“STUDY AND DESIGN OF AN OPTIMISED SOLAR POWER PLANT WITH TRACKING SYSTEM FOR FEEDING FRONTIER MINING CAMP”

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By

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I, **Kasongo Hyacinthe Kapumpa** student of M.Tech (Electrical Engineering) under school of electronics and electrical engineering of Lovely Professional University, Punjab, hereby declare that all the information furnished in this Dissertation report is an authentic record of my own work carried out under the supervision of **Mr. Mukul Chankaya,** Assistant Professor /Associate Professor School of Electronics and Electrical Engineering. The matter presented in this dissertation has not been submitted to Lovely Professional University or to any other university or institute for award of any degree.

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CERTIFICATE

This is to certify that KASONGO HYACINTHE KAPUMPA bearing Registration No. 11510418, has completed objective formulation of thesis title **“STUDY AND DESIGN OF AN OPTIMIZED SOLAR POWER PLANT WITH TRACKING SYSTEM FOR FEEDING FRONTIER MINING CAMP”** under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of the thesis has ever been submitted for any other degree at any University.

The thesis is fit for submission and the partial fulfillment of the conditions for the award of **MASTER OF TECHNOLOGY (ELECTRICAL ENGINEERING).**

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ABSTRACT

Solar energy as clean, green and renewable energy is one of the most used resource of energy, but the capture of this energy is subjected to many losses. To overcome the losses in a solar power plant it is imperial to understand the principal element which constitutes a solar power plant, in occurrence here a photovoltaic solar panel. In this work, discussion of various types of solar cells and problems affecting the efficiency of photovoltaic solar panels has been done, in addition some techniques for boosting the efficiency are proposed.

In the interest of reducing pollution, minimizing the cost of energy and promoting green energy, this thesis designs a possible 1MW standalone solar power plant to satisfy Frontier Mining Camp load. In order to overcome the losses in solar photovoltaic system, a proposed solution for MPPT (Maximum Power Point Tracking) with an application of Fuzzy Logic Controller has been opted to increase the efficiency of the photovoltaic system. The simulation of the power plant using fuzzy logic controller to determine automatically the suitable duty cycle for a buck boost converter in order to optimize the output from the power plant is done using MATLAB/Simulink R2016a.

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CHAPTER 1

INTRODUCTION TO PHOTOVOLTAIC TECHNOLOGY

I. Introduction

A photovoltaic cell (PV cell) is a specialized semiconductor diode that converts visible light into direct current (DC), some PV cells have higher range of spectrum from infrared to ultraviolet radiation and convert them into DC electricity. From a wide range of producing electricity from solar, photovoltaic system is one of them and the only direct method.

In this chapter, we will discuss about the types of solar panels, material used in manufacturing solar panels, their efficiency, how marketable they are depending on the type and in addition technics used to boost the efficiency of solar panel.

II. Solar power generation

In the introduction, it was stated that electrical energy can be produced in several ways from sun irradiation; Figure 1, gives a view of electrical energy generation from sun. [1]

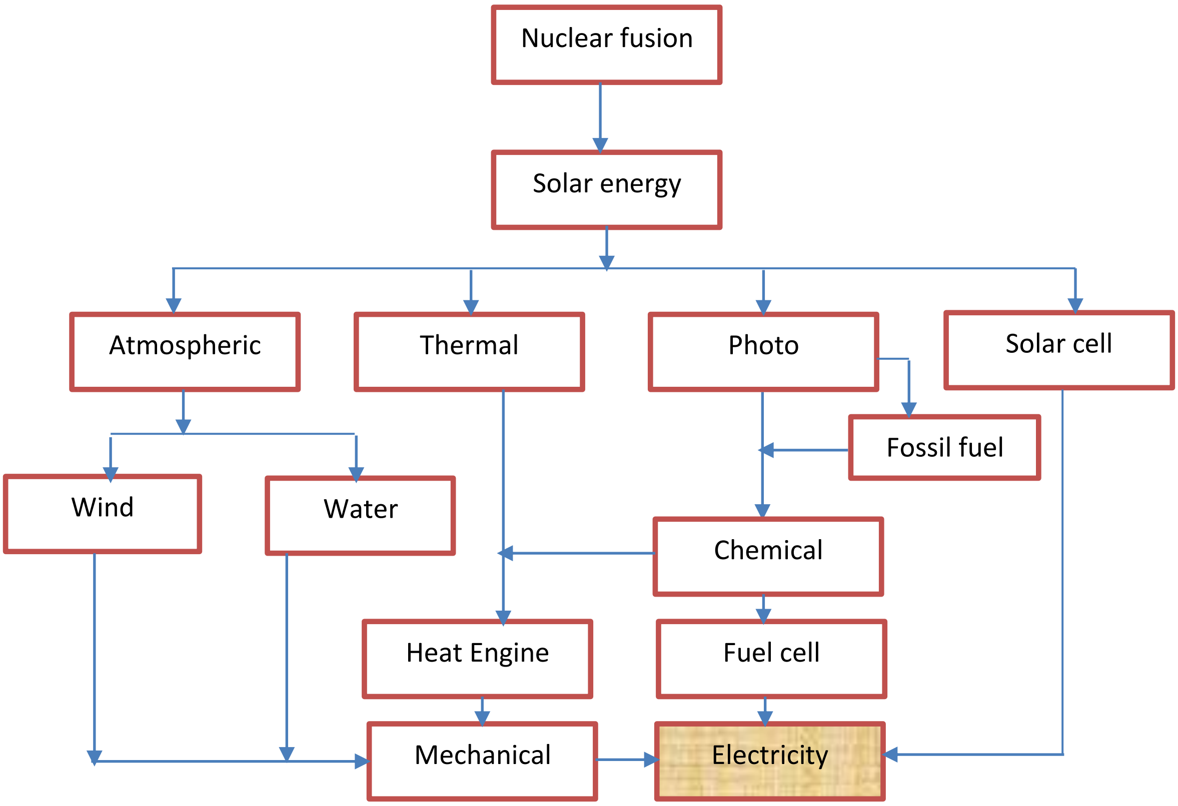


Figure1. Solar power generation [1]

From the above figure, it’s observed that electricity can be produced differently depending on the collector used for capturing the sun irradiation, which is consequence of nuclear fusion of the sun. The type of collector used will define how the extraction of solar energy will be done and in what type of energy solar radiation will be transformed. Some types of collectors are discussed below;

1. Tank-type collector

In an Integral amasser stowage unit, the solar radiations are engrossed by water collected in the stowage reservoir. These tanks are typically mounted in an insulation packet and have glazing on single side and are tinted black, gloomy blue or layered with a discerning surface. The sun sheens through the glazing and hits the tinted tank, warming the water within the reservoir. Steel is usually used to manufacture these reservoirs, although copper is used for water tubes [2].

2. Pool collector

Heating swimming pool water is amongst one of the significant applications of vigorous solar heating systems. To heat water in the seasonal swimming pool, special kinds of amassers have been advanced. These kinds of amassers are generally unglazed and distinct copolymer plastic is used for their manufacturing. These amassers are not capable to with stand solidifying situations and are functioned at an estimated temperature range of 10 – 20 ºC [3].

3. Flat-plate collector

In solar space heating and domestic solar water heating applications, Flat-plate collectors are amongst the most extensively used amassers in the world [2]. These sorts of amassers are usually used till a temperature range of 75 ºC [4]. Though, it is possible to have greater temperature functioning range from high efficiency amassers. As the vaporization temperature of water is 100 ºC, it has to be substituted by certain other heat transmission liquid in such sort of high efficiency amassers. These amassers are of two basic sorts’ i.e. liquid type and air type [5]. They do not involve any tracking system and charge of maintenance is too less [6].

4. Evacuated tube collector

Evacuated tube collectors contrast extensively in their operation and manufacture. They are prepared of a number of annealed glass tubes, having an absorber platter inside all of them. As tubes are the natural configuration of an evacuated amasser, they turn into unlike plat-plate collectors which are prepared in the similar mode and accomplish from one band to another [7].

5. Concentrating collector

They are used for higher temperatures by means of optical systems (reflectors and refractors) to focus energy on an engrossing surface. The reflectors are typically mirrors, parabolic plates, etc. These amassers can accomplish very high temperatures 150-500 ºC since the diffused solar reserve is concentrated in a minor area. In order to have a well-organized operation, the reflectors must capable to trajectory the sun uninterruptedly. The geometrical concentration area ratio is given by [6]:

$$C = \frac{A_a}{A_r} = \frac{R^2}{r^2} = \frac{1}{sin^2\theta_s} \quad (1)$$

Where
C – Concentration ratio, non-dimensional value;
Aa– area of the collecting aperture, m^2;
Ar – area of the absorber, m^2;
R – Distance from the sun to the concentrator, m;
r – Radius of the sun, m;
θs – half of an angle subtended by the sun, º.

This proportion is subjected to whether the concentration is a three-dimensional (circular) concentrator like a paraboloid or two-dimensional (linear) concentrator like a cylindrical parabolic concentrator [6].

III. Photovoltaic solar cells

It is likely to transform solar energy straight into electrical energy by the use of a photovoltaic cell. The solar cell functions on the principle of photovoltaic effect, which is the procedure of producing an EMF (electromagnetic field) as the consequence of the absorption of ionizing radiation [1]. However it can be believed that a solar cell is a transducer which transforms the sun’s radiant energy straight into electrical energy and mainly a semiconductor diode.

1. Circulation of current and voltage out put

With the N-type and P-type semiconductors, current is generated in this method: when proton of energy “hv” (h = plank’s constant $6.62x10^{-27}$ and v = velocity of light $2.99x10^{8}$ m/s) is on P region will have a tendency to migrate to N region, when ‘hv’ exceeds and when ‘hv’ is less it is the N region neutron will tend to P region proton.

The diffusion of free electron from N to P region and holes from P to N region, the current will begin flowing in the circuit. [1].

As the semi-conductor material used in a solar panel turns like a diode which presents that there is a voltage through it. Dependent on the material used as semi-conductor the voltage differs from 0.5-1 volts [1].

Additional to the voltage capacity, the wattage of the panel influenced by the current producing capacity of the panel and the current influenced by the dimension of the panel. The produced current of Si-cell is approximately 30mA/cm^2 at 100W/m^2 of solar radiation consequently a standard Si-cell of 15cm x15cm will produce about 6.75A. Therefore, module of 36 solar cells will generate power of about 15x6.75=101.25W$_p$ (W$_p$= peak power output) [9].Figure 2 presents the V-I (voltage-current) characteristic of solar cell.

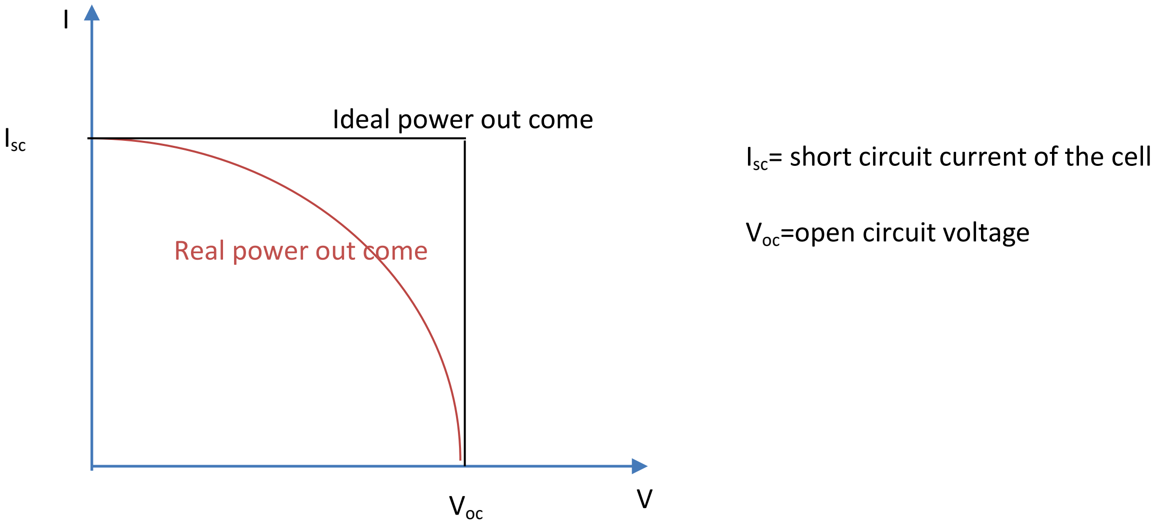


Figure2.V-I characteristics of a solar cell.

The I-V equation of a single solar cell is given as:

$$I = I_L - \left[I_0 e^{\frac{q(V+IR_S)}{nkT}} - 1 \right] \qquad (2)$$

Wherever is the light producing current, is the overturned saturation current, is the series resistance, *n* is the diode (semiconductor) ideality factor, *k* is the Boltzmann’s constant and *T* the temperature.

2. Performance ratio (Fill factor) of a solar cell

The performance ratio or fill factor is a correlation among the real yield power and the directed power. No power is produced underneath short or open circuit circumstances. The extreme power P generated by the conversion cell is calculated with the assistance of fill factor. This is presented graphically in Figure 2, in which the position of the maximum power point characterizes the area of the rectangle [6, 10].

$$FF = \frac{P_{pratical}}{P_{theoritical}} = \frac{V_m x I_m}{V_{oc} x I_{sc}} \tag{3}$$

ff= fill factor

V_m =maximum voltage output in practical conditions

I_m =maximum current output in practical conditions

V_{oc}=voltage at opened circuit

Isc = current at Short circuited conditions

1. Type of Photovoltaic solar cells

The solar cells can be categorized by the material used as semiconductor. Numerous materials can be used, and we will converse about few of them, their structure and competency of generating electrical power.

a) Silicon photovoltaic cell

There are three types of Silicon photovoltaic cell, depending on the structure used on the configuration of the semiconductor.

- Monocrystalline silicone solar cell

The P-type semiconductor is doped by ‘baron’ and the N-type by ‘phosphor’. For a 10x10 cm cell, with a radiation of 1000w/cm^2, enclosed by synthetic glass; we have 0.5V output opened circuit voltage and 1 watt as power output. It has competency in the rage of 20-24% and utilized in power plants.

- Polycrystalline silicone solar cell

In this liquid silicone are utilized, dripped in small blocks and engrave in to plats. When solidification is completed, various types of crystal structure are formed and the size based on the weather situations such as temperature, humidity and solar radiation. In similar situation the competency observed is about 19-24.4%.

- Amorphous silicon solar cell (Thin film)

When silicone is set down on a subtract material such as glass, this process is known as amorphous (formless or shapeless). The layer is approximately 1μm wide (in few situations even fewer than this) and having a competency of approximately 13%. It is utilize for low power application like calculators or watches.

b) Cadmium sulphide photovoltaic cell

The Cadmium sulphide (CdS) is generally chosen for the constancy under ambient situations and CdS is utilized when the surface of the cell is doped with Copper (Cu) atoms. Copper is utilized as donor material P-Type, CdS as accepter material N-Type and PEDOT: PSS (Poly3, 4 ethylene dioxythiophene) polystyrene-sulfonate is utilized as buffer coating. In open circuit situations the output voltage is 0.59V and competency of almost 14%.

c) Cadmium telluride photovoltaic cell

The cadmium Telluride (CdTe) is utilized with the epitaxial process which composed of overlaying crystals in the similar direction. The difficulty with the Epitaxial CdTe is to search suitable substrate. A few of the substrates are described [12] as:

- Highly doped CdTe buffer layer: It is very complicated to acquire a heavily doped CdTe buffer due to which the doping of CdTe buffer is limited.
- Expended bandgap buffer layer: By accumulating a higher bandgap buffer layer to work as an electron reflector can have affirmative influence on the effectiveness of the cell up to 20% of competency, this is because of the velocity of exchange of the material.
- Incorporation of an InSb (Indium antimonide) tunnel diode: The incorporation of an InSb (Indium antimonide) tunnel performing as a diode enhances the competency till 27.4 %, which is one of the maximum efficiency found [12].

d) Copper Indium Selenium photovoltaic cell

When proton of In are substituted by Ga, the Copper Indium Selenium (CIS) photovoltaic cell is too called as Copper indium gallium selenide (*CIGS*). This procedure is of free polarity (can conduct current in every directions) and almost no reduction of the material with a competency of 17.2% [8]. The most attractive thing of this material is that the payback time is comparatively low; almost 0.75 years while other materials such as Silicone is approximately 1.5 years. In appending, its fill factor is too high [8].

e) Organic and others photovoltaic cells

Organic and other material utilized in photovoltaic cells are not commercialized as they are very expensive and their constructing time is high.

The figure 3 illustrates the landscape of materials utilized in the construction of photovoltaic solar cells.

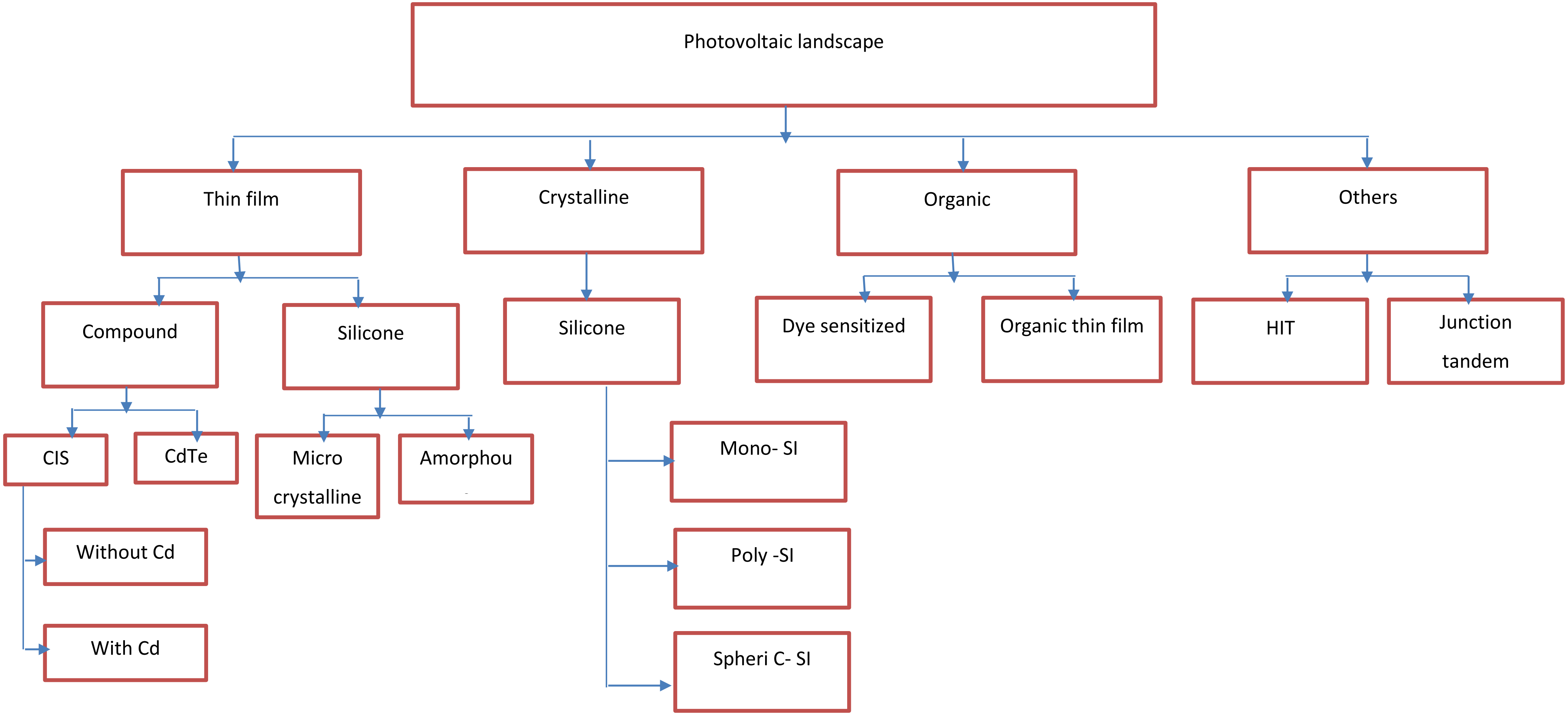


Figure3. Photovoltaic landscape

IV. Factors affecting efficiency of a solar power plant

A solar power plant is made by solar panels so to understand the factors affecting the whole plant we should be able to understand the factors affecting the panels first. Solar panels are known having less efficiency in the range of 10-30%, this is due to many factors; here we will discuss some of the main factors that influences the efficiency of solar panels[34];

1. Temperature

The temperature has an important influence on the efficiency of a solar panel; it is known that solar panels works better in cool than in hot weather [30]. Solar panels are tested in laboratories in average conditions such as 25°C of temperature and at $1000 W/m^2$ of irradiation, but in normal condition they are subjected to extreme condition where the temperature can vary widely. Some studies have proved that for 1°C raise in temperature above the normal condition of 25°C the efficiency of the panel decreases about 0.25% for amorphous cells and 0.4-0.5% for crystalline type [38].

From November to February where the temperature is very high in central Africa and the average in Sakania DRC can reach 35°C the solar panel temperature could reach 65°C that means the solar panel efficiency could decrease about 22.5% for crystalline and 11.25% for amorphous type of cells [36][38]. A formula can help us find the relationship between external temperature and solar panels temperature:

$$T_{mod} = T_{amb} + KP_{in} \tag{4}$$

Where,

T_{mod} is temperature of the module

T_{amb} is the ambient temperature

P_{in} is the radiation intensity in W/m2

K is a constant $0.02<K<0.03$ depending on wind speed, humidity etc.

2. Cable characteristics

220V is the nominal working voltage for appliances in our homes which compared with the solar panel output rage between 12-48V is very high. Considering the same power (Watt) higher currents may get involved in the Panel system, this is can be observed with resistance losses in wiring. For more explanation and see how the choice of a cable can be significant we can consider the following example:

For 20m of cable between panel and consumer, a panel of Current 6.44A, Voltage 28.5V[28]. Considering a cable with the following characteristics:

- 1.5mm^2 cross section has a resistance of 0.012Ω per meter [39], the total resistance of the cable will be 20x0.012=0.24Ω. Considering Ohm's law the voltage drop across the wire will be V=0.24x6.44 = 1.55V, that means will have a drop of 1.55V from the panel voltage due to the cable and this is nearly 5.44% of the nominal voltage.
- 6mm^2 cross section has a resistance of 0.003Ω per meter [39], the total resistance of the cable will be 20x0.003=0.06Ω. in this case the voltage drop will be V=0.06x6.44=0.39V, nearly 1.37% of the nominal voltage

With this two analysis we can see how the choice of a cable can have effect on the efficiency of a panel however the economical aspect must be taken in consideration thicker is the cable higher is the price [38]

3. Solar irradiation

The power output of a solar panel depends at higher percentage on the solar irradiation hitting it, the relationship between power output of a solar cell and the solar irradiation is almost linear and proportional, this means that if solar irradiation increases, the power output will also increase and the same if the solar irradiation decreases the power output will too decrease. This relation between solar irradiation power output of the solar cell result into the change of the power output throughout the day [30].

4. Charge controller

It is observed that when a solar panel is connected to a battery by the aim of a simple charge regulator the voltage of the panel is pulled down to that of the given battery and as consequence; leading the apparent output power of the panel to drop. Only when the battery is fully charged then the extraction of maximum power from the solar panel can be possible.

The solution to will be to keep the battery always fully charged or at list half charge not totally discharged to reduce its burden to the panel [35][38].

5. Inverter

Most of the appliances in our homes uses alternative current(AC), but the solar panels produces Direct current(DC), that means an inverter will be needed to transform DC to AC. These inverters are known to have high efficiency some can reach 80% to 90%, although the high efficiency there is a loss of 10% to 30% which cannot be omitted and should be taken in consideration [38].

6. Battery

Batteries are used for backup when solar panels are not producing electricity like in shaded or night times. As said earlier batteries are actually loads when not charged totally that means at some instance they will be consuming power from the panel. It is known that a battery output power is always inferior to the input; that implies a selective choice of battery having high efficiency.

Practically the charging energy for a battery is given by:

$$E_{in} = I_C x\, V_C x\, \Delta T_C \tag{5}$$

Where; I_C is the constant charge current at voltage V_C for time duration ΔT_C

And output energy by

$$E_{out} = I_D x\, V_D x\, \Delta T_D \tag{6}$$

Where, I_D discharge current, V_D discharge voltage during a time ΔT_D

The efficiency is calculated using;

$$\eta = \frac{E_{out}}{E_{in}} = \frac{I_D x\ V_D x\ \Delta T_D}{I_C x\ V_C x\ \Delta T_C} \tag{7}$$

Lead-acid batteries, including both charging and discharging losses are known to have efficiency in the rage of 75-85% [37].

V. Method used for boosting efficiency of solar cell

Several methods are used for boosting the efficiency of a panel, here will discuss some of them;

1. Solar Tracker

The tracking system consist of following the direction of the sun like a sun flower to maximize the solar irradiation on the panel, they exist two types of tracking systems;

- Single axis tracking; they rotate on one axis moving frontward and backwards in a single direction as shown on figure4 a.

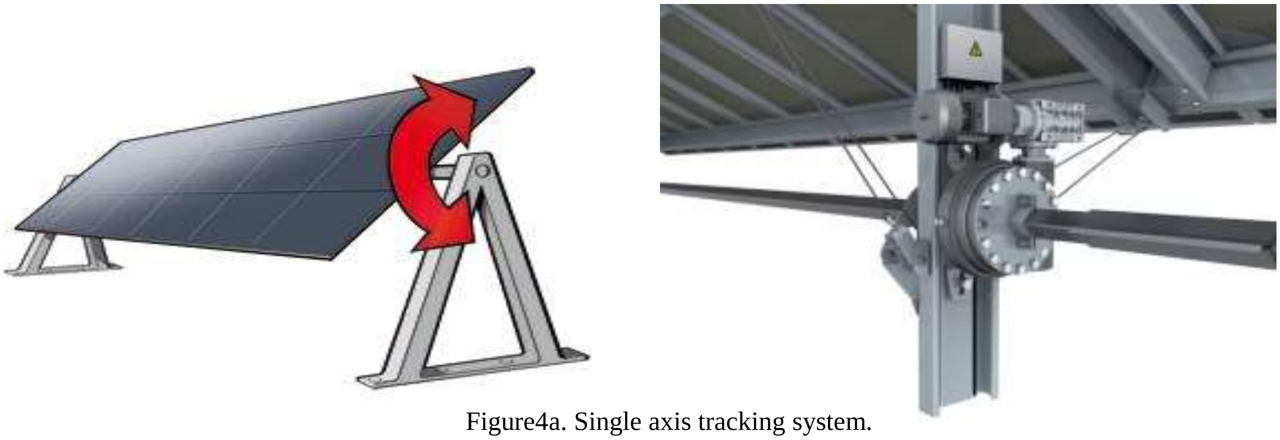


Figure4a. Single axis tracking system.

- Dual axis tracking; rotating in two different directions they are able to face the sun every time and maximizing the solar irradiation on them. Figure4 b shows an example of a dual axis solar tracking system.

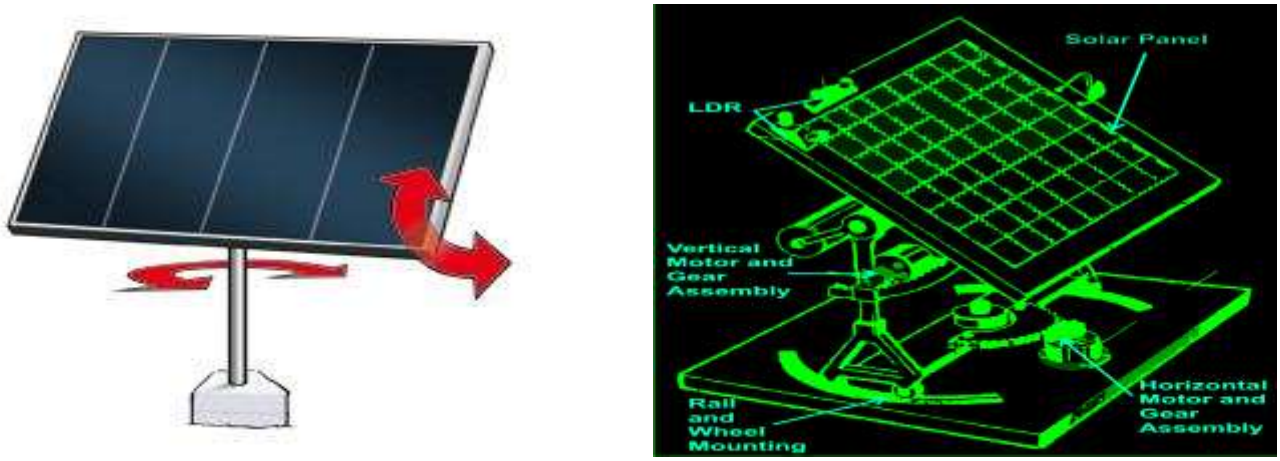


Figure4b. Dual axis tracking system.

Other classification of tracking system methods are also known like active and passive trackers, the active one uses motors and sensors, the passive one move from a compressed gas fluid drive from one side to another depending on the heating and density[40].

This methods increases the efficiency of the panel up to 40% but the side effect is that more equipment are added in the system this makes the investment cost increase, more maintenance is required and also the motor will be an additive load to the power output of the panel.

2. Cleaning

The cleaning method consists of removing the dust or any material on the solar panel preventing it to receive the maximum solar irradiation, this method is divided in to three;

- Rugged robot; these are used in desert areas where we cannot use water to clean the surface of solar panels and to reduce the human labor. One of the robots used is the NOMADD (NO-water Mechanical Automated Dusting Device), this robot can clean 200-300m of solar panel in one go. Figure 5 shows use NOMADD used in the Arabic desert [42].

Figure5. NOMADD (NO-water Mechanical Automated Dusting Device)

- self-cleaning technology; it consist of an extra layer of a transparent material on the solar panel which monitored by dust sensors and in critical condition a signal is send to the material which sends electrical wave which are dust – repelling , this can attain 90% of dust removal after 2min of electrical discharge[43].

- Vacuum cleaner Robot; design to work on slippery and inclined surface this robot uses two technology to clean properly the surface of a solar panel, a brush is placed in a rolling manner brings the dust towards the vacuum for aspiration. The rolling energy is created by a small motor of high speed, the motor receives its energy from the panel or it can itself have a panel imbedded on top of it as shown on figure4. It will be noted that the robot will follow a predefine path with sensing devices on it.

Figure6. Robotic Vacuum Cleaner with a Docking Station

3. Cooling technique

The cooling method is used to reduce the temperature of the cell. As stated earlier higher is the temperature of the cell, lower will be its efficiency. The cooling is done in a similar manner to a car radiator or just the inverse method of water heating from a flat collector, where water runs through a tube placed adjacent to the panel and makes a close loop system in order to reduce temperature of the cell as shown in figure7 [30].

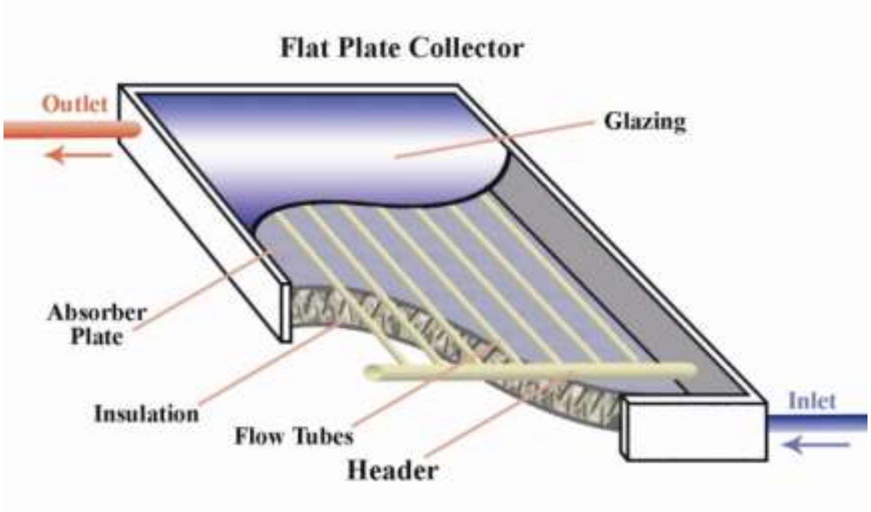


Figure7. Cooling Technique

4. Antireflective coating (ARC)

Some solar panel can reflect a considerable quantity of light before it can be used; this is the case of Silicon cells which can reflect up to 35% of light before utilizing it; to overcome this we use an antireflective material placed on top of the panel. The ARC material is similar to the one of a camera lens, made of a thin layer of dielectric material which produces waves. The waves produced must be out of phase with respect to the wave formed by the reflection so that the resultant should be zero for reflection, but to attend zero reflection is very difficult some ARC material attend 75-80% of efficiency [44]

5. Implementation of artificial intelligence

a) A fuzzy algorithm can also be developed to achieve optimal solar tracking. The function of the fuzzy controller is to generate pulses for motor drivers in case of a servo motor so that their step angle can be controlled as per the desired angles [46][47].

b) PI (Proportional Integral) control can also be applied to the system to control a permanent magnet DC motor (PMDC), which rotates the panel so that the tracking can be achieved at desired angles [21].

c) Two fuzzy logic controllers can be implemented on modern FPGA (Field Programmable Gate Array) card to increase the energy generation efficiency of solar cells. The tracking mechanism is composed of photovoltaic module, stepper motor, sensors, input/output interface and expert FLC controller implemented on FPGA so that it can track the sun and keep the solar cells always face the sun throughout the day [41].

d) PO (pattern and observation) mostly used or any other optimization technique can be used to create a smart charger for batteries, which are actually load to the panel as explained earlier. These smart chargers are imbedded with MPPT (maximum power point tracking) controller system which tries to keep the panel at its maximum voltage and current output for better charging of the battery and automatically disconnect it when fully charge. While trying to keep the panel at it maximum output this increases the efficiency of the panel.

VI. Economic view of solar cells

The economical point of view of solar cells is very important in order to find the ideal point between the technical parts and the commercial parts of the cell. The commercial point of view of some of the solar cells is discussed here to have an optimal feasible choice of the material to be used.

As per the overview of the solar cell market in 2015, the more commercialized materials used for the production of solar cells [8, 13]

- Standard Crystalline Si 83%
- cadmium Telluride (CdTe) 6%
- Amorphous Si(thin Film) 5%
- Supper Mono Crystalline 4%
- Copper indium gallium selenide (*CIGS*) 2%

With the growth in percentage of each type of PV cell [8, 13]:

- Standard Crystalline Si 246%
- cadmium Telluride (CdTe) 141%
- Amorphous Si(thin Film)169%
- Supper Mono Crystalline 141%
- Copper indium gallium selenide (*CIGS*) 257%

From the data above, it can be concluded that the Standard Crystalline PV cell is the most used solar cell. However, the crystalline PV cell can be expensive on a small term investment but will make a comparison in short and long term investment of this type of PV cell [14].

Table 1: Long and short term investment for Si - PV Cell

	Short term	Long term
In put (g/Wp)	11.4	4.0
Fraction used	46%	37%
Wafer(g/Wp)	5.2	1.5
Wafer thickness (μm)	300	100
Cell efficiency	14.7%	16.5%
Specific cost($/Wp)	0.23	0.08

Therefore, long term investments for Silicone photovoltaic solar cells are cheaper than short term investment.

CHAPTER 2

LITERATURE REVIEW

I. Photovoltaic Solar cells descriptions.

Miles R.W., et al.

The authors give an overview of the materials and methods used in the manufacturing process of photovoltaic cells. A review of materials such as silicon (monocrystalline, polycrystalline and amorphous), polycrystalline compounds (cadmium telluride, copper gallium indium selenide and copper indium disulphide) and compounds (gallium arsenide, indium phosphide and gallium antimonide), etc. as been done [14].

Gary Cook, , et al.

In this book, the description of fundamental technology used in photovoltaic solar cells, the history, preliminary view of photovoltaic technology and types of collectors has been discussed. The book highlights the evolution of photovoltaic technology, and some future trends [15].

Chetan Singh Solanki

The book gives deeper explanations on photovoltaic systems, how current is created, the output voltage and how the efficiency of the cell is calculated. In addition the author gives some factors that affect the efficiency of photovoltaic cell and a minor way to overcome the given factors. [9]

II. Tracking system used for solar photovoltaic cells

Minor M. Arturo and García P. Alejandro

In this work, it was proposed an innovative method for tracking the sun which is based on the use of simple commercial webcam (camera) as sensor element. An electro-mechanism prototype was designed to evaluate the accuracy and efficacy of tracking the sun under different weather conditions. The system had shown a better accuracy than using elements like LDRs (light dependent resistors) and other photodiodes. [16]

P Madhu and V Viswanadha

The authors used a Light Dependent Resistor (LDR) sensor and attached it to a parabolic dish concentrator in order to ensure that the dish remains perpendicular to the sun. The LDR detects the sunlight and the signal is transmitted to an Atmega32 microcontroller. Then, the microcontroller gives commend to a motor to move step wise accordingly in order to maintain an angle of 90degree with the sun for maximum efficiency. [17]

Alboteanu L., et al.

This paper combines the two automatic types of tracking systems; one using solar sensors and the other that follows a predetermined trajectory. In order to achieve low power consumption, the system uses an interference allowing the monitoring and control of the tracking system locally and remotely. A prototype was build and used to verify the solutions and algorithms proposed in the paper by the authors. [18]

Rahman. S, et al.

The authors present a tracker system which tracks the sun and changes the position of the panel accordingly to maximize the output power. The tracking system proposed in this paper consists of; sensors, comparators and microcontroller combine to control a motor which gives direction to panel, an additive of gear-bearing arrangements with supports and mountings for a smooth movement and maximizing the movement of the motor is done.

Light Dependent Resistors (LDRs) are used as sensors in the proposed dual axis tracking system. Diodes are used for neglecting the negative voltages coming from the comparators and microcontroller generates the suitable control signals to move the motor in the proper direction the proposed paper demonstrates an efficiency of 52.78% is found compared to a fixed mounted solar panel [19].

III. Artificial intelligence used for higher efficiency of photovoltaic solar cells

Huang Y.J., et al.

In this paper a solar tracking system controlled with an implementation of a smart controller. Here the authors propose a light sensitive cadmium sulfide resistor as sensing element for sun tracking. The smart controller is based on a fuzzy algorithm which gives suitable pulses to the motor drive which based on PWM (pulse width modulation) technics and at its turn will determine the steps required for the motor to move with the desired angles [20].

Usta M.A., et al.

A Matlab/Simulink model is designed by the authors incorporating, Fuzzy logic controller and PI (proportional Integral) controller, where the two controllers are compared to realize a better tracking system. The two controllers separately connected to a motor to determine suitable steps for tacking the sun [21].

Karthika S., et al.

A MPPT (Maximum Power Point Tracking) algorithm is designed with P&O (Pattern and observation) controller to determine the suitable duty cycle of a boost DC-DC converter in order to extract the maximum output from the solar panel. The voltage extracted from the solar panel stays stable and maximum as much as possible. This technique consists of having the maximum output from the panel in any condition independently of fluctuations the panel can be subjected to [22].

Basil M. Hamed and Mohammed S. El-Moghany.

The authors present a technique which consists of implementing two fuzzy logic controllers on a FPGA (Field Programmable Gate Array) card to increase the efficiency of a solar cell. The tracking system is designed to work in real time independently of any change in conditions the panel is subjected to the output should stay stable. The tracking mechanism is composed of photovoltaic module, sensors, a stepper motor, an interface and a Fuzzy Logic Controller implemented on FPGA, all put together to track the sun and keep the solar cells always facing the sun all day in real time. The simulation of the given tracking system done using MATLAB/Simulink [23].

S. Jaw-Kuen, et al.

In this paper the authors present a MPPT controller using different types of algorithms based on Fuzzy logic Controller. In the paper six algorithms are proposed with each time a set of two inputs and 1 output. The inputs sets chosen are; i) slope and change in slop, ii) slop and variation of power, iii) variation of both power and voltage, iv) variation of power and current, v) sum and increment of the conductance and finally vi) Sum and increment of arctangent of conductance, all these inputs have only one output the duty cycle of a buck boost converter [24].

CHAPTER 3

DESIGN OF A FUZZY LOGIC BASED MPPT (Maximum Power Point Tracking) CONTROLLER

Here the design of a FLC (Fuzzy Logic Controller) rules and logics has been done in a manner that we can optimize the output of a particular solar panel. The following, will give in detail the algorithm used to design the MPPT.

I. MPPT algorithm for solar system

Fuzzy Logic has been chosen as controller and optimization technique to determine automatically the suitable duty cycle of a Buck-boost converter in any condition, in order to extract the maximum output from a given array of solar panels. In addition, in this part an explanation of what is and how works the MPPT system with the different algorithms chosen is done.

Two combinations of variables have been chosen for the design of controller, which should determine the duty cycle of the Buck-boost converter used in the MPPT; (i) variation of power (ΔP) with the variation of voltage (ΔV) and (ii) variation of power (ΔP) with the variation of current (ΔI).

The algorithm designed aims to optimize the output power of the converter, by gradually increasing and decreasing the duty ratio of the converter. [24] The controller will have to automatically adjust the step size of the duty ratio of the converter depending on the output of the solar panel; the adjustment should be done as human rezoning there for fuzzy logic is chosen as artificial intelligent technique. [25]

The block diagram of the MPPT will consist of a solar panel, Buck-boost converter and a MPPT controller her FLC as shown on figure 8.

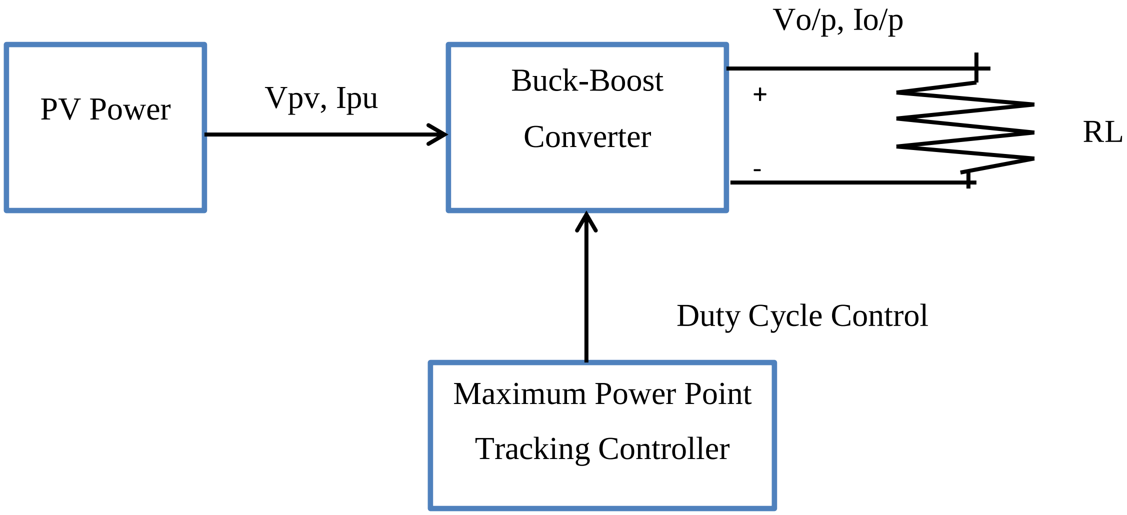


Figure8. MPPT Block Diagram

II. Design of the controller

1. Introduction to fuzzy logic

Since time, scientists have been trying to develop an intelligent machine capable of rezoning like a human being. Many points of similarity between computer processing and human thinking are observed, one of the approximate human rezoning logic found to date is the “fuzzy logic”. By its definition “fuzzy” as an adjective is difficulty to perceive, indistinct or vague. [27]

The advantage of Fuzzy logic compared to other computer logics is that, Fuzzy Logic has a human approach of problems as many computers have a crisp set input (0 and 1) fuzzy logic can lead to a human approach where the approximation of all infinite values between 0 and 1.

For better understanding, an example is given; for many logics it can only, either be hot or cold, but using fuzzy logic we can give a degree of belonginess to “hot” or “cold” which can be divided in many members as its needed, some of commonly used degrees of belonginess are: very, less, extremely, etc. [26]

The architecture of fuzzy logic is as follow:

- Fuzzification Module:

Here the inputs are transformed; usually these inputs crisp numbers, then transformed into fuzzy sets and splits the input signal membership functions.

- Knowledge Base:

The rule maker determines which language is suitable depending on the relation between input and output, here are some linguistic variable used IF-THEN, IF-AND-THEN, IF-OR-THEN, etc.

- Inference Engine:

Here the simulation using human reasoning is done by the fuzzy inference in MATLAB/Simulink on the inputs by using IF-THEN, IF-AND-THEN, IF-OR-THEN, etc. rules chosen by the expert.

- Defuzzification Module:

The transformation of fuzzy sets obtained by the operation done in the inference engine is then transformed back into suitable or desirable crisp values.

2. Fuzzy logic algorithm

The fuzzy logic algorithm is defined as follow;

- Defining linguistic terms for variables,
- Constructing membership functions for each variable defined,
- Construction of a table of rules based using linguistic terms defined,
- Conversion of crisp value(data) using defined membership functions(Fuzzification),
- Evaluation of rules and combination of results from each rule (interface engine),
- Converting evaluated output into suitable or desired non-fuzzy (crisp) values (Defuzzification).

Some disadvantages of Fuzzy logic system are that; (i) it is suitable and adaptable for non-high accuracy problems, so when so when accuracy or fix value is needed fuzzy logic is not desirable, (ii) there is no systematic or defined approach to fuzzy design, a fuzzy logic design depends totally on the expert needs and (iii) understandable only when logic is simple, where more elements are combined to build the logic and rules, the expert may get trapped because of complexity. [26]

The structure of a structure of fuzzy logic algorithm is give on figure below,

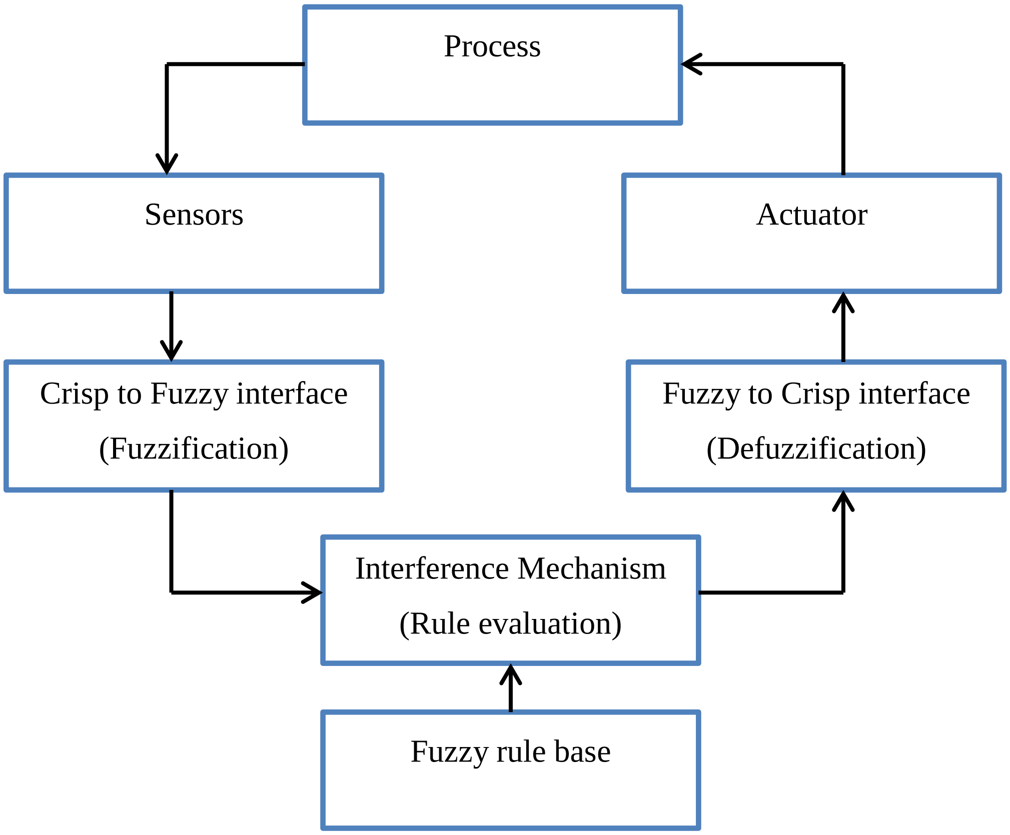


Figure9. Structure of fuzzy logic algorithm

3. Fuzzy logic algorithm for MPPT controller

Three variables have been chosen to design three types of controllers for the MPPT, the variables chosen from real datasheet of a solar panel [28] extended into an array are: (i) variation of power(ΔP), (ii)variation of voltage(ΔV) and (iii) variation of current(ΔI). The combinations of these variables are grouped into two to design 2 types of controllers which will be compered and then chose the best output. The combinations are taken as follow:

- Variation of current(ΔI) and variation of power(ΔP),
- Variation of power (ΔP) and variation of voltage (ΔV).

The purpose of building this Fuzzy logic controller is to define the optimum duty cycle for the DC to DC converter to extract the maximize the output of the solar panel array, for this work a Buck-boost converter has been chosen because of its advantage over other converters to be able to step-up or step-down the input voltage depending on the duty cycle. For maximizing the output, the converter is operated in continues conducting mode, the duty cycle of a Buck-boost converter is expressed as follow [29]:

$$D = \frac{V_{out}}{V_{in}+V_{out}} \tag{8}$$

$$V_{out} = \frac{D \times V_{in}}{1-D} \tag{9}$$

Where,
D= duty cycle
V_{out} = voltage output
V_{in} = voltage input

By observing the equation (8) we can conclude that when the duty cycle is the rage [0, 0.5[the converter behaves like a buck converter and in the rage of] 0.5, 1[is a boost converter. When the duty cycle D= 0.5 no change is observed at the output, D = 0 the output is 0 and D=1 the output will be infinite (∞).

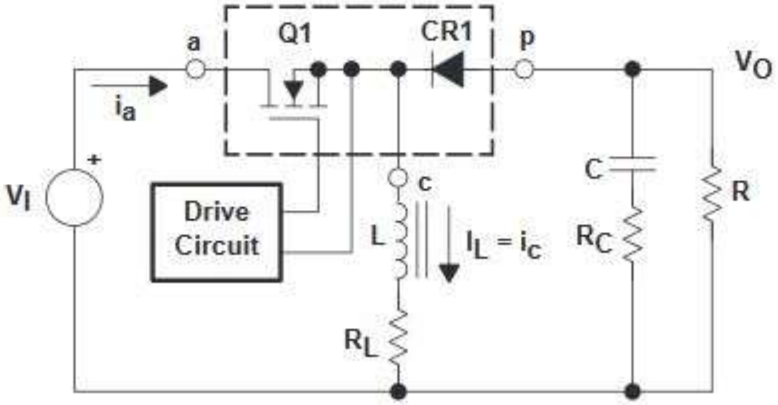


Figure10. Circuit diagram of a buck-boost converter

The operation of a buck-boost is explained as follow; when Q1 (switch) is repeatedly switched on and off, the switching on and off times in a period is decided by the control circuit. The switching actions give rise to a train of pulses at the junction of Q1, CR1, and L. Although L (inductor) is connected to the output C (capacitor), only when CR1 conducts, an effective L/C output filter is formed and filters the train of pulses to make a DC output voltage [29].

With the above details, it will now be able to design the fuzzy logic for our controller; this will be done as follow:

a. Definition of linguistic terms and variables.

For building our fuzzy logic controller will use the following five linguistic variables; VS (very small), S (small), M (medium), H (high) and VH (very high) and the variables are the same defined previously.

b. Construction of membership functions for the variables.

Here will define the rage of every variable so that we can choose the membership function suitable to be used in the controller. [28]

- Current [0, 6.68]
- Voltage [0,28.5]
- Power [0,183.3]
- Duty cycle [0,1]

These are the rages of one solar panel or for the design of the plant will make a combination of 10 arrays and one array is a combination of 600 panels (20 in series and 30 in parallels) which will give the following rages;

- Current [0, 193.2]
- Voltage [0, 570]
- Power [0,10^5]
- Duty cycle [0,1]

The three first are considered as fuzzy input and the forth is the output of the controller. The membership function for this controller is the triangular membership function because of its simplicity and facility in calculation [26]. With triangular membership function it is possible to uses direct; this method consists of giving each element y, a membership grad A (y) depending on the best opinion of the expert and defining linguistic terms represented by the fuzzy set A. for this work the overlapping of fuzzy sets has been decided by using Yager method witch defines that the overlapping of two membership function should be in the rage of 25 to 50% of its base, even though there is no predefined method to determine the overlapping of membership functions [26] [47] [48].

The inference mechanism used is the "*Mamdani*" this method has been chosen because of its min and max operator where the IF AND THEN rule can be used and most suitable for controller systems [26].

c. Constructing knowledge base on rules.

The rules have been done by choosing two inputs in the fuzzy controller and having one output. Two rules have been done by the combination decided above, the rules will be defined by the relation in equation (6) which defines the relation between the voltage and the duty cycle of a Buck-boost converter, therefore the relationship between current and power with the duty cycle can be deduced.

Table 2: variation of current (ΔI) and variation of power (ΔP)

ΔI / **ΔP**	**VS**	**S**	**M**	**H**	**VH**
VS	VS	S	M	H	VH
S	VS	S	M	H	H
M	VS	S	M	M	M
H	VS	S	S	S	S
VH	VS	VS	VS	VS	VS

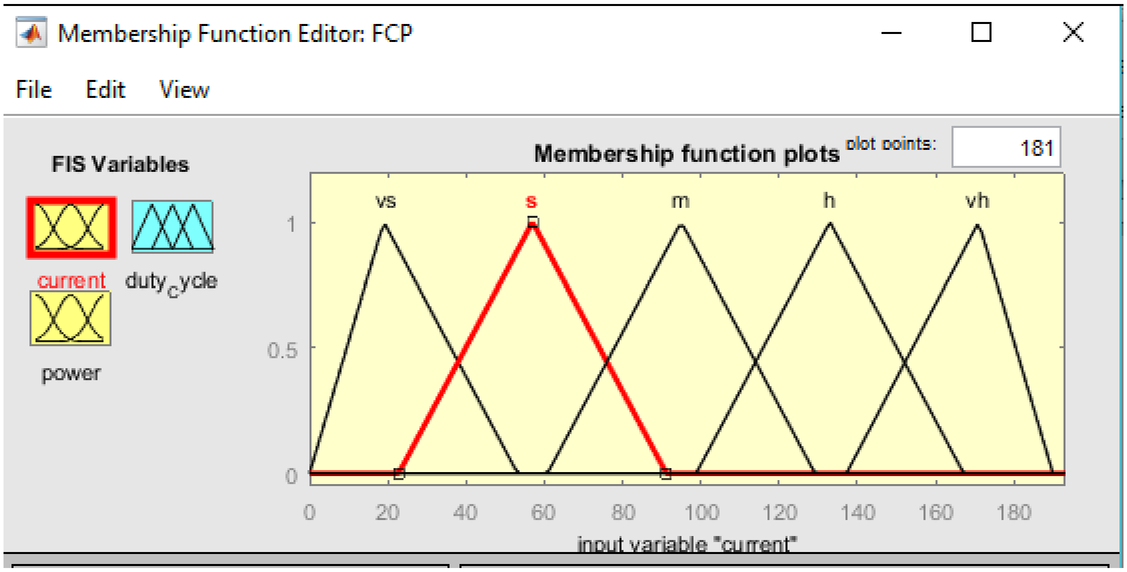
Table 3: variation of power (ΔP) and variation of voltage (ΔV)

ΔP **ΔV**	**VS**	**S**	**M**	**H**	**VH**
VS	VH	H	M	S	VS
S	H	H	M	S	VS
M	M	M	M	S	VS
H	S	S	S	S	VS
VH	VS	VS	VS	VS	VS

d. Converting crisp data into fuzzy data, using membership functions (Fuzzification).

The membership functions of every variable are shown on the figures below; the Fuzzification has been done using MATLAB R2016a.

Current [0, 193.2]



plot points: 181

Figure11. Membership functions of current

Voltage [0, 570]

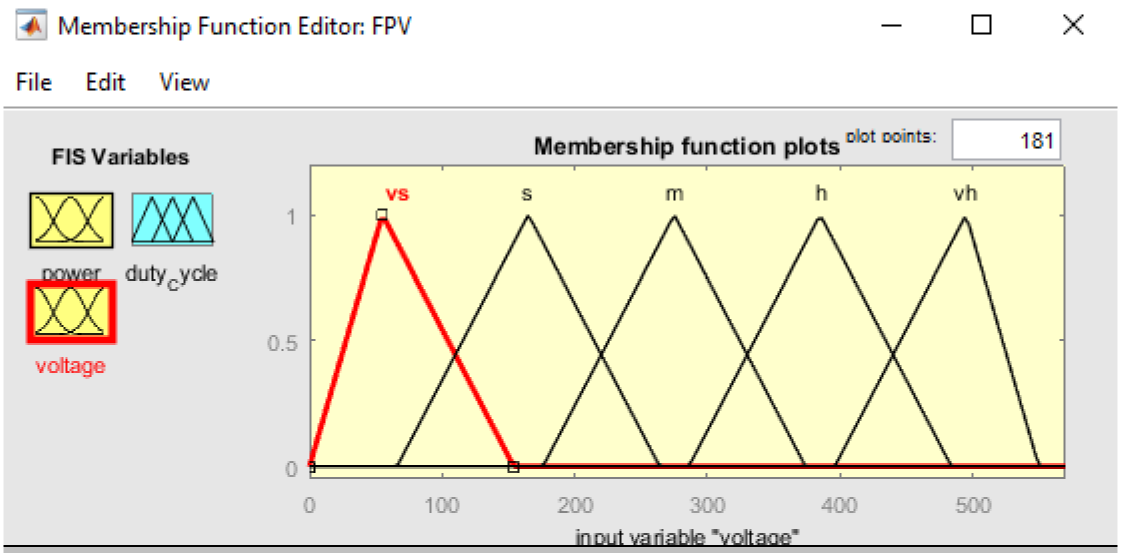

plot points: 181

Figure12. Membership functions of voltage

Power [0,10^5]

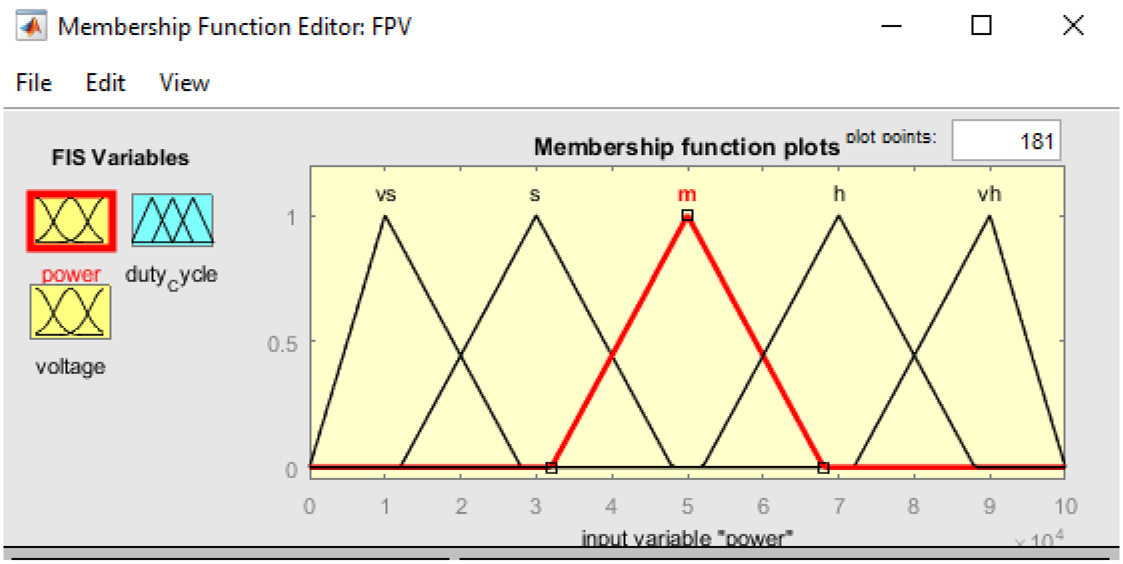
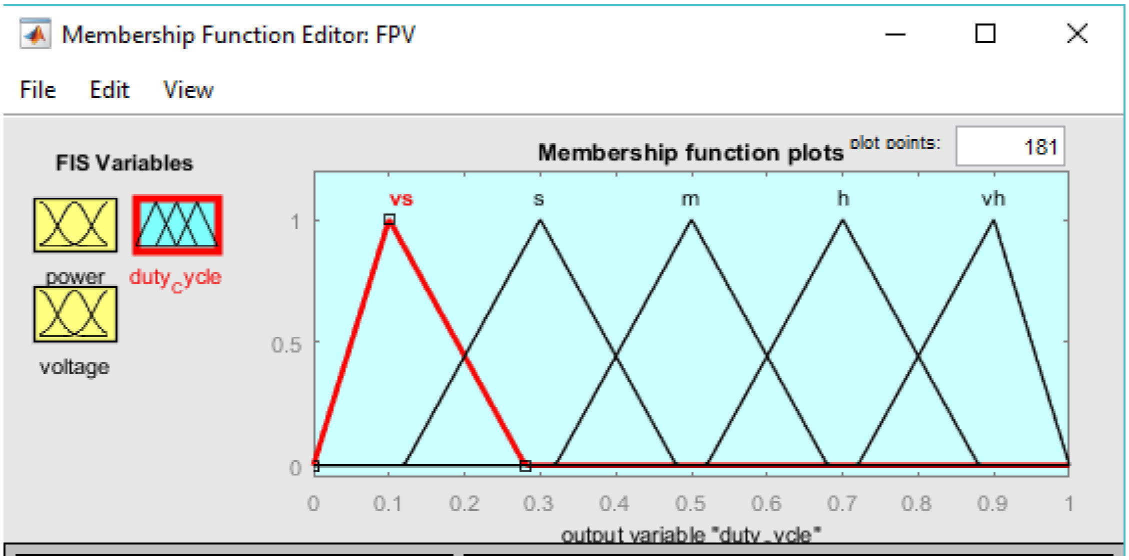

plot points: 181

Figure13. Membership functions of Power

Duty cycle [0, 1]



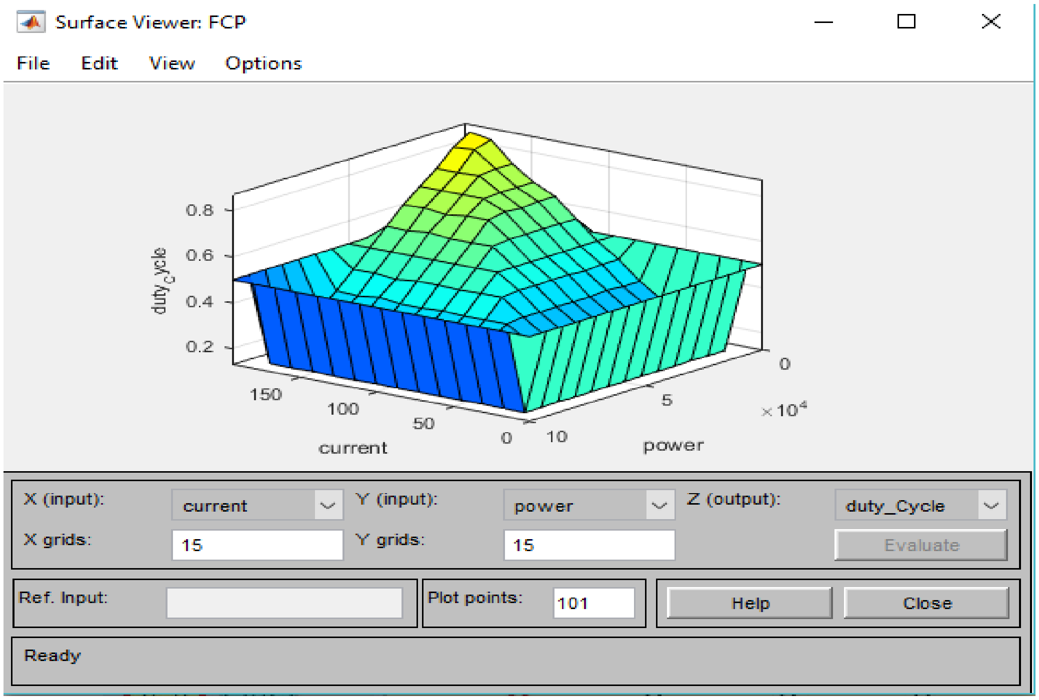
plot points: 181

Figure14. Membership functions of duty cycle

e. Evaluating rules in the rule base (interface engine).

The two rules based in the interface engine can be seen in the figures bellow, where the surface and the ruler of rules are shown.

Variation of current (ΔI) and variation of power (ΔP)



X (input): current

Y (input): power

Z (output): duty_Cycle

X grids: 15

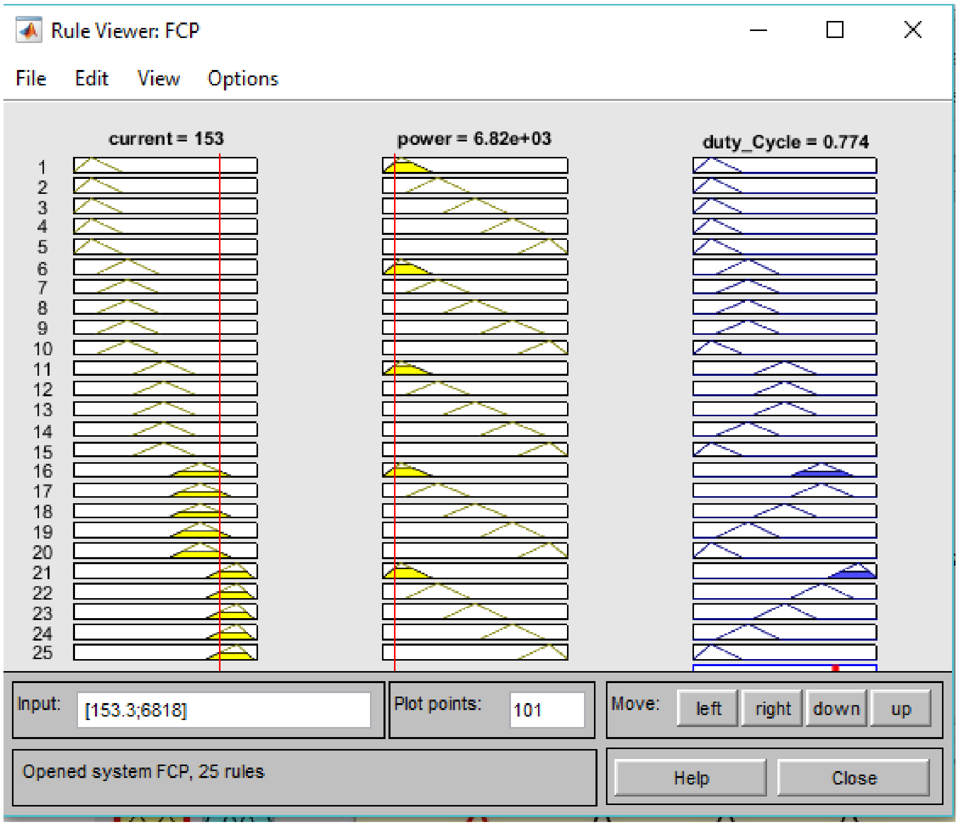
Y grids: 15

Ref. Input:

Plot points: 101

Ready

Figure15A. Surface view of Current and Power combination



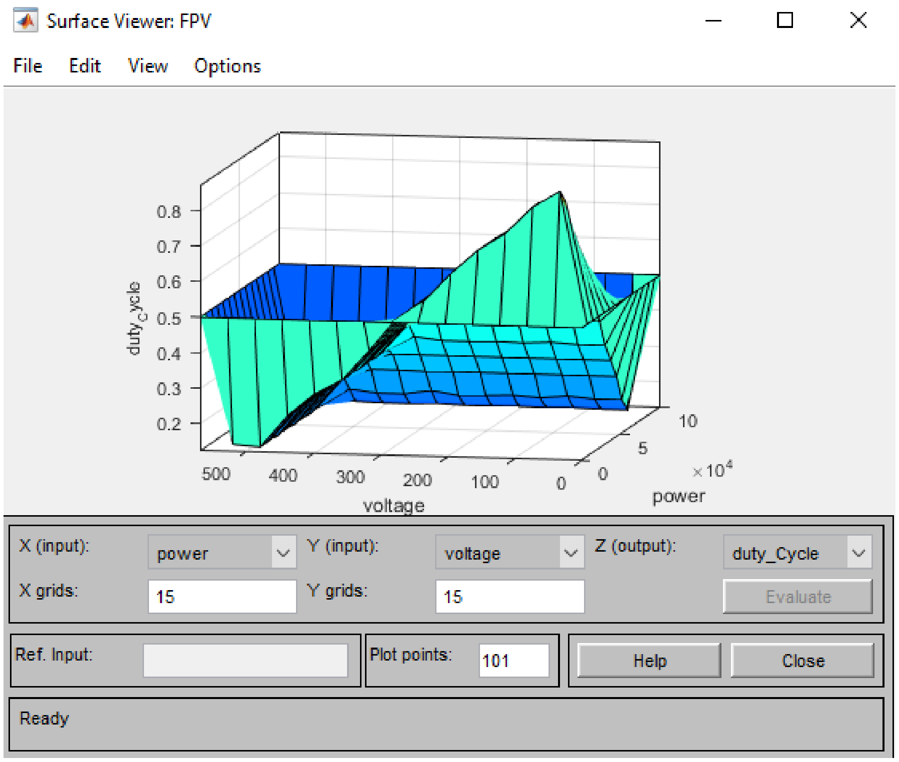
Input: [153.3;6818]

Plot points: 101

Opened system FCP, 25 rules

Figure15B. Interface engine of rules view of Current and Power combination

Variation of power (ΔP) and variation of voltage (ΔV)



X (input): power

Y (input): voltage

Z (output): duty_Cycle

X grids: 15

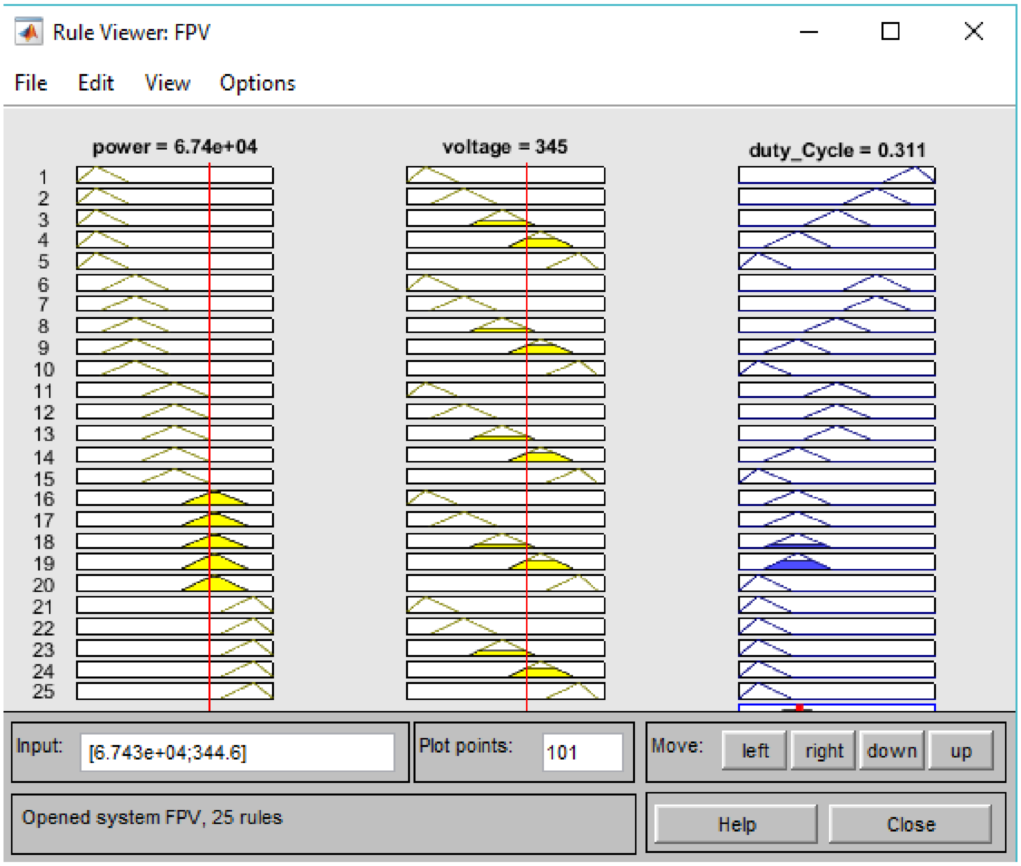
Y grids: 15

Ref. Input:

Plot points: 101

Ready

Figure16A. Surface view of Power and voltage combination



Input: [6.743e+04;344.6]

Plot points: 101

Opened system FPV, 25 rules

Figure 16B: interface engine of rules view of Power and voltage combination

f. Combining results from each rule (interface engine).

The combination results of each rule are shown in the figures 15B and 16B of each combination taken. This can be seen in the fuzzy engine by the variation of each input how the output response is done.

g. Converting outputs data into non-fuzzy values (Defuzzification).

The defuzzification is done by using the center of gravity method, the defuzzification value of a given fuzzy set A is said to be its centroid. The process is done by the fuzzy engine.

4. Fuzzy logic controller

After defining all the rules and parameters needed the logic must be imported in a FLC (fuzzy logic controller) so that it can be used in a circuit for simulation and optimization results. The simulation is done with MATLAB/Simulink R2016a.

As all the rules and logics have been defined the next step of the work will be to implement the rules in a FLC in the build solar power plant model done in MATLAB/Simulink R2016a and compere the output of each logic and chose the best of them.

CHAPTER 4

DESIGN OF A 1MW SOLAR POWER PLANT

The objective of the proposed research is to design a remunerable solar power plant for frontier Mining Camp; the given power plant should be able to feed the load totally and in a reliable way by using the MPPT controller designed in the previous chapter. In this chapter the full design of the power plant will be done with consideration of all geographical conditions.

I. Geographical conditions and placement of the power plant

The designed solar power plant is to be placed in Sakania in D.R.Congo, a central African country which lays on the equatorial.

1. Geographical coordinates

Frontier Mining SA, is a member of ENRC a copper mine placed in a small town of Sakania in south part of D.R.Congo and at the border with Republic of Zambia, these two countries share a belt of copper known as *The Copper Belt* which starts from the province of Copperbelt in Zambia and ends in the town of Kolwezi in Katanga D.R.Congo it is one of the most richest region of copper minerals in the world. The coordinates of frontier mine are *12°44'34"S 28°29'24"E* as shown of the figure bellow;

Figure17. View of frontier mining (Google Earth)

Here, figure 18 shows the placement of the solar power plant in Frontier mine which is circled in red and colored in yellow. This placed is totally empty and was used for throwing the sterile from the metallurgy process of copper.

Figure18. View of the placement of the solar power plant (Google Earth)

2. Climate

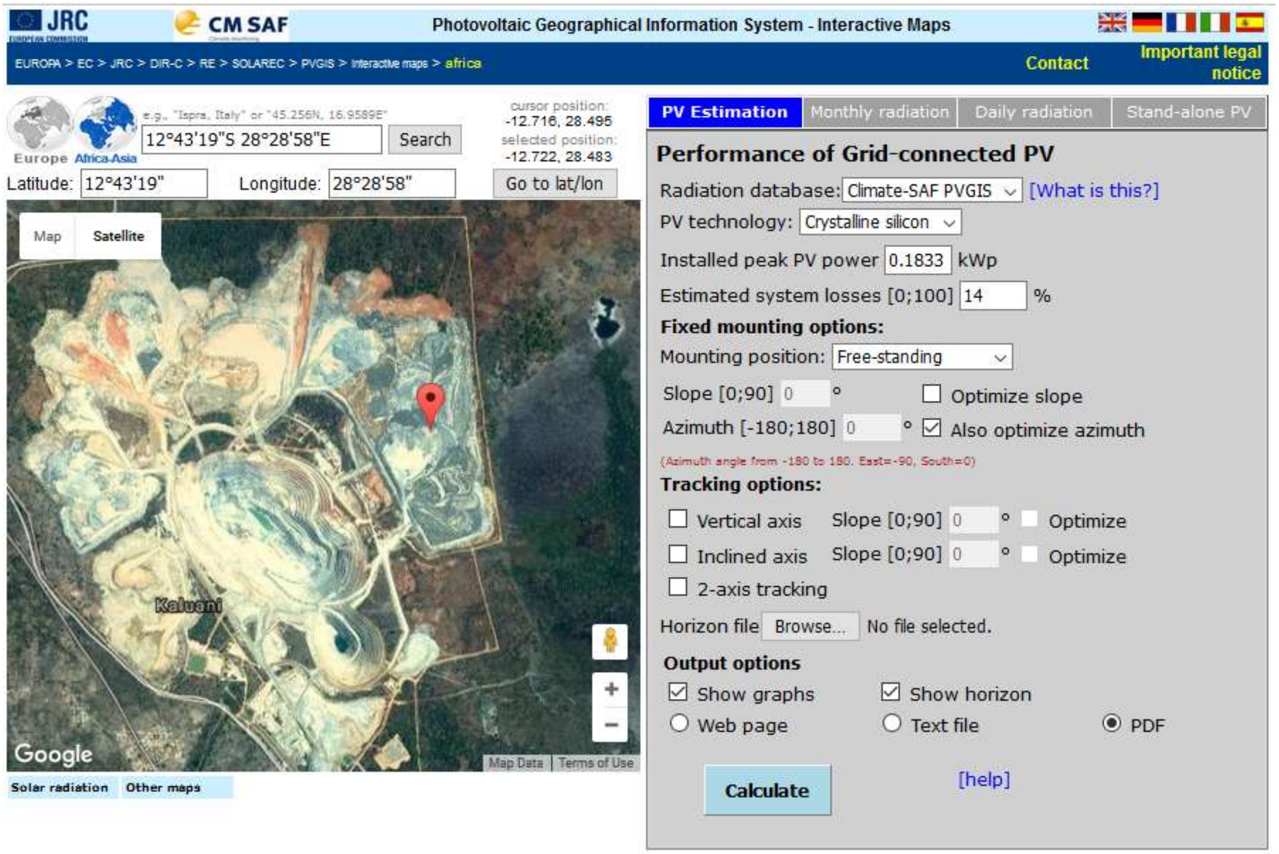
The weather conditions in Sakania is quite friendly and as an average temperature is 20.5°C and an average daily solar irradiation of 6240 $W/m^2/day$ this is good condition for a solar power plant. The table below shows the temperature fluctuations and humidity index in the region of Sakania through a year period.

Table 4: Average Temperature in Sakania through a year

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Min-Temp	17	17	17	15	12	09	09	11	14	16	17	17
Avg-Temp	22	22	22	22	20	17	17	20	23	24	23	22
Max-Temp	27	27	27	28	27	25	25	28	31	32	29	27
Relative Humidity	82	84	81	75	65	61	56	46	43	48	70	81

II. Mounting of panels

The mounting style (direction and inclination) of the panels used in the power plant has been decided using an online calculator *PVGis-apps*, which is accredited by the European Union for renewable energy, the given detail results can be seen in the indexes. The figure below shows the view of *PVGis-apps* application used for calculations.



e.g., "Ispra, Italy" or "45.256N, 16.9589E": 12°43'19"S 28°28'58"E
cursor position: -12.716, 28.495
selected position: -12.722, 28.483
Latitude: 12°43'19"
Longitude: 28°28'58"

Performance of Grid-connected PV

Radiation database: Climate-SAF PVGIS
PV technology: Crystalline silicon
Installed peak PV power 0.1833 kWp
Estimated system losses [0;100] 14 %

Fixed mounting options:

Mounting position: Free-standing
Slope [0;90] 0 ° ☐ Optimize slope
Azimuth [-180;180] 0 ° ☑ Also optimize azimuth
(Azimuth angle from -180 to 180. East=-90, South=0)

Tracking options:

☐ Vertical axis Slope [0;90] 0 ° ☐ Optimize
☐ Inclined axis Slope [0;90] 0 ° ☐ Optimize
☐ 2-axis tracking
Horizon file No file selected.

Output options

☑ Show graphs ☑ Show horizon
○ Web page ○ Text file ● PDF

Figure19. View of *PVGis-apps* application

Using Crystalline Silicone types of solar panel chosen because of its high level of commercialized type of panel and acceptable efficiency as demonstrate in chapter I, with an irradiation of average of 800W/m^2, the mounting of this panel will be done as follow [Index1, 2 and 3]:

- At a location of: 12°43'19" South, 28°28'58" East and elevation of 1289 m.a.s.l
- Inclination at 19 degree.
- Orientation of plan toward the truth north (azimuth angle) of -178 degree.

III. Design of the plant

A solar panel of characteristics; 6.44A nominal current, 28.5V nominal voltage and 183.3 Watt nominal power [28], has been used in the power plant, for the better design of the power plant, a division of the plant is done as follow;

1. Array

An array of 600 panels with combination of 30 parallel and 20 series that will give the nominal values to, Current 193.2A, Voltage 570V and Power $1.1\text{x}10^5$Watt, the average value of power will be considered to 100kWatt for one array.

Instead of making a MPPT controller for each panel which will be very costly, it was decided to extend it to an array that means each array will be provided with its own MPPT system.

After comparison of the two fuzzy based MPPT controller designed using the two combinations (i) Variation of current (ΔI) and variation of power (ΔP) and (ii) Variation of power (ΔP) and variation of voltage (ΔV). It has resulted that the combination (ii) is having better results where the voltage is stable at 456.5V which represents 80.08% of the maximum output voltage from the array; while in combination (i) voltage is 231.1V equivalent to 40.45% of the array voltage.

Considering the output power; (i) gives an average of $4.622\text{x}10^4$ Watt equivalent to 46.2% of maximum power and (ii) gives $9.13\ \text{x}10^4$ Watt about 91.3% of the maximum array power. Figure 20 shows the array in MATLAB/Simulink R2016a.

The plot of the array can be seen in figure 19 with the point of maximum power tracking corresponding points;

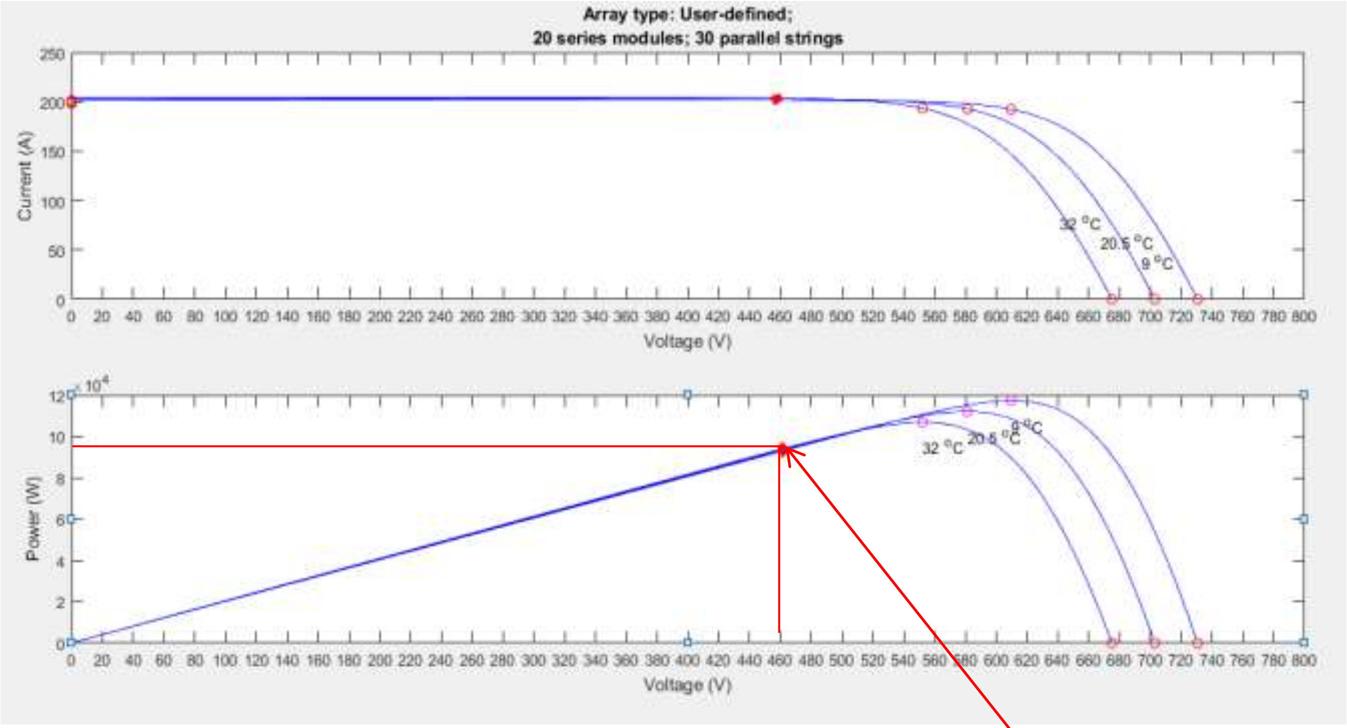


Figure20. Plot of array characteristics and MPPT view

MPPT point of
Logic (ii) equivalent to 9.13 x10^4
Watt, efficiency of 91.3%

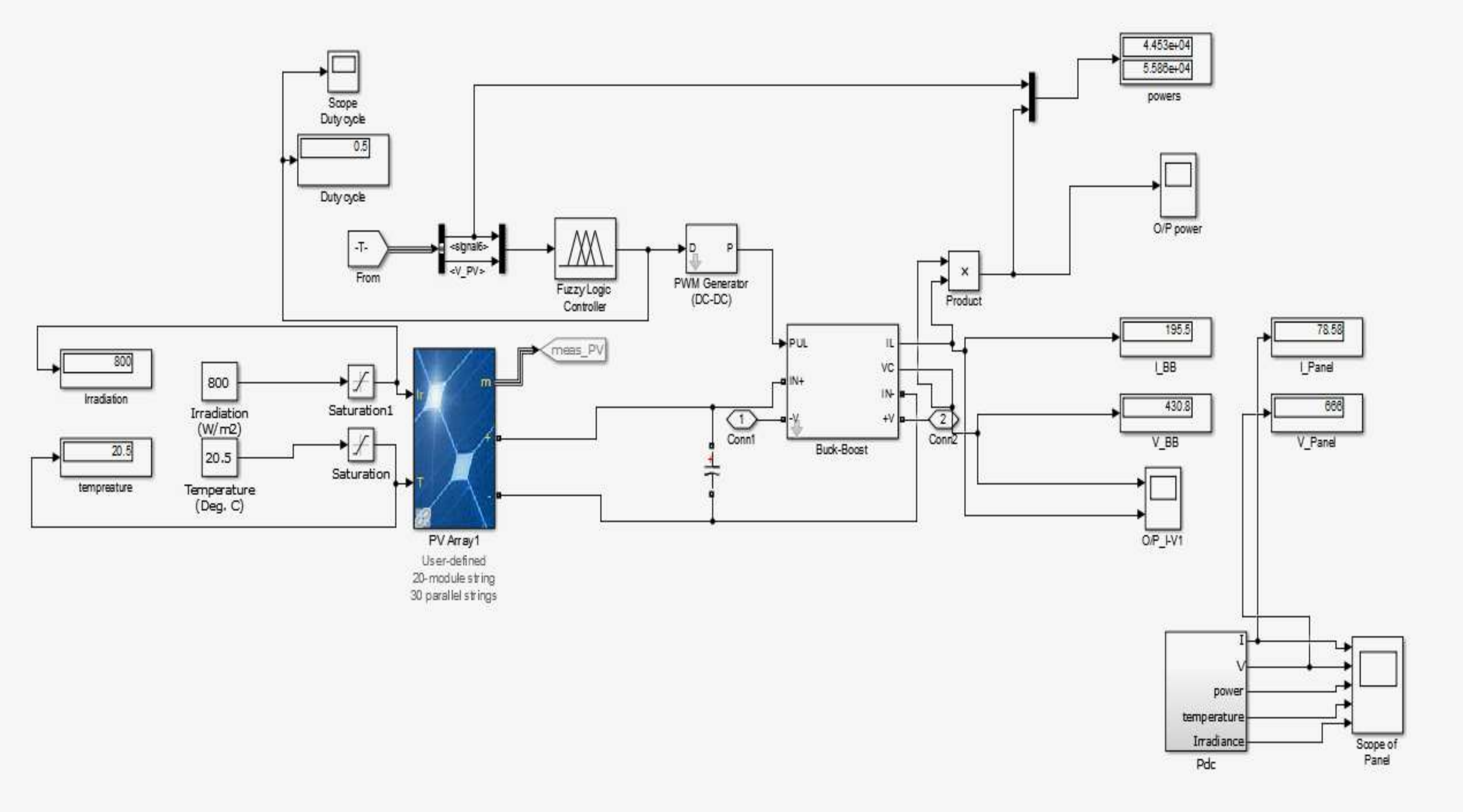


Figure21. View of the Array in MATLAB/Simulink R2016a

2. Power Plant

Each array has a maximum power of 100kWatt that means for a 1MWatt plant a combination in parallel of 10 arrays as seen in figure 23, will be needed to maintain same voltage level but increase in power, this will results to 10x600=6000 panels will be used for the full plant, at a surface of 1.2 hectares.

The actual mounting of a panel is (1.22x1.34)m equivalent to 1.6348m^2 of surface, for 6000 panels the equivalent surface needed will be 6000x1.6348=9,808.8m^2,if including spacing for cabling and array position the surface of 1.2 hectares(12,000 m^2) will be sufficient.

For question of reliability the stand alone solar power plant will be divided into two plants of 500kWatt each with its inverter system, where the two inverts are interconnected but feeding individually the its load. The division in two is done to avoid a black out situation in case of failure or any problem in one unite, the load can still be supplied by the other remaining unite after load shading.

The injection of the standalone solar power plant system in the electrical diagram of Frontier Mining is shown in annex 4.

- Inverter characteristics

A five level cascaded Multi level inverter is used as invert in the Simulink, and practically we can use the full characteristic of a single phase inverter describe in the data sheet [49].

- Load characteristics

The load is a full RL (resistive and inductive) load, practically in our homes we do have small motors like fans, water pumps, air dryer, etc. which are inductive in nature but the main load is resistive, the aim of applying a practical situation we used a RL load.

The THD (total harmonic distortion) in a solar system is usually very high due to switches used in the system both by DC to DC converters and inverter units, the load characteristic and the lack of reactive power in the system. The solar system doesn’t produce reactive power and due to this there is a lot of harmonic and voltage drop in the system, to overcome this only solution is to add a capacitor bank in parallel connection with the load, placed at the load end for reactive power compensation and maintain voltage level.

Using FFT (Fast Fourier Transform) analysis in MATLAB/Simulink R2016a with 1000Hz maximum frequency and computation at same frequency, the THD is 6.82% which is an acceptable value in a power system as shown in the figure below and the voltage across the load is about 212.1 V as RMS value.

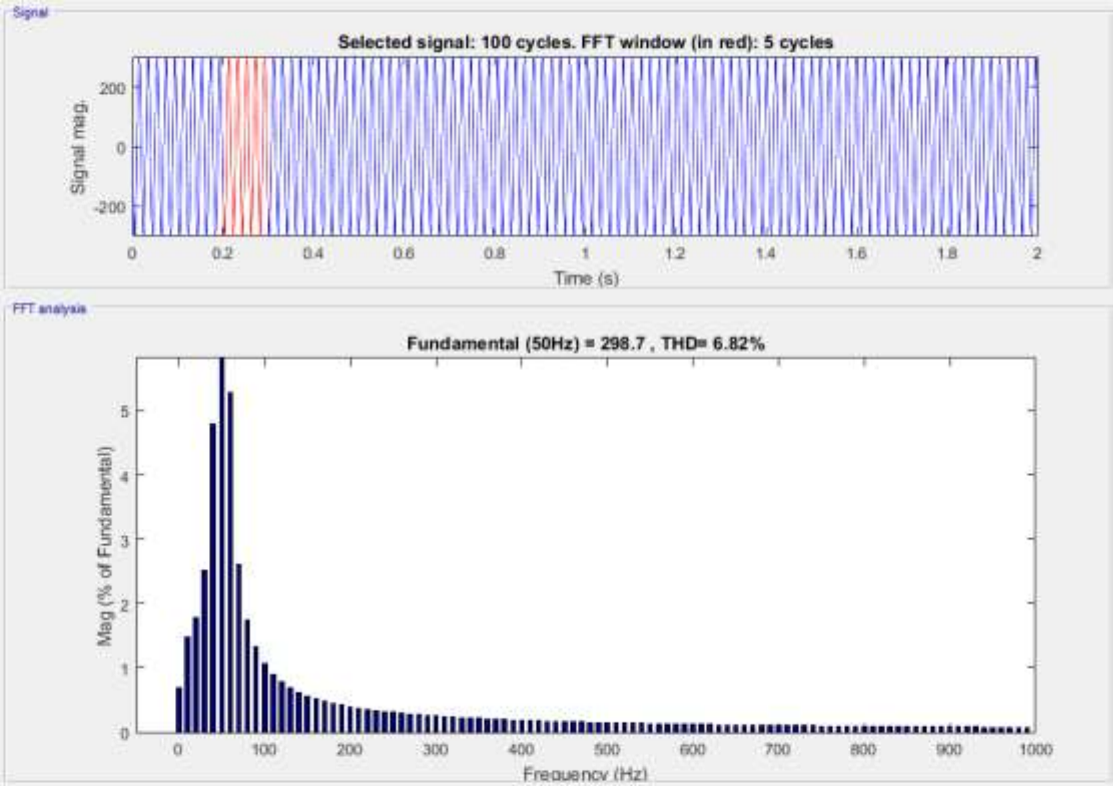


Figure22. View of THD analysis in MATLAB/Simulink R2016a

IV. Economic benefits of the plant

The average cost of electrical bill of the mine is 1,700,000 USD a month. The mine average demand of electricity is 30MWh in a month the average consumption will be:

Demand per month = Demand per hour x 24h x 30days = 30x24x30= **21,600MWmonth**

Or the plant will be producing power for an average of 7h a day of sun in Sakania D.R.Congo. That will lead to a production per month of:

Power produced by Plant per month = Peak power produced per hour x 7h x 30days x 0.9 x 0.98 = 1x7x30x0.9x0.98 =**185.22MWmonth**

0.9 and 0.98 respectively inverter efficiency and wiring losses.

By the rule of proportion;

21,600MW→1,700,000 USD

1MW→ 1,700,000 USD/21,600

185.22→ (1,700,000 USD/21,600) x 185.22 = **14,577.5 USD**

So for a month by using the plant the mine can economize at list a minimum of **14,577.5 USD** and for a year **174,930.00 USD**

V. Future trend of the project

The trend of this project will be the estimation of the installation cost of the solar power plant from panel cost, wiring up to the labor. The installation cost of any solar system is usually high but after a given payback time the plant becomes absolutely a free energy resource with less maintenance cost.

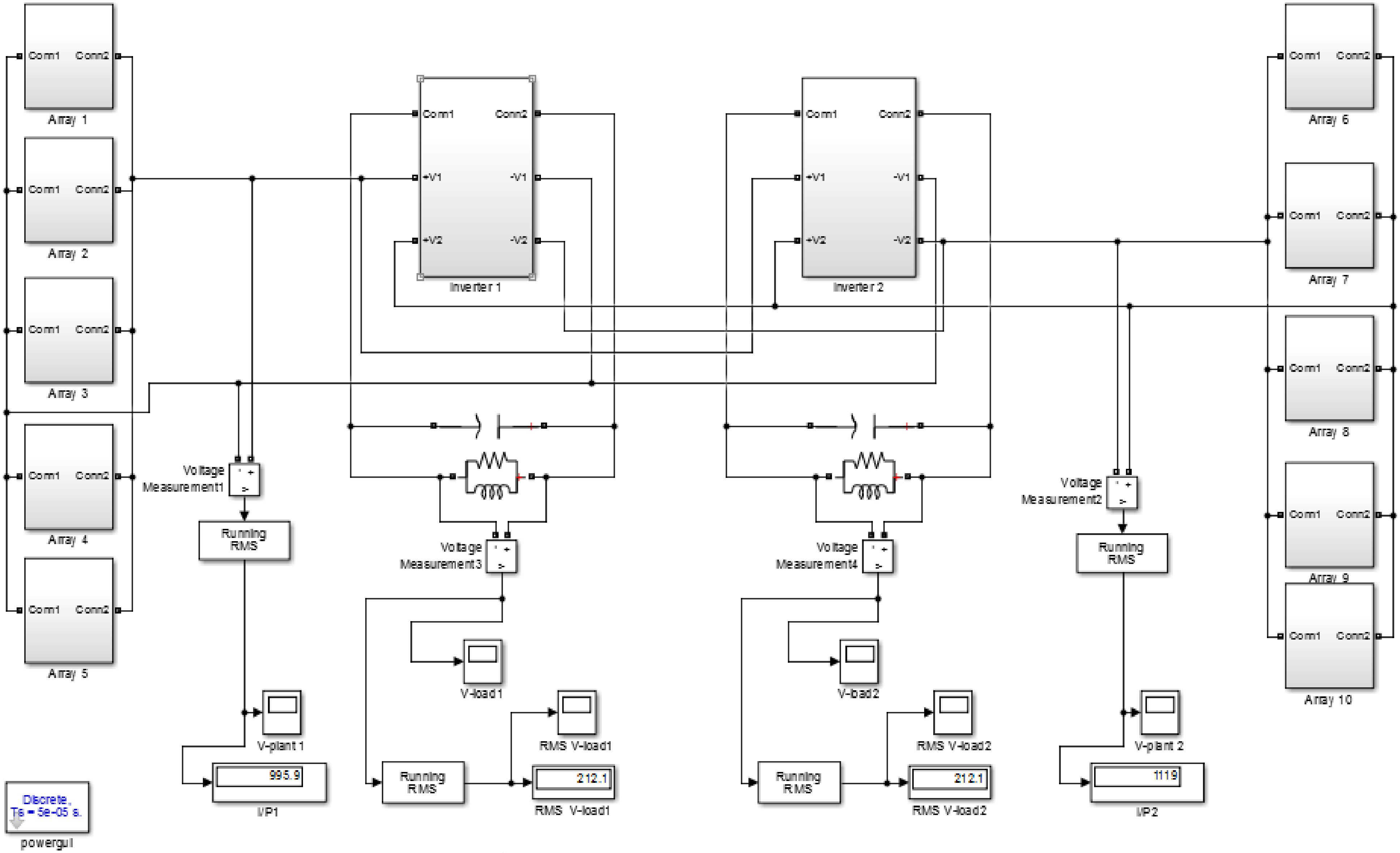


Figure23. View of 1MW solar power plant in MATLAB/Simulink R2016a

CONCLUSION

A comprehensive review of solar photovoltaic systems has been carried out, understanding factors affecting the efficiency of a photovoltaic system and proposition of some practical solutions to overcome these factors. In this work a MPPT (Maximum power point tracking) system using Fuzzy logic controller to determine automatically a desirable duty cycle for a bust boost converter has been opted as solution.

Two Fuzzy logics were compered for this work; one based on the combination of variation in current (ΔI) and variation in power (ΔP) and the other on variation in power (ΔP) and variation in voltage (ΔV). After implementation of both combinations the first gave an efficiency of 46.2% in power output and the second 91.3%, therefore the second combination was opted as controller for the MPPT system.

With the aim of reducing the cost of energy and tending toward green energy, this thesis designs a 1MWatt solar power plant capable of feeding Frontier mining camp for a minimum of 7h a day without any storage system. With this solar power plant it will be able to reduce an average minimum amount of *14,577.5 USD* for a monthly bill of electricity and yearly *174,930.00 USD.*

The installation cost has to be calculated, although its known that solar system initial investment cost is usually high, but after a given payback period between 3 to 5 years, the plant can be a free source of electrical energy. In addition a solar power plant has a minimum life period of 25 years at 90% of its efficiency afterwards 80% [50]. With this it can be seen that after a given period time a colossal amount of money can be preserved.

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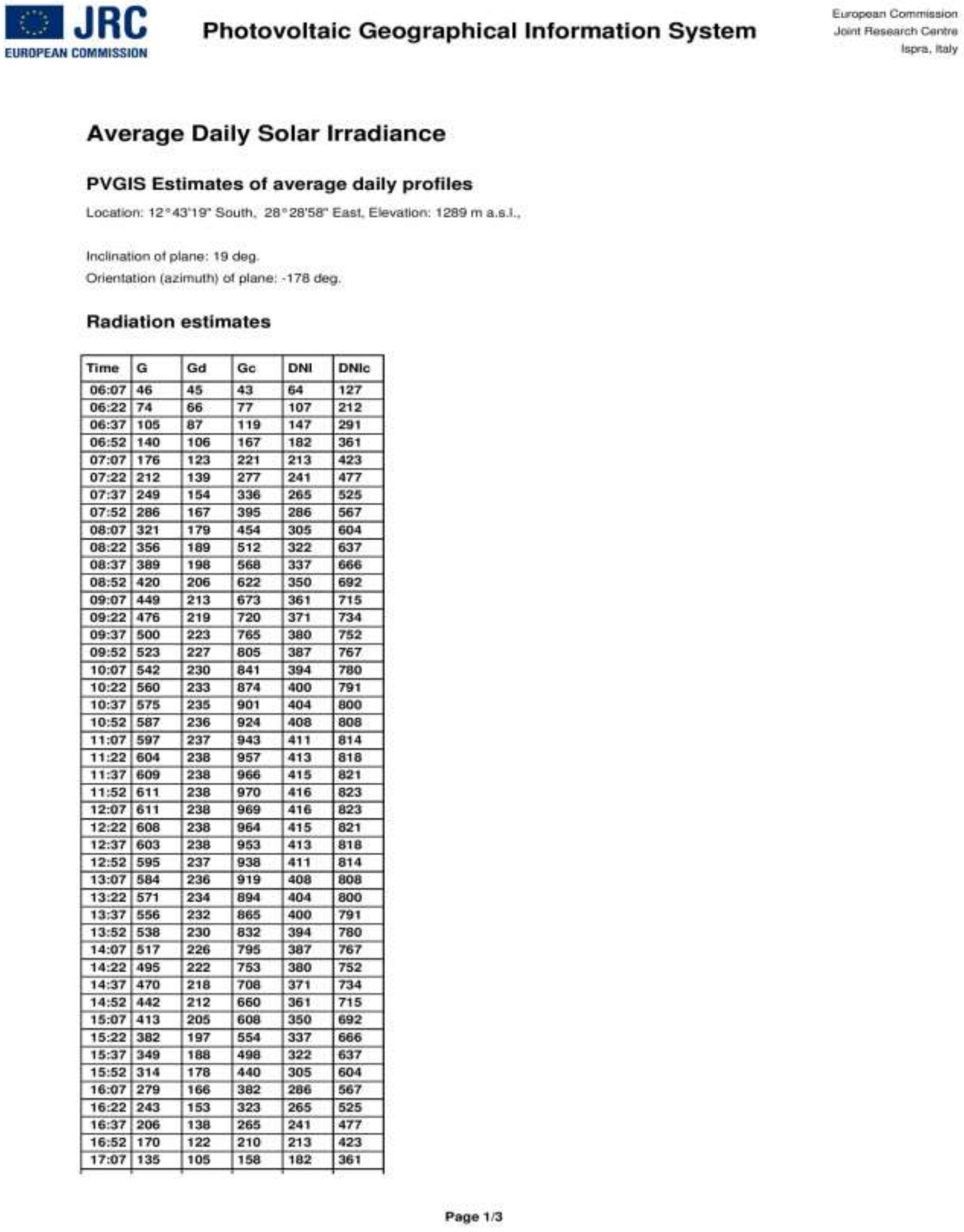
ANNEXES

ANNEX 1: DAILY IRRADIANCE



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Average Daily Solar Irradiance

PVGIS Estimates of average daily profiles

Location: 12°43'19" South, 28°28'58" East, Elevation: 1289 m a.s.l.,

Inclination of plane: 19 deg.
Orientation (azimuth) of plane: -178 deg.

Radiation estimates

Time	G	Gd	Gc	DNI	DNIc
06:07	46	45	43	64	127
06:22	74	66	77	107	212
06:37	105	87	119	147	291
06:52	140	106	167	182	361
07:07	176	123	221	213	423
07:22	212	139	277	241	477
07:37	249	154	336	265	525
07:52	286	167	395	286	567
08:07	321	179	454	305	604
08:22	356	189	512	322	637
08:37	389	198	568	337	666
08:52	420	206	622	350	692
09:07	449	213	673	361	715
09:22	476	219	720	371	734
09:37	500	223	765	380	752
09:52	523	227	805	387	767
10:07	542	230	841	394	780
10:22	560	233	874	400	791
10:37	575	235	901	404	800
10:52	587	236	924	408	808
11:07	597	237	943	411	814
11:22	604	238	957	413	818
11:37	609	238	966	415	821
11:52	611	238	970	416	823
12:07	611	238	969	416	823
12:22	608	238	964	415	821
12:37	603	238	953	413	818
12:52	595	237	938	411	814
13:07	584	236	919	408	808
13:22	571	234	894	404	800
13:37	556	232	865	400	791
13:52	538	230	832	394	780
14:07	517	226	795	387	767
14:22	495	222	753	380	752
14:37	470	218	708	371	734
14:52	442	212	660	361	715
15:07	413	205	608	350	692
15:22	382	197	554	337	666
15:37	349	188	498	322	637
15:52	314	178	440	305	604
16:07	279	166	382	286	567
16:22	243	153	323	265	525
16:37	206	138	265	241	477
16:52	170	122	210	213	423
17:07	135	105	158	182	361

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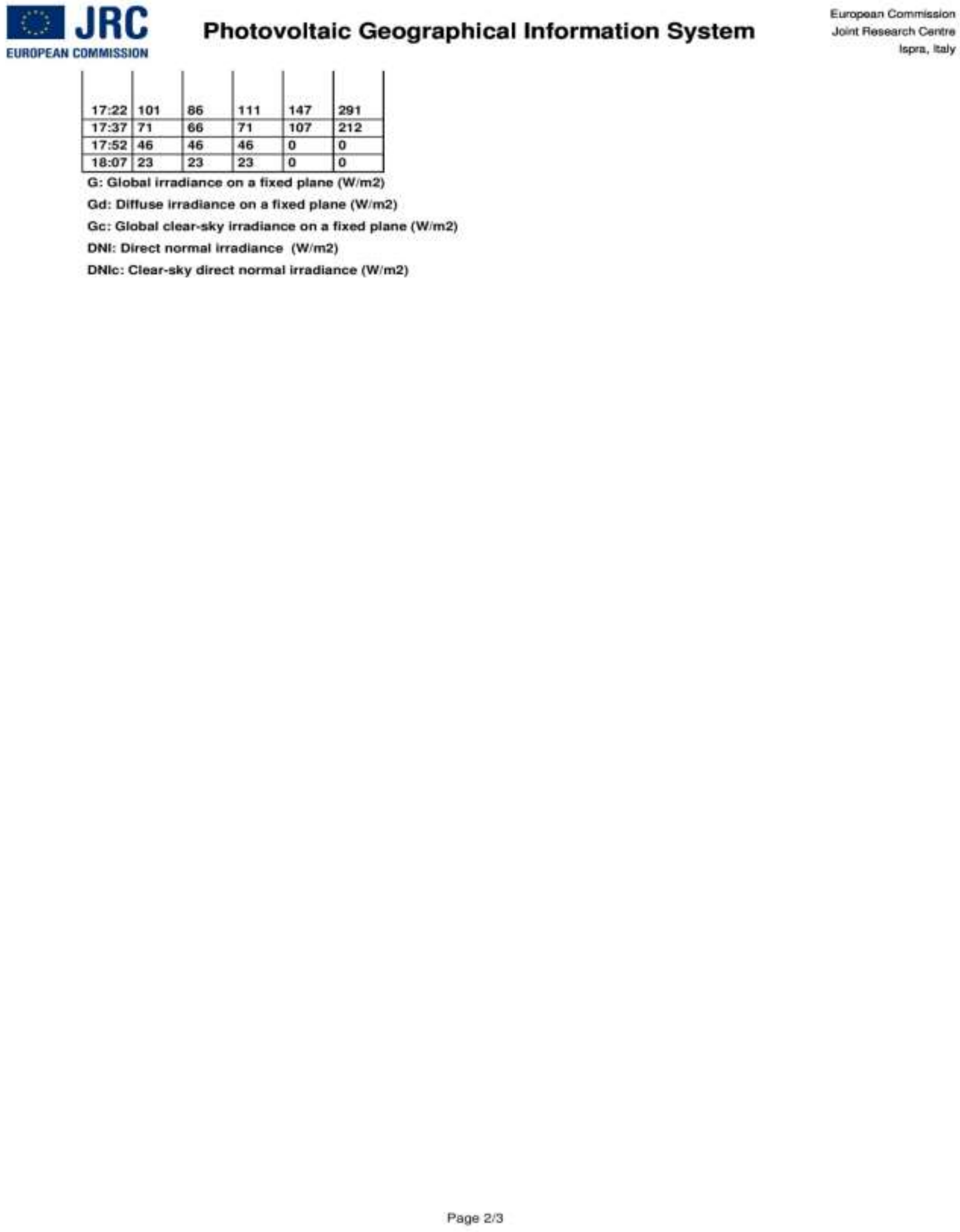

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17:22	101	86	111	147	291
17:37	71	66	71	107	212
17:52	46	46	46	0	0
18:07	23	23	23	0	0

G: Global irradiance on a fixed plane (W/m2)

Gd: Diffuse irradiance on a fixed plane (W/m2)

Gc: Global clear-sky irradiance on a fixed plane (W/m2)

DNI: Direct normal irradiance (W/m2)

DNIc: Clear-sky direct normal irradiance (W/m2)

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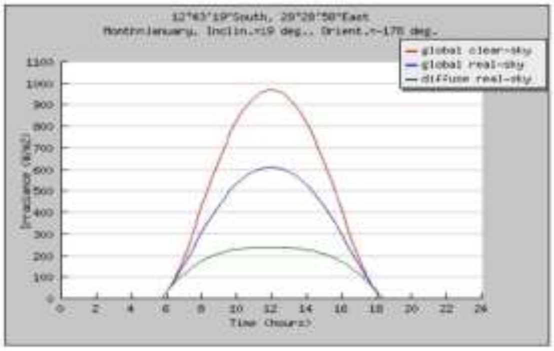
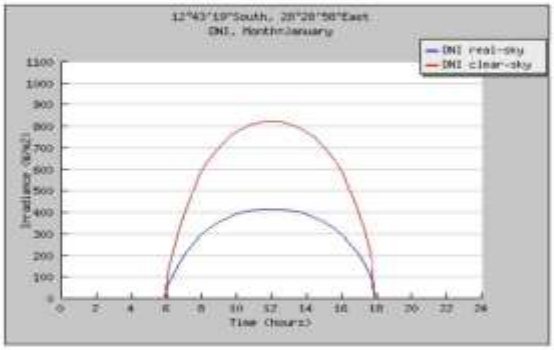
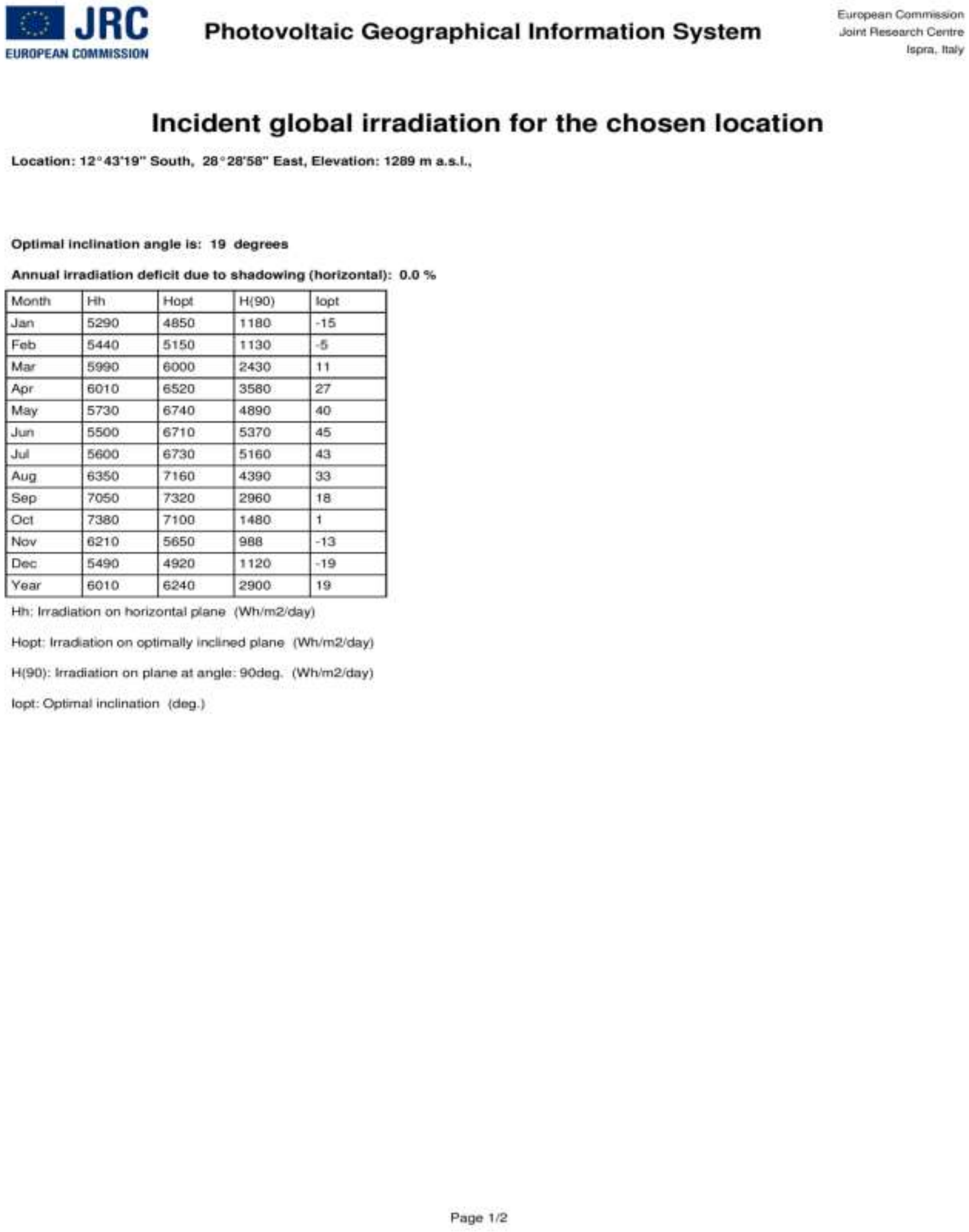


Daily Irradiance on a fixed plane



Direct normal irradiance

ANNEX 2: MONTHLY IRRADIATION



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Incident global irradiation for the chosen location

Location: 12°43'19" South, 28°28'58" East, Elevation: 1289 m a.s.l.,

Optimal inclination angle is: 19 degrees

Annual irradiation deficit due to shadowing (horizontal): 0.0 %

Month	Hh	Hopt	H(90)	Iopt
Jan	5290	4850	1180	-15
Feb	5440	5150	1130	-5
Mar	5990	6000	2430	11
Apr	6010	6520	3580	27
May	5730	6740	4890	40
Jun	5500	6710	5370	45
Jul	5600	6730	5160	43
Aug	6350	7160	4390	33
Sep	7050	7320	2960	18
Oct	7380	7100	1480	1
Nov	6210	5650	988	-13
Dec	5490	4920	1120	-19
Year	6010	6240	2900	19

Hh: Irradiation on horizontal plane (Wh/m2/day)

Hopt: Irradiation on optimally inclined plane (Wh/m2/day)

H(90): Irradiation on plane at angle: 90deg. (Wh/m2/day)

Iopt: Optimal inclination (deg.)

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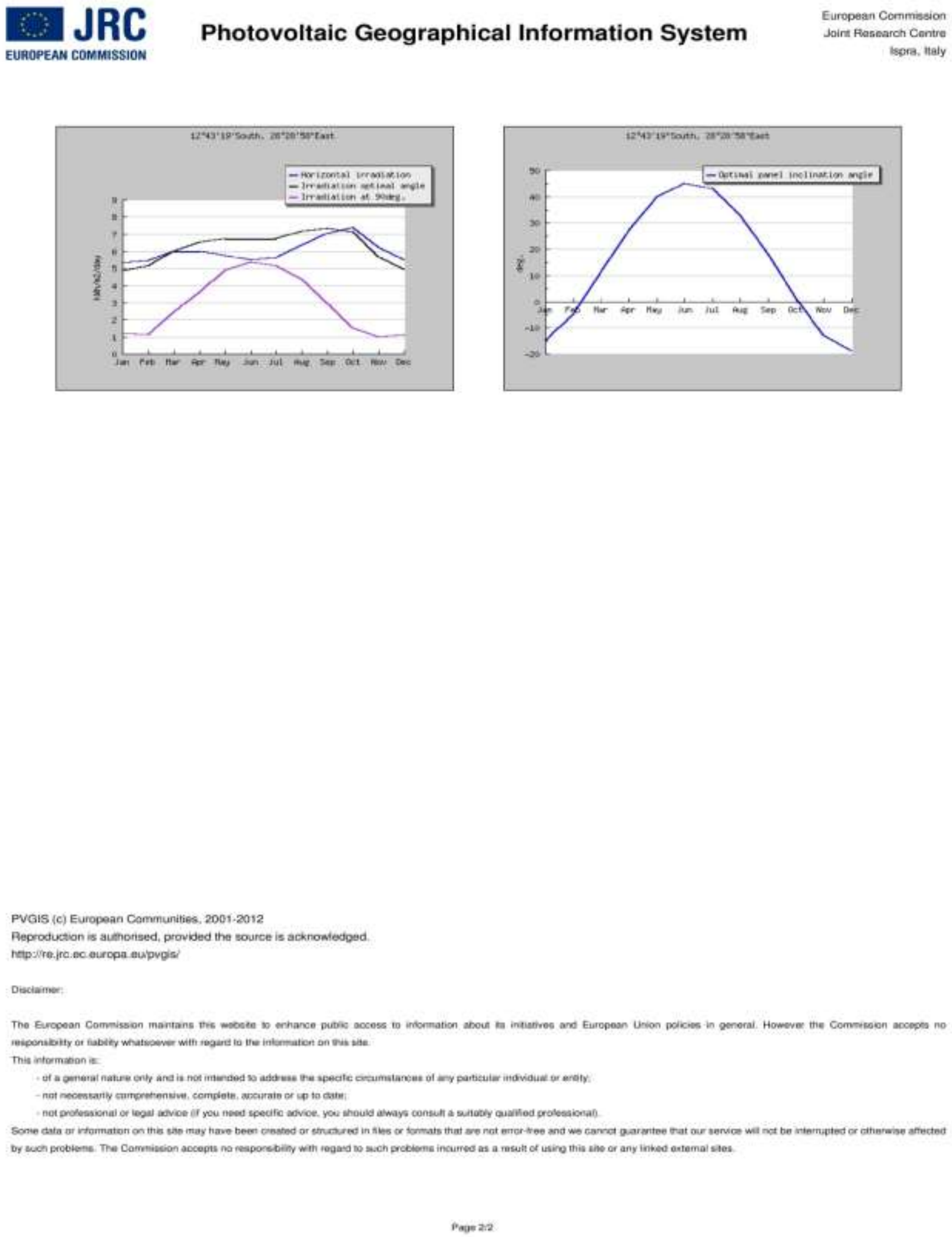
ANNEX 4



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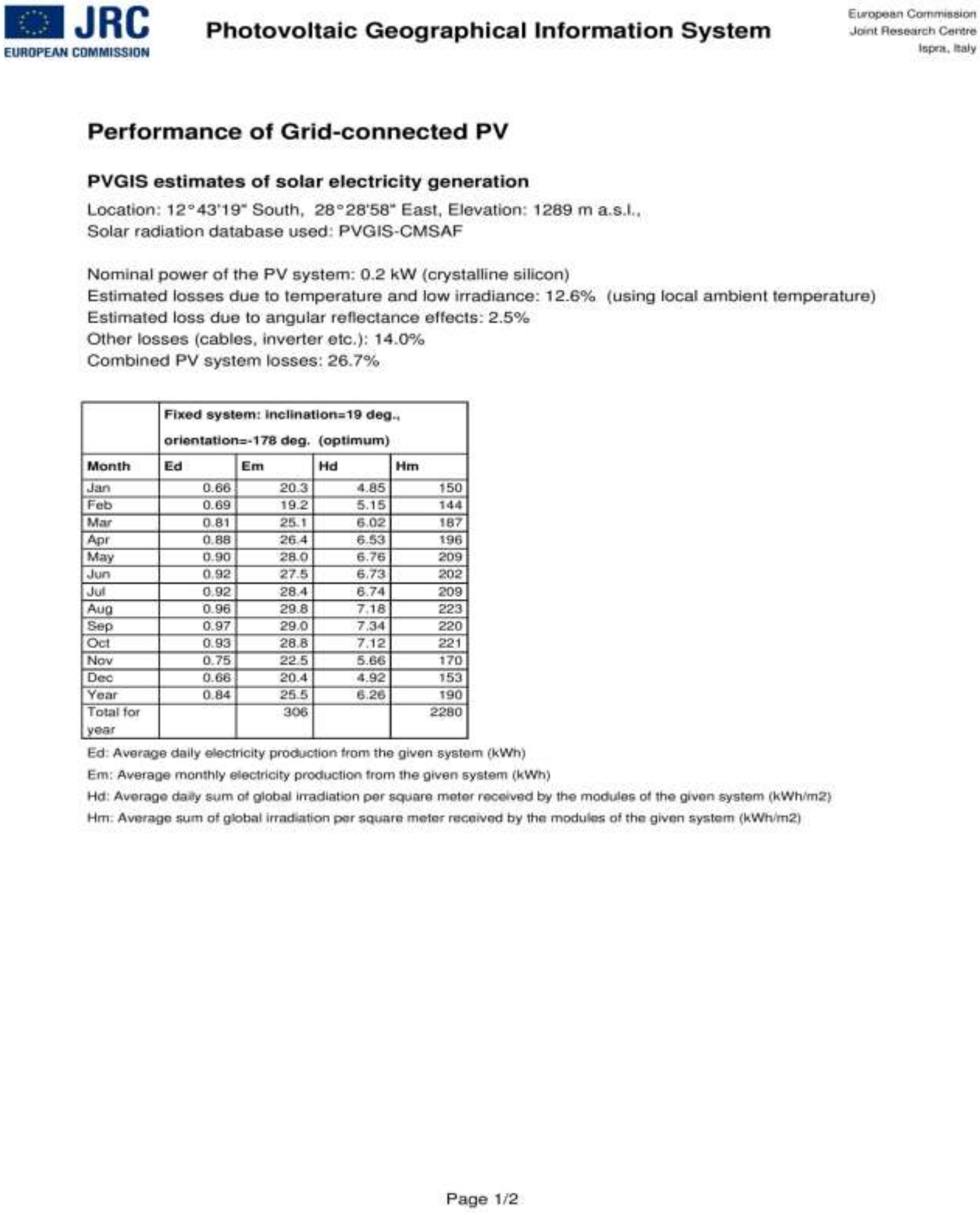
ANNEX 3: MOUNTING INFORMATION



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Performance of Grid-connected PV

PVGIS estimates of solar electricity generation

Location: 12°43'19" South, 28°28'58" East, Elevation: 1289 m a.s.l.,
Solar radiation database used: PVGIS-CMSAF

Nominal power of the PV system: 0.2 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 12.6% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 2.5%
Other losses (cables, inverter etc.): 14.0%
Combined PV system losses: 26.7%

	Fixed system: inclination=19 deg., orientation=-178 deg. (optimum)			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	0.66	20.3	4.85	150
Feb	0.69	19.2	5.15	144
Mar	0.81	25.1	6.02	187
Apr	0.88	26.4	6.53	196
May	0.90	28.0	6.76	209
Jun	0.92	27.5	6.73	202
Jul	0.92	28.4	6.74	209
Aug	0.96	29.8	7.18	223
Sep	0.97	29.0	7.34	220
Oct	0.93	28.8	7.12	221
Nov	0.75	22.5	5.66	170
Dec	0.66	20.4	4.92	153
Year	0.84	25.5	6.26	190
Total for year		306		2280

Ed: Average daily electricity production from the given system (kWh)
Em: Average monthly electricity production from the given system (kWh)
Hd: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2)
Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

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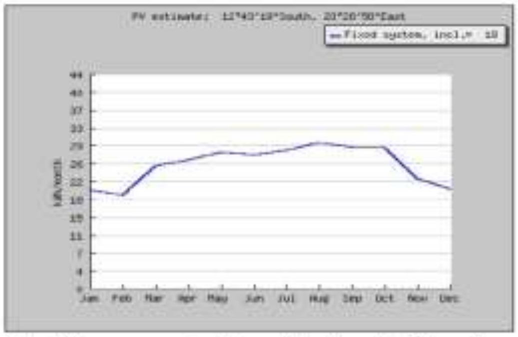
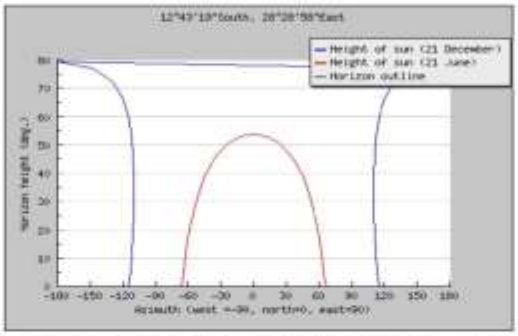


Monthly energy output from fixed-angle PV system

Monthly in-plane irradiation for fixed angle



Outline of horizon with sun path for winter and summer solstice

http://re.jrc.ec.europa.eu/pvgis/

ANNEX 4: INJECTION VIEW OF SOLAR POWER PLANT ON FRONTIER DRAWINGS