaic System Using PVsyst Software," vol. 12, no. 22, pp. 27–32, 2017.

[37] D. K. Sharma, "Review and analysis of solar photovoltaic softwares Review and Analysis of Solar Photovoltaic Softwares," no. April 2014, 2019.

[38] T. L. André Mermoud, "PARTIAL SHADINGS ON PV ARRAYS: BY-PASS DIODE BENEFITS ANALYSIS," pp. 3–6, 2529.

[39] "https://www.pvsyst.com/help/performance_ratio.htm." .