



ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF MECHANICAL ENGINEERING

**MODELLING OF PHOTO VOLTAIC SOLAR PANEL FOR CONSTANT
ELECTRIC LOAD UNDER WEATHER CONDITION OF JIGJIGA**

A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of
Masters of Thermal Engineering

By

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ADDIS ABABA UNIVERSITY SCHOOL OF GRADUATE STUDIES

**ADDIS ABABA INSTITUTE OF TECHNOLOGY SCHOOL OF
MECHANICAL AND INDUSTRIAL ENGINEERING**

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Student's declaration

I hereby declare that the work which is being presented in this thesis entitled "Modeling of Photo Voltaic Solar Panel for Constant Electric Load under Weather Condition of Jigjiga" is original work of my own, has not presented for a degree in any other university. I have fully cited and referenced all materials that are not original to this thesis work.

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CERTIFICATION

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Abstract

This paper presents simulation of a typical PV panel (which is Kyocera 200GT) for constant electric loads (which are 2Ω , 4Ω , 6Ω , and 8Ω) under weather condition of a tropical region. The specific case of the city Jigjiga (9.35°N , 42.8°E), located in the Eastern region of Ethiopia is considered. Electrical characteristics of the PV module are determined on the basis of detailed numerical algorithm, which was designed based on tested numerical technique from reviewed articles. The thesis starts from modeling electrical characteristics of the PV devices by taking the manufacturers data sheet or specification as input based on a single diode PV model, including the effect of the series and parallel resistances. The result is accurate and can be validated with experimental results.

An optimum tilt angle that improves the annual performance of the PV panel is calculated; and every analysis of the PV system is carried on the optimum angle. Parallely, radiation flux improvement on the PV module, due to the fixing of the PV panel to its optimum angle is analyzed for different months.

The overall evaluation of the hourly variation in the electrical performance of the PV module is done by means of graphical technique, which determines the operating point of the PV module on voltage versus current plane for each load. Hourly variation in electrical performance of the PV module (i.e. current, voltage, and power output) compared for different days under 2Ω electric load. Finally, power and energy output of the PV panel is compared for each load. The 4Ω electric load resulted a best operating performance of the PV panel on a daily basis for 11 days of the month of January (out of 12 days on which measurements are taken for the month), but in the last day it resulted a poorer performance with respect to the other two electrical loads (i.e. 6Ω and 8Ω electric loads). Hence it is concluded that every weather condition doesn't favor a single load all the time, hence to select a single electric load for a PV panel for its optimized operation at a specific weather condition or site, the same type of analysis shall be done on annual basis.

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List of nomenclature

$\eta_{mp,STC}$	the maximum power point efficiency under standard test conditions [%]
$T_{C, STC}$	the cell temperature under standard test conditions [25°C]
$G,$	the solar radiation incident on the PV array in the current time step [W/m ²]
G,STC	the incident radiation at standard test conditions [1 000 W/m ²]
T_c	PV cell temperature in the current time step [C ⁰]
$T_{C,STC}$	The PV cell temperature under standard test conditions [25 °C]
$T_{c,NOCT}$	The nominal operating cell temperature [°C]
$T_{a,NOCT}$	The ambient temperature at which the NOCT is defined [20°C].
$G_{n,NOCT}$	The solar radiation at which the NOCT is defined [800W/m ²]
G	The solar radiation striking the PV array [W/m ²]
T_a	The ambient temperature [°C]
θ_z	The zenith angle [°]
θ	angle of incidence [°]
ϕ	the azimuth of the surface [°]
L	The latitude [°]
δ	The solar declination [°]
H	The hour angle [°]
G_n	The extraterrestrial normal radiation [W/m ²]
N	The day of the year
G_H	The extraterrestrial normal radiation [W/m ²]:
$G_{on},$	The extraterrestrial horizontal radiation [W/m ²]
β	The slope /tilt angle of the surface [°]

List of abbreviations and acronyms

PV	Photovoltaic
CO ₂	Carbon monoxide

KWh	Kilo Watt Hour
GHG	Greenhouse gas
AC	Alternating current
DC	Direct current
MPPT	Maximum Power Point Tracking
A_m	Area of solar panel module
AST	Apparent Solar Time
a	Diode ideality constant
C	Sky diffuse factor
E	Energy
E_g	Band gap Energy
ET	Equation of time
N	Day of a year
N_s	Number of solar arrays in series
P	Power
q	Electron charge
R	Resistance
R_B	Beam radiation tilt factor
V	Voltage

Subscripts

a	Ambient
A_v	Average
B	Beam

<i>BH</i>	Beam horizontal
<i>Bt</i>	Beam tilt
<i>DH</i>	Diffuse on horizontal
<i>Dt</i>	Diffuse tilt
<i>H</i>	Horizontal
<i>m</i>	Module
<i>max</i>	Maximum
<i>mpp</i>	Maximum power point
<i>n</i>	Nominal
<i>NOCT</i>	Nominal Operating Cell Temperature
<i>Oc</i>	Open circuit
<i>P</i>	Parallel
<i>PV</i>	Photovoltaic
<i>Rt</i>	Reflected on tilt
<i>s</i>	Series
<i>sc</i>	Short circuit
<i>t</i>	Tilt

CHAPTER ONE

1.1. Introduction

Renewable energy systems have beneficial impact on the environmental, economic, and political issues of the world [1]. According to Johanson et al. [2], by the middle of the 21st century, renewable energy sources could account for three fifths of the world's electricity market and two fifths of the market for fuels used directly. Moreover, making a transition to a renewable energy-intensive economy would provide environmental and other benefits not measured in standard economic terms. It is predicted that by 2050 global carbon dioxide (CO₂) emissions would be reduced to 75% of their 1985 levels, provided that energy efficiency and renewable are widely adopted.

Solar systems, including solar thermal and photovoltaics, offer better environmental advantages over electricity generation using conventional energy sources. The benefits arising from the installation and operation of solar energy systems fall into two main categories: environmental and socio-economic issues. From an environmental point of view, the use of solar energy technologies has several positive implications that include: reduction of the emission of greenhouse gases (mainly CO₂, NO_x) and of toxic gas emissions (SO₂, particulates), recovery of degraded land, reduced requirement for transmission lines within the electricity grid and improvement in the quality of water resources [3-5,7-9]. The socio-economic benefits of solar technologies include: increased regional and national energy independence, creation of employment opportunities [4-5], acceleration of electrification of rural communities in isolated areas and diversification and security (stability) of energy supply [4-6].

Photovoltaic systems sometimes called solar cells have found widespread application because they are simple, compact, and have high power-to weight ratio[10]. PV cell behaves more like a current source than a voltage source. Which means while the current output of the PV cell increases with an increase in solar insolation, the voltage output will remain constant irrespective to a variation in solar insolation [11], and this information is valuable in sizing PV panel for specific application.

The output characteristics of PV cell depends mainly on the solar insolation, the cell temperature and output voltage of PV cell. Variations in solar irradiance and temperature will nonlinearly affect the current–voltage output characteristics of the array, and the current–voltage curve will move and deform depending on irradiance level and temperature. Consequently, the power curve for the array will shift and deform [12].

1.2. Back ground

1.2.1. Photovoltaic History

The history of photovoltaic materials started in 1839 when a French physicist, Alexander Edmund Becquerel, discovered the photo-galvanic effect (Anani, 2013)[13]. He observed that electric currents were produced from light induced chemical reactions. Few decades later, other scientists were noticed similar effects in solid “selenium”. However, the first solar cell has been developed with an efficiency of 6% at the late 1940s. The first use of the PV cell was to power a satellite in 1958 and they are still used to power some spacecraft and satellites. Table-1 below provides a short summary about the development of the PV cells (Chaar et. al., 2011)[14].

Table-1-1: Dates of relevance to photovoltaic solar energy development.

Scientist and innovation	year
Becquerel discovers the photovoltaic effect.	1839
Adams and Day notice photovoltaic effect in selenium.	1876
Planck claims the quantum nature of light.	1900
Wilson proposes Quantum theory of solids.	1930
Mott and Schottky develop the theory of solid-state rectifier (diode).	1940
Bardeen, Brattain and Shockley invent the transistor.	1949
Charpin, Fuller and Pearson announce 6% efficient silicon solar cell.	1954
Reynolds et al. highlight solar cell based on cadmium sulphide.	1954
First use of solar cells on an orbiting satellite Vanguard 1.	1958

1.2.2. Solar Energy Usage

The sun is mankind's most abundant renewable energy source. The amount of solar radiation that strikes a position on the Earth depends on geographical location, local landscape, weather, the time of the year, and the time of the day. Radiation received by a surface will have two components, one of which is called a direct source. It is dependent on the distance the solar radiation has to travel through atmosphere. The second radiation component is called diffuse radiation, and this component comes from solar radiation that diffuses through clouds and dust in the atmosphere. A depiction of the two radiation components is shown in Figure 1.1

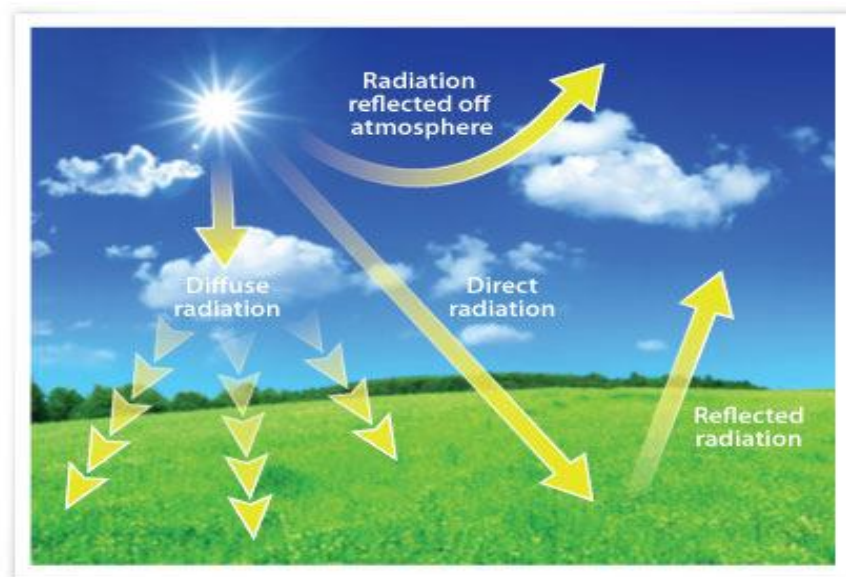


Figure 1.1 : Radiation components.

The sun is the only star of our solar system located at its center. The earth and other planets orbit the sun. Energy from the sun in the form of solar radiation supports almost all life on earth via photosynthesis and drives the earth's climate and weather.

About 74% of the sun's mass is hydrogen, 25% is helium, and the rest is made up of trace quantities of heavier elements. The sun has a surface temperature of approximately 5500 K, giving it a white color, which, because of atmospheric scattering, appears yellow. The sun generates its energy by nuclear fusion of hydrogen nuclei to helium. Sunlight is the main source of energy to the surface of the earth that can be harnessed via a variety of natural and synthetic processes. The most important is photosynthesis, used by plants to capture the energy of solar

radiation and convert it to chemical form. Generally, photosynthesis is the synthesis of glucose from sunlight, carbon dioxide, and water, with oxygen as a waste product. It is arguably the most important known biochemical pathway, and nearly all life on earth depends on it.

Basically, most of the energies, which exist in different forms, come from solar power. For instance, oil, coal, natural gas, and wood were originally produced by photosynthetic processes, followed by complex chemical reactions in which decaying vegetation was subjected to very high temperatures and pressures over a long period of time. Even wind energy and tide are caused by uneven heating of the earth by the sun.

Since prehistory, the sun has dried and preserved humankind's food. It has also evaporated seawater to yield salt. From then people realized that a good use of solar energy is beneficial. The greatest advantage of solar energy compared with other forms of energy is that it is clean, so can be supplied without environmental pollution. Over the past century, fossil fuels provided most of the energy, because they were much cheaper and more convenient than energy from alternative energy sources, and until recently, environmental pollution has been of little concern.

The sun's energy has been used by both nature and human kind throughout time in thousands of ways, from growing food to drying clothes; it has also been deliberately harnessed to perform a number of other jobs. Solar energy is used to heat and cool buildings (both actively and passively), heat water for domestic and industrial uses, heat swimming pools, power refrigerators, operate engines and pumps, desalinate water for drinking purposes, generate electricity, for chemistry applications, and many more operations[15].

1.2.3. Photovoltaic Cell

A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be photovoltaic. A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it. If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current. The driving force to power photovoltaics comes from the sun, and it is interesting to note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand.

The history of photovoltaic's (PVs) began in 1839 when a 19-year-old French physicist, Edmund Becquerel, was able to cause a voltage to appear when he illuminated a metal electrode in a weak

electrolyte solution (Becquerel, 1839). Almost 40 years later, Adams and Day were the first to study the photovoltaic effect in solids (Adams and Day, 1876). They were able to build cells made of selenium that were 1% to 2% efficient. Selenium cells were quickly adopted by the emerging photography industry for photometric light meters; in fact, they are still used for that purpose today.

In 1920s in what would turn out to be a cornerstone of modern electronics in general, and photo voltaics in particular, a Polish scientist by the name of Czochralski began to develop a method to grow perfect crystals of silicon. By the 1940s and 1950s, the Czochralski process began to be used to make the first generation of single crystal silicon photovoltaics, and that technique continues to dominate the photovoltaic (PV) industry today.

In the 1950s there were several attempts to commercialize PVs, but their cost was prohibitive. The real emergence of PVs as a practical energy source came in 1958 when they were first used in space for the Vanguard I satellite. For space vehicles, cost is much less important than weight and reliability, and solar cells have ever since played an important role in providing onboard power for satellites and other space craft. Spurred on by the emerging energy crises of the 1970s, the development work supported by the space program began to pay off back on the ground.

By the late 1980s, higher efficiencies and lower costs brought PVs closer to reality, and they began to find application in many off grid terrestrial applications such as pocket calculators, off-shore buoys, highway lights, signs and emergency call boxes, rural water pumping, and small home systems. While the amortized cost of photovoltaic power did drop dramatically in the 1990s, a decade later it is still about double what it needs to be to compete without subsidies in more general situations. By 2002, worldwide production of photo voltaic had approached 600 MW per year and was increasing by over 40% per year (by comparison, global wind power sales were 10 times greater). Photovoltaic use semiconductor materials to convert sunlight into electricity.

The technology for doing so is very closely related to the solid-state technologies used to make transistors, diodes, and all of the other semiconductor devices that we use so many of these days. The starting point for most of the world's current generation of photovoltaic devices, as well as almost all semiconductors, is pure crystalline silicon [16].

1.2.4. Photovoltaic Arrays

The PV cell generates small voltage around 0.5 to 0.6V. In order to make a PV module or panel obtain higher voltage, current and power, solar cells can be connected in series and parallel configuration. The number of cells connected in parallel determines the output current of the panel, while the number of cells connected in series determines the panel output voltage (Anani, 2013)[13].

In series configuration a bypass diodes are used to limits the voltage across the shaded PV cell. As shown on figure-3 below, when the bypass diode conduct, it will allow the current from the non- shaded cells to flow to the external circuit. Therefore, the maximum reverse voltage across the shaded cell is going to be reduced to about a single diode drop, so that larger voltage differences cannot arise in the reverse current direction across the cell (Alternative Energy Tutorials,2013)[17].

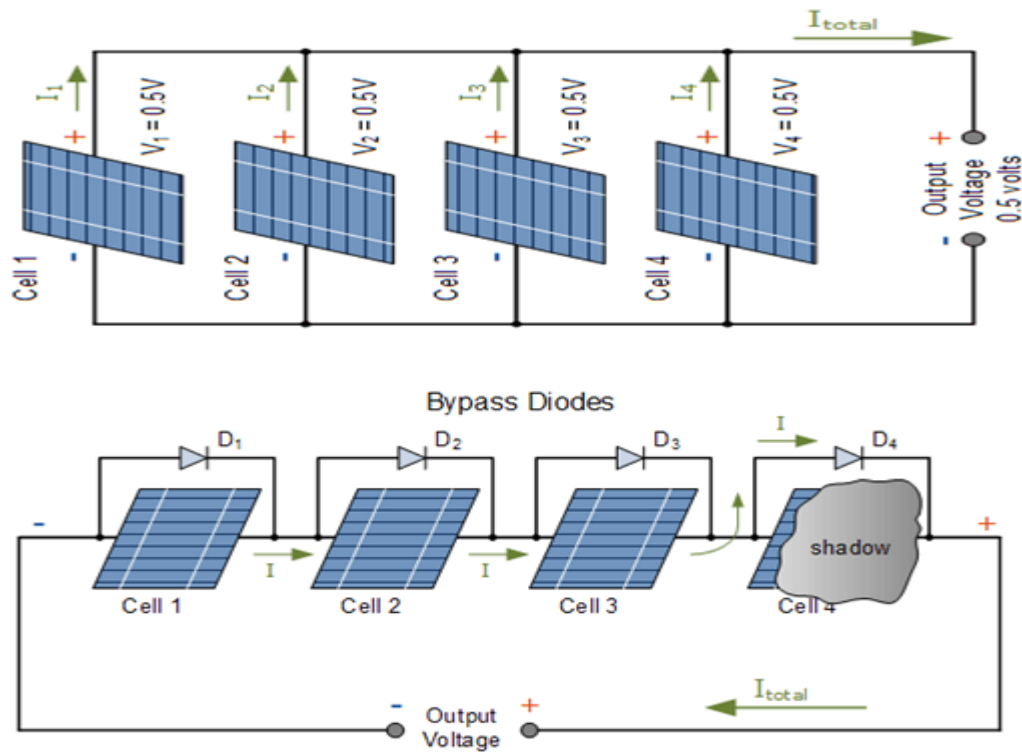


Figure 1.2. PV arrays parallel and series configuration

1.2.5. Photovoltaic Characteristics

Three parameters that are very important in classifying the PV characteristics of a solar cell are the short circuit current (I_{sc}), the open circuit voltage (V_{oc}), and the maximum power point

(I_{mp} , V_{mp}). The short circuit current is the maximum current that can be delivered by the PV cell. The open circuit voltage is the maximum voltage that can be delivered by the PV cell. The maximum power point of the current voltage curve (IV curve) is the operating point at which the PV cell is delivering its maximum power. The values for I_{mp} and V_{mp} are typically less than I_{sc} and V_{oc} .

1.2.6. Photovoltaic Cell Construction

A typical photovoltaic cell is constituted of two separate layers of semiconductor, usually silicon, tightly bonded together as shown in figure-2. N-type is the silicon layer that has excess electrons and P-type is the silicon layer with has excess holes. Sandwiching these layers together generates a PN junction, which is creating an electric field. The free electrons in the N-type material will cross into the P-type material, attempting to fill the electron holes. During this process, the semiconductors layers act as a battery, creating an electric field at the surface where they meet, called "junction". Since holes are move in the opposite direction toward the positive surface. The generated electric field will be in the opposite direction of the natural diffusion. In balance, the current through the PN junction is null (Hecktheuer et. al., 2002)[18].

The "photovoltaic effect" is a basic physical process that converts the sunlight or light into electricity. Light is composed of photons, which are containing various amounts of energy corresponding to the different wavelengths of the solar spectrum. When light (photons) strikes the PV cell surface, some electrons absorb the energy of the photons. In this case, electron will be able to escape from it normal position to become part of the electrical circuit current, which can drive through an external load (Hecktheuer et. al., 2002).[18]

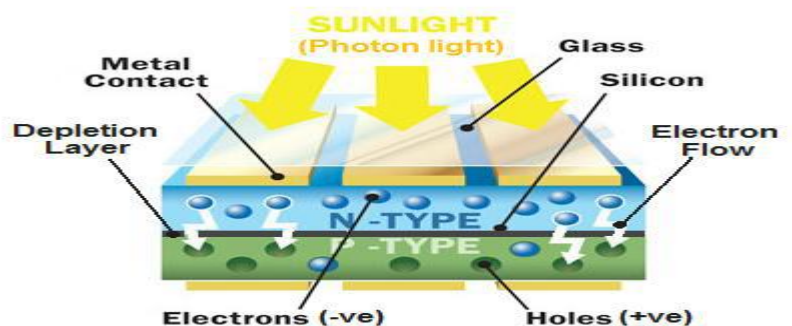


Figure-1.3 : Construction of a PV Cell

1.2.7. Crystalline Materials

1.2.7.1 Mono-Crystalline Silicon

Mono-crystalline silicon has been used for manufacturing solar cells since Bell labs developed this technology in 1954[19] . Two reasons for silicon's success are its material properties and economic timing. Silicon is attractive because it has good stability and adequate electronic, physical, and chemical properties. The stability in particular allows this technology to have a lifespan of approximately 25 years. Economic timing influenced the success of mono crystalline silicon because silicon based technology was already successful in microelectronics, a massive industry.

1.2.7.2. Poly-Crystalline Silicon

This technology is currently the most dominant PV technology. Polycrystalline silicon cells are less expensive to produce, easier to assemble, less sensitive to silicon impurities, less wasteful in production, and only slightly less efficient than single-crystal silicon solar cells. The inexpensive assembly of polycrystalline cells is easier than lower efficiency. While energy needs may require more polycrystalline PV cells than mono-crystalline PV cells, it would be less expensive to purchase the larger number of poly-crystalline cells than the mono-crystalline cells.

1.2.8. Classification of PV Cell

1.2.8.1. Single Layer PV Cell

The simplest organic photovoltaic cell is the single layer PV. The cell is made up of three components: an anode (made of materials such as indium tin oxide (ITO) coated glass), the organic electronic material, and a cathode layer of aluminum, magnesium, or calcium. They are typically arranged by having the high work function anode on top, followed by the organic electronic material in the middle, and the low work function cathode on bottom.

The typical electrical output of single layer OPV cells shows that they have low quantum efficiencies (usually less than 1%) and low power conversion efficiencies (<0.1%). A major problem with this configuration is the electric field created from the difference between the two conductive electrodes. This electric field is rarely sufficient to divide the photo generated excitons. As a result, layer of electric field electron-hole recombination occurs before the charged particles can reach their intended electrode.

1.2.8.2 Bi layer PV Cell

The bi layer cell uses the same electrodes as the single layer PV cell but utilizes the differences between the two organic materials by taking advantage of their electron affinities and ionization energies. The layer with higher electron affinity and ionization potential is the electron acceptor, and the other layer is the electron donor.

These layers generate electrostatic forces at their boundary. Bi layer PV materials must be chosen so that the properties of the materials have unequal band gaps that generate a strong electric field which can divide excitons more efficiently than in the single layer PVs.

1.2.8.3 Bulk Hetero Junction PV Cell

The polymer thickness and the small diffusion length of the excitons need to be optimized to improve the efficiency of the bi layer PVs. This can be achieved by forming a polymer blend of the electron donor and acceptor. The resulting architecture is called bulk hetero junction. This structure allows for the polymer blend length to become similar to the exciton diffusion length. This would allow the excitons generated in either material to reach the interface where excitons can break efficiently. This hetero junction has an increased efficiency compared to the bi layer PVs. The slight disadvantage to this PV configuration is electrons or holes may become trapped in “islands” of active layer without making their way to their designated electrodes. This creates the absence of an electron, or the absence of a hole, in the material that needs to be filled by the next exciton that diffuses in range of this “island.” This slows down the charge separation leading to lower device efficiencies.

The technology for doing so is very closely related to the solid-state technologies used to make transistors, diodes, and all of the other semiconductor devices that we use so many of these days. The starting point for most of the world’s current generation of photovoltaic devices, as well as almost all semiconductors, is pure crystalline silicon. It is in the fourth column of the periodic table, which is referred to as Group IV. Germanium is another Group IV element, and it too is used as a semiconductor in some electronics. Other elements that play important roles in photo voltaics are boldfaced. As we will see, boron and phosphorus, from Groups III and V, are added to silicon to make most PVs. Gallium and Arsenic are used in GaAs solar cells, while cadmium and Tellurium are used in CdTe cells. Silicon has 14 protons in its nucleus, and so it has 14 orbital electrons as well. As shown in Fig. 1.4 a, its outer orbit contains four valence electrons—that is, it is tetravalent. Those valence electrons are the only ones that matter in electronics, so it

is common to draw silicon as if it has a +4 charge on its nucleus and four tightly held valence electrons, as shown in Fig. 1.4b.

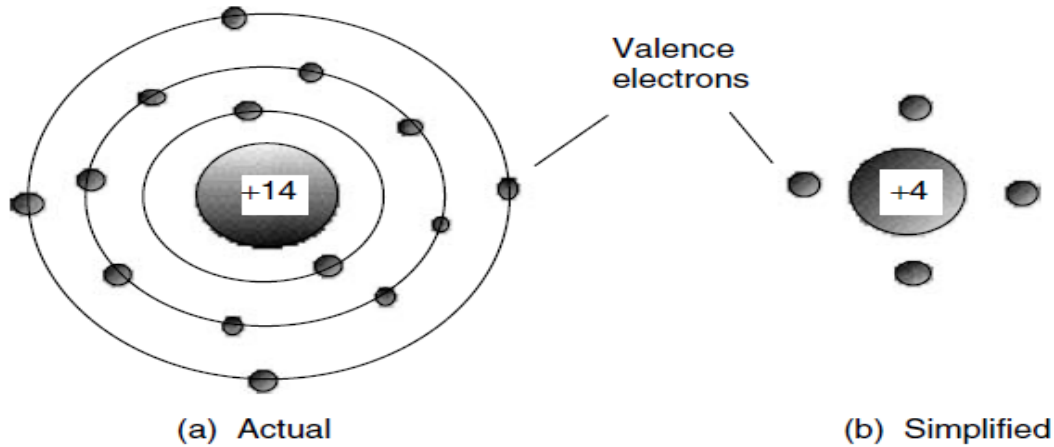


Figure. 1.4. Silicon has 14 protons and electrons as in (a). Convenient shorthand is drawn in (b), in which only the four outer electrons are shown, spinning around a nucleus with a +4 charge.

In pure crystalline silicon, each atom forms covalent bonds with four adjacent atoms in the three-dimensional tetrahedral pattern shown in Fig. 1.4 [16].

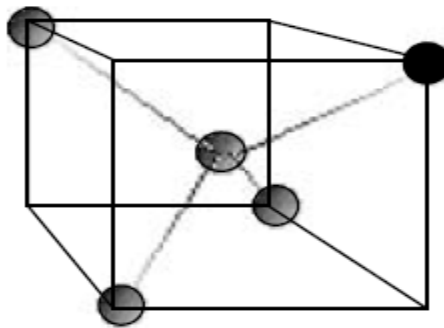


Figure. 1.5. Crystalline silicon forms a three-dimensional tetrahedral structure

Semiconductors can change their electrical properties and degree of conduction by the addition of impurities. The procedure of adding impurities to a semiconductor is called doping. The impurities that are used are called dopants. There are two different types of dopants: N-type and P-type. Some of the most common N-type dopants are located in group 15 of the Periodic Table (Nitrogen, Phosphorus, Arsenic, Antimony, and Bismuth). The N-type dopant adds negatively

charged electrons to the semiconductor. Sometimes these dopants are called donors because they donate electrons to the semi conductor.

Phosphorus, arsenic, and antimony are donor dopants in silicon, making it N-type. A donor atom is easily ionized, yielding a free (-ve) electron and leaving behind a positive ion core.

P-type dopants are found in group 13 of the Periodic Table (Boron, Aluminum, Gallium, Indium, and Thallium). These dopants introduce something called holes because they steal electrons from the semiconductor. As a result of these electron deficiencies, the total negative charge is reduced and the holes can be thought of as positive charges.

1.2.9. Distribution of Energy in Sunlight

1.2.9.1. Solar Spectrum

The efficiency of a PV device depends on the spectral distribution of the solar radiation. The Sun is a light source whose radiation spectrum may be compared to the spectrum of a black body near 6000 K. A black body absorbs and emits electromagnetic radiation in all wavelengths. The theoretical distribution of wavelengths of the black body radiation is mathematically described by Planck's law, which establishes the relations and interdependencies of the wavelength (or frequency), the temperature and the spectral distribution of the black body. Fig.1.5 shows the spectral distribution of the black body radiation compared with the extraterrestrial and terrestrial solar radiations.

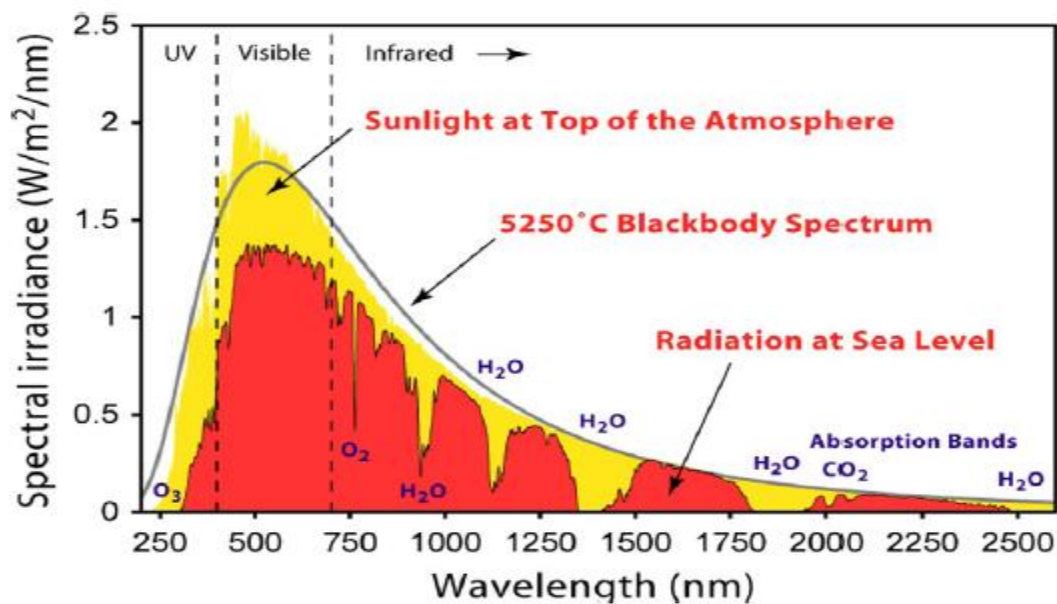


Figure. 1. 6. Solar Spectrums

The study of the effect of the solar radiation on PV devices is difficult because the spectrum of the sunlight on the Earth's surface is influenced by factors such as the variation of the temperature on the solar disc and the influence of the atmosphere. In the extraterrestrial space, at the average distance between the Sun and the Earth, the irradiated solar energy is about 1.353 KW/m². On the Earth's surface, the irradiation is approximately 1 KW/m² (this is a reference value only, as then net irradiation on Earth's surface depends on many factors).

PV devices are generally evaluated with reference to a standard spectral distribution. The American Society for Testing and Materials (ASTM) defines two standard terrestrial spectral distributions: the direct-normal and global AM1.5. The direct-normal standard corresponds to the incident radiation that perpendicularly reaches a Sun-facing surface directly from the Sun. The global or total standard corresponds to the spectrum of the direct and diffuse radiations. Diffuse radiation is the radiation influenced by the atmospheric steam and the reflection on Earth's surface. The AM1.5 standards are defined for a PV device whose surface is tilted at 37° and faces the Sun rays.

The AM initials stand for air mass, which means the mass of air between a surface and the Sun that affects the spectral distribution and intensity of sunlight. The AM_x number indicates the length of the path of the solar radiation through the atmosphere. With longer paths more light deviation and absorption occur. These phenomena change the spectral distribution of the light received by the PV device. The length of the path of the sun rays (given in number of atmospheres) is indicated by the *x* coefficient of AM_x defined as

$$x = \frac{1}{\cos\theta_z} \quad 1.1$$

Where θ_z is the angle of the Sun with reference to the zenith, as shown in Fig.1.3. A bigger *x* corresponds to a longer path and a greater air mass between the Sun and the surface of the terrestrial PV device. The standard AM1.5 distributions correspond to the spectrum of the solar radiation with a solar angle $\theta_z = 48.19^\circ$. Fig.1.6 illustrates the definitions of the AM1.5 path and the direct normal and global radiations.

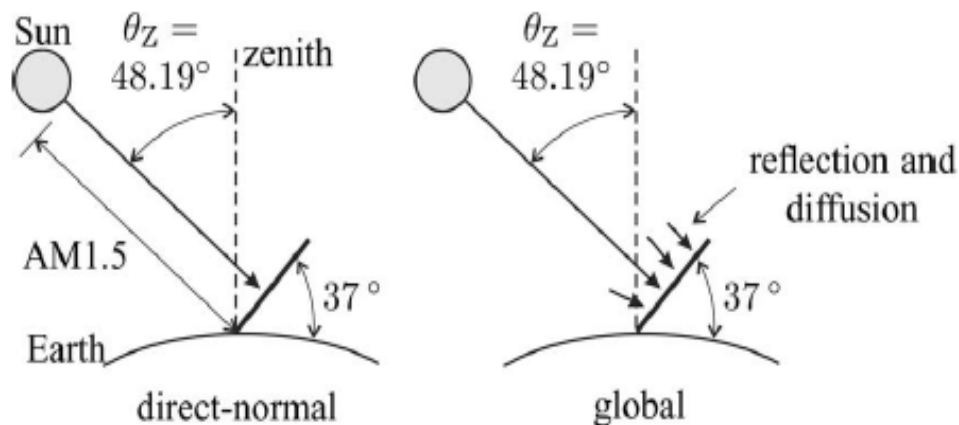


Figure. 1. 7. Illustration of the AM1.5 path and the direct-normal and global incident radiations on a Sun-facing surface at 37° tilt.

The intensity and spectral distribution of the solar radiation depend on the geographic position, time, day of the year, climate conditions, composition of the atmosphere, altitude, and many other factors. Due to the factors that influence the solar radiation, the AM1.5 spectral distributions are only average estimates that serve as references for the evaluation and comparison of PV devices. The AM1.5 distributions are used as standards in the PV industry. Data sheets generally bring information about the characteristics and performance of PV devices with respect to the so-called standard test condition (STC), which means an irradiation of 1000 W/m^2 with an AM1.5 spectrum at 25°C . [1].

1.2.10. General working principles Photovoltaic Cells

PV cells convert sunlight directly into electricity by taking advantage of the photoelectric effect. Cells are constructed from semiconductor materials coated with light-absorbing materials. When photons in sunlight strike the top layer of a PV cell, they provide sufficient energy to knock electrons through the semiconductor to the bottom layer, causing a separation of electric charges on the top and bottom of the solar cell. Connecting the bottom layer to the top with a conductor completes an electrical circuit and allows the electrons to flow back to the top, creating an electric current and enabling the cycle to repeat with more sunlight (Clean Energy Associates). Figure 1.7.illustrates how photovoltaic cells work.

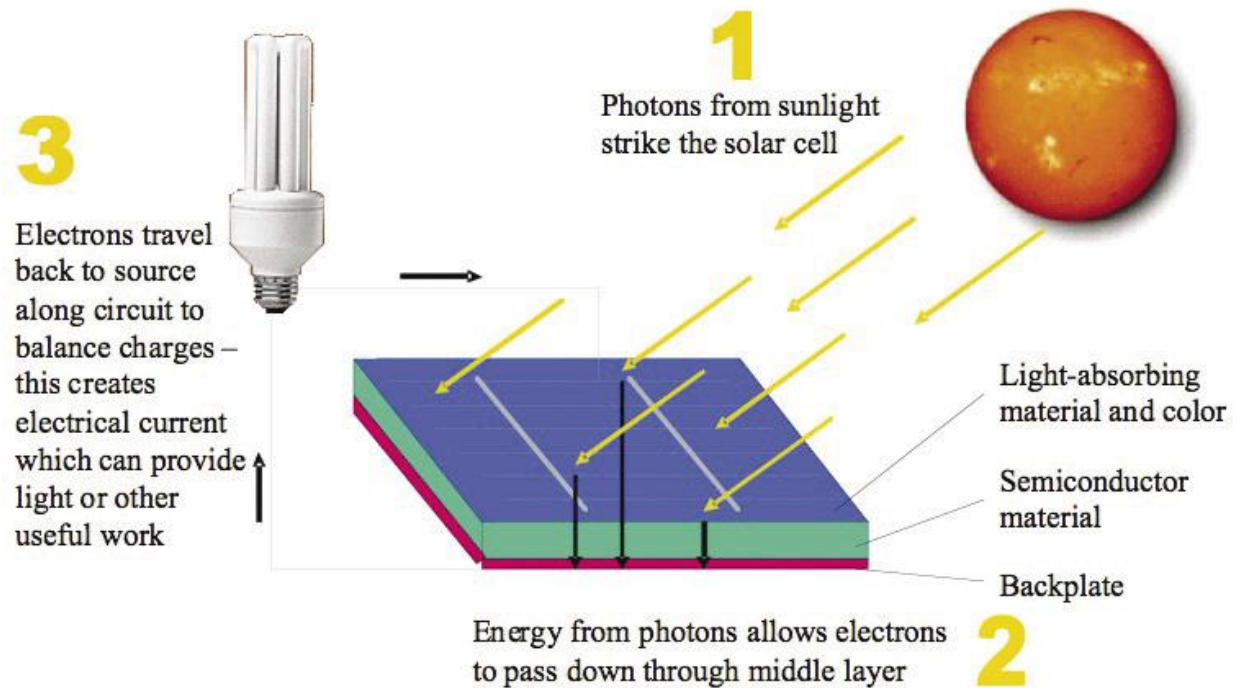


Figure 1.8: How Photovoltaic Cells Work (Clean Energy Associates).

1.2.11. Photovoltaic Cells and Efficiencies

PV cells are made up of semiconductor material, such as silicon, which is currently the most commonly used. Basically, when light strikes the cell, a certain portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely. PV cells have one or more electric fields that act to force electrons that are freed by light absorption to flow in a certain direction. This flowing of electrons is a current and by placing metal contacts on the top and bottom of the PV cell we can draw that current off to be used externally. For example, the current can power a calculator. This current, together with the cell's voltage, which is a result of its built-in electric field or fields, defines the power in watts that the solar cell can produce (Patel, 2006).

There are currently five commercial production technologies for PV cells:

- **Single Crystalline Silicon:** This is the oldest and more expensive production technique, but it's also the most efficient sunlight conversion technology available. Cells efficiency averages between 11% and 16%

- Polycrystalline or Multi-crystalline Silicon: This has a slightly lower conversion efficiency compared to single crystalline and manufacturing costs are also lower. Cells efficiency averages between 10% and 13%. But Kyocera's advanced cell processing technology and automated production facilities have produced multi-crystalline solar cells with efficiencies of over 16.5%.

1.2.12. Photovoltaic Modules

A PV module is composed of interconnected photovoltaic cells encapsulated between a weather-proof covering (usually glass) and back plate (usually a plastic laminate). It will also have one or more protective by-pass diodes. The output terminals, either in a junction box or in a form of output cables, will be on the back. Most have frames. Those without frames are called laminates. In some, the back plate is also glass, which gives a higher fire rating, but almost doubles the weight.

The cells in the modules are connected together in a configuration designed to deliver a useful voltage and current at the output terminals. Cells connected in series increases the voltage output while cells connected in parallel increases the current. A group of several PV modules are connected together are called a solar array.

1.2.13 Photovoltaic Manufactures

Photovoltaic's modules are available in a range of sizes. Those used in grid tied or stand alone systems range from 80W to 300W. The performance of PV modules and arrays are generally rated according to their maximum DC power output (watts) under the Standard

Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25°C (77 F), an incident solar irradiant level of 1000 W/m² and under Air Mass 1.5 spectral distribution. Since these conditions are not always present PV modules and arrays operate in the field with performance of 85 to 90 percent of the STC rating.

Tables 5-1 present the PV modules specification used in this thesis. All the data was taken from the manufacture's data sheet.

1.2.14. Solar resource

Solar energy is available everywhere on Earth, in varying amounts. Solar radiation that reaches the earth's surface in an unbroken line is called *direct*, while sunlight scattered by clouds, dust, humidity and pollution is called diffused. The sum of the direct and diffuse sunlight is called global-horizontal insolation. Concentrating solar technologies, which use mirrors and lenses to

concentrate sunlight, rely on direct radiation, while PV cells and other solar technologies can function with diffused radiation.

Solar radiation provides a huge amount of energy to the earth. The total amount of energy, which is irradiated from the sun to the earth's surface, equals approximately 10,000 times the annual global energy consumption. On average, 1,700 kWh per square meter is insolated every year (Patel, 2006).

The light of the sun, which reaches the surface of the earth, consists mainly of two components: direct sunlight and indirect or diffuse sunlight, which is the light that has been scattered by dust and water particles in the atmosphere. Photovoltaic cells not only use the direct component of the light, but also produce electricity when the sky is overcast. To the average total solar energy received over the year, rather than to refer to instantaneous irradiance. The daily radiation of Somalia region is very high although there are zonal and seasonal variations.

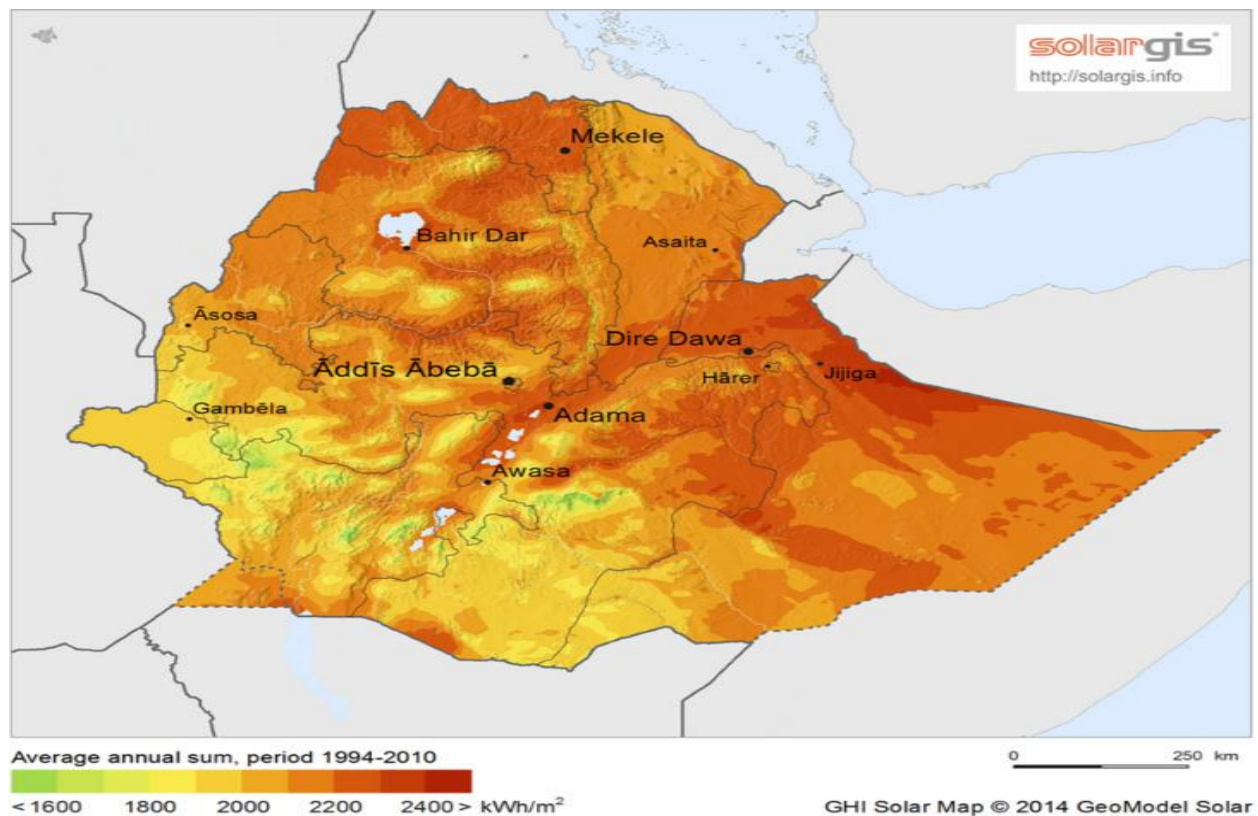


Figure 1.9. Global Horizontal Irradiation of Ethiopia (source-Sun connect news)

In order to capture as much solar energy as possible, the photovoltaic cell must be oriented towards the sun. If the photovoltaic cells have a fixed position, their orientation with respect to the south (northern hemisphere), and tilt angle, with respect to the horizontal plane, should be optimized. For regions nearer to the equator, this tilt angle will be smaller, for regions nearer to the poles it will be larger. A deviation of the tilt angle from the optimum angle, will lead to less power to be capture by the photovoltaic system.

The current study was carried-out in Jigjiga area located on 9.35° latitude and 42.8° longitude coordinate, meaning that the tilt angle for the Jigjiga should be $9^{\circ}.35^{\circ}$ S and 42.8° S.

1.2.15. Storage devices

Stand-alone PV systems or direct coupled PV systems are designed and sized to supply DC and/or AC electrical loads. It is called direct coupled systems because, the DC output of a PV module or array is directly connected to a DC load.

There is no electrical energy storage (batteries) in direct-coupled systems as because of that, the load only operates during sunlight hours. In this study model comprise of solar PV connected directly to a DC- load, as there is no battery bank, this means no energy is stored and is capable of powering common appliances such as fans, pumps among others that are used during the day.

1.3. Problem statement

The current population growths, technological advancement, enhancement in human life standards and comfort levels have resulted in unmatched increase in the energy consumption worldwide. Energy needed to meet these demand is predominantly generated by burning fossil fuels which not only have a limited life but also release harmful gaseous during operation. More specifically, the current energy related problems such as reduction of conventional energy resources, energy supply problems, global warming, air pollution, ozone depletion, forest destruction, emission of radioactive substances and climatic change have urged the necessity for a complete change of energy production, supply and consumption ways.

When a cell is exposed to a solar radiation, a voltage potential builds up across it. Photovoltaic cells are devices that convert light into electricity. Because the source of light (or radiation) is usually the sun, they are often referred to as solar cells. The word photovoltaic comes from “photo” meaning light and “voltaic” means voltage. The output of a photovoltaic cell is direct current (DC) electricity; the generated DC electricity can supply power directly into the utility

grid, stand-alone systems that charge batteries, perhaps with generator back-up, and applications in which the load is directly connected to the PV as is the case for most water-pumping systems. Terrestrial applications of photovoltaic (or any solar) devices are complicated by two variables: the Earth's rotation about its axis and revolution about the Sun and atmospheric effects. The rotation produces hourly variations in radiation intensities (which is one of the two crucial factors that affect the performance of solar panel) at a given location on the ground and completely shades the device during nighttime hours. In addition, a device located in the Northern Hemisphere receives more energy during summer than in the winter, thus giving rise to seasonal variations in power intensities.

Most of previous research papers on solar PV system are concerned only on modelling the electrical characteristics of the PV system using a single diode electrical model, and investigates the effect of environmental parameters, which are radiation intensity and cell temperature on the performance of PV systems. In case of directly coupled PV system the electric load has also an effect on the performance of the PV system. Perhaps, resistor matching technique is one way of optimizing performance of a PV system. In this study, beside the environmental parameters, the effect of electrical loads on the performance of the PV system is investigated on real environmental parameter.

1.4. Research objectives

1.4.1. General Objective

The primary objective of this study, modeling the Photo Voltaic solar panel for constant electric load and determined the effect of load on the performance of PV system on real environment.

1.4.2. Specific Objective

- Modelling variation in instantaneous radiation flux on the PV panel that would be tilted at an angle for optimum performance of the panel.
- Modeling hourly variation of the operating cell temperature of the solar panel which is the key parameter in determining performance of a PV panel.
- Determining instantaneous variation of performance of the PV panel, such as current, voltage, and power output under constant load and under the determined operating condition of the PV panel (that will be radiation flux and cell temperature).

- To simulate a daily variation on electrical performance of a PV panel at constant electric load and determine the effect of electrical loads on the performance of the PV system.
- To predict and evaluate the performance of PV cells within the overall energy harvesting and conversion system in both nominal and various environmental conditions such as temperature fluctuations and manufacturing variations.
- With the outcome of this thesis and further development of the overall model, on PV is expected to predict the electrical characteristics of the new PV cells and assess their electrical performance in the overall system from source to the sink (electrical load).

1.5. Study area

The Federal Democratic Republic of Ethiopia (FDRE) is a landlocked country in the horn of Africa, bounded to the north by Eritrea, to the west by Sudan, to the south by Kenya and to the east by Somalia and Djibouti; it lies within the tropics between 3°24` and 14°53` North; and 32°42` and 48°12` East (see figure 1.9). It covers 1,120,000 square kilometers in nine regional states. The current study was carried-out in Jijiga area located on 9.35° latitude and 42.8° longitude coordinate.

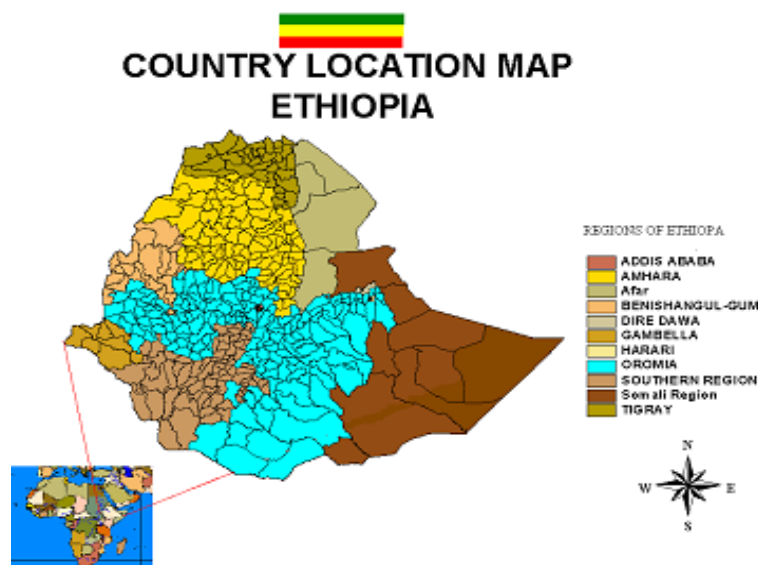


Fig.1.10. location of map [12]

1.6. Research Methodology

The following methods are used to do this thesis work:

- a) Literature survey: - ideas from different books and journals are gathered that helped me to do this work.
- b) Data collection: - the data which are necessary for analysis work collected from Metrology Agency of Ethiopia and manufacturing data sheet.
- c) Computer simulation and data analysis: by the use of ideas and data collected, simulate an hourly variation on electrical performance of a PV panel at constant electric load using Mat-lab Soft Ware.

1.7. Scope and limitation of thesis

1.7.1. Scope of the thesis

The analysis of this research is based on the available metrological data of Jigjiga region, which is provided by Ethiopian National Metrology Agency. The scope of this thesis

- Modeling hourly variation of the operating cell temperature of the solar panel which is the key parameter in determining performance of a PV panel.
- Determining instantaneous variation of performance of the PV panel, such as current, voltage, and power output under constant load and under the determined operating condition of the PV panel (that will be radiation flux and cell temperature).
- Determining the effect of electrical loads on the performance of the PV system is investigated on real environmental parameter.
- With the outcome of this thesis and further development of the overall model, on PV is expected to predict the electrical characteristics of the new PV cells and assess their electrical performance in the overall system from source to the sink.

1.7.2. Limitation of the thesis

The data provided by the Ethiopian National Metrology Agency comprises currently only 12 days data for each month, hence all set of data, which is provided by agency is not sufficiently enough to judge the annual performance of a typical PV module, and to select the optimum size of electric load under which the PV module will operate under its optimum performance.

In this study model comprise of solar PV connected directly to a DC- load, as there is no battery bank, this means no energy is stored. This is limited for judge annual performance characteristics PV model without storage device.

1.8. Significance of the thesis

In this work, a simulated PV model that closely replicates the electrical characteristics of the KYOCERA PV cell is proposed. In addition to the model of the solar cell, a simulation modeling a complete PV system is developed which can account for differing environmental fluctuations such as irradiation and temperature values, as well as different PV technology parameters and different capacity energy storage systems. Due to the quickly evolving technology, the ability to account for various parameters will prove to be tremendously beneficial. This research is fundamental to the expansion of PV technology.

1.9. Structure of thesis

The thesis starts with a review on researches which are conducted on solar panels. Next, modeling of electrical characteristics of a PV panel from manufacturer's data sheet is presented. Hourly variation on operating cell temperature of a PV module discussed followed by data analysis and result and discussion of the electrical performance of a particular PV module.

Briefly the thesis can be summarized as follows.

Chapter one: included solar energy usage and photovoltaic cell, characteristics and classification of photo voltaic cell, how solar cell works, and distribution of energy in sunlight, research problem, research objectives, research methodology, scope and limitation of thesis as well as significance of the research.

Chapter two: reviews similar researches which are conducted on modeling of electrical characteristics of PV panels, as well as researches those focus on modeling of cell operating temperature of solar panels.

Chapter three: described modeling of electrical characteristics of PV device, and the relation between cell operating temperature and efficiency. In addition, the chapter discussed a technique that can determine the operating point of a PV panel on voltage versus current plane.

Chapter four: Included the type and structure of data provided by the Metrology Agency of Ethiopia, a mechanism to sort out this data to a specific date, mathematical derivation to get the optimum tilt angle at which the annual performance of the PV module will be improved,

comparison of the performance of the PV module at its tilt angle to that of horizontal position to prove the improvement of the PV module due to its tilt angle.

Chapter five: discusses the result of the thesis work

Chapter six: Presented the conclusion from the theoretical findings and recommendation for future work.

CHAPTER TWO

2.1. Literature review

Solar energy can be recognized as one of the most promising renewable energy sources. Along with other forms of renewable energy sources, i.e. biomass energy, geothermal energy, wind energy, fuel cell, ocean energy, it has a great potential for a wide variety of applications because of its abundance and accessibility. Direct conversion of solar energy (the energy contained in photons of light) into electricity (an electrical voltage and current) usually refers to a photovoltaic (PV) system.

Marcelo G. V. et al., [19], proposed a method of modeling and simulation of photovoltaic arrays. With The main objective of finding parameters of the nonlinear $I-V$ equation by adjusting (electrical power vs. voltage) curve to find the best $I-V$ equation to single-diode photovoltaic model.

Solar cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted to electricity through a photovoltaic effect. Being exposed to the sunlight, photons with energy greater than band-gap energy (EG) of the semi conductor are absorbed and create some electron-hole pairs proportional to the incident irradiation. Under the influence of the internal electric fields of the p-n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar irradiance. A PV system naturally exhibits non-linear $I-V$ and $P-V$ characteristics which vary with the radiant intensity and cell temperature [20].

PV system use semiconductor materials to convert sunlight into electricity. The technology for doing so is very closely related to the solid-state technologies used to make transistors, diodes, and all of the other semiconductor devices that we use so many of these days.

PV systems produce DC electricity when sunlight shines on PV solar cell, without any emissions. PV systems, presently is accepted as the most important way to convert solar energy into electricity. According to predictions by many energy experts, photovoltaic electricity will necessarily play a significant role in any sustainable energy future.

The basic component of PV system is the PV cell (solar cell). A simplified equivalent circuit model is used since it is quite simple to implement and is compatible with the electrical behaviour of the actual cell.

The equivalent electric circuit diagram of PV cell is which consists of a photocurrent source, a diode, a parallel resistor (R_{sh}) expressing a leakage current and a series resistor (R_s) describing internal resistance to the current flow [21].

This curve clearly shows that the output characteristics of a PV cell are non-linear and are crucially influenced by solar radiation G , operating cell temperature T_c and load condition R . Each curve has a maximum power point (MPP), at which the solar array operates most efficiently [22].

The future competitiveness of PV depends on many factors, such as technological advances, production volume of PV components, ecological tax on traditional energies, and also on the most judicious use of this new energy technology (especially in advance material aspects). The latter point in particular relates to the performance of PV system generators under site-specific climatic conditions. The question is: What energy output of different generators can be expected under actual operating conditions at climatologically different sites? To answer this question, the physical behavior of solar cells and photovoltaic modules under varying solar illumination and changing climatic conditions needs to be known. Usually these data are not provided by the manufacturers and suppliers of PV products. Moreover, the data provided at Standard Test Conditions (STC) most often are taken under test conditions which never occur in practice [23].

It can be drawn also that climatic conditions (solar irradiance, G and ambient temperature, T_a ,) great affected on the whole operation parameters (mostly electrical) of PV module, which directly affected on PV module performance.

In order to capture as much solar energy as possible, the PV cell must be oriented towards the sun. If the photovoltaic cells have a fixed position, their orientation with respect to the south (for northern hemisphere location), and tilt angle with respect to the horizontal plane, should be optimized.

Solar radiation incident on a solar PV collector is composed of three components, i.e. the direct beam, diffusion and reflection from the ground, which has different dependence on the slope of collector, the sum of these three components is called global radiation. Installing a collector properly can enhance its application benefit because the amount of radiation flux incident upon the collector is mainly affected by the surface orientation i.e. azimuth and tilt angles that it is installed.

In the northern hemisphere, the best azimuth is due south (facing equator), but the tilt angle varies with factors such as the geographic latitude, climate condition, utilization period of time, etc [24].

Generally, the amount of solar radiation that will be intercepted by a surface on the earth, influenced by several factors as follow:

- day of the year (due to tilt of earth),
- geographic location (latitude and longitude),
- time of day (where the sun is in the sky),
- surface orientation,
- Local atmospheric conditions (cloud/fog cover, ambient temperature, wind).

The surface orientation a module with respect to direction of the sun, consisted of two parameters, i.e. tilt and surface azimuth angles, as presented in Fig. 2.1. Tilt angle is the angle between the plane of the module and horizontal. Meanwhile, azimuth angle is between plane of module and due South (due North).

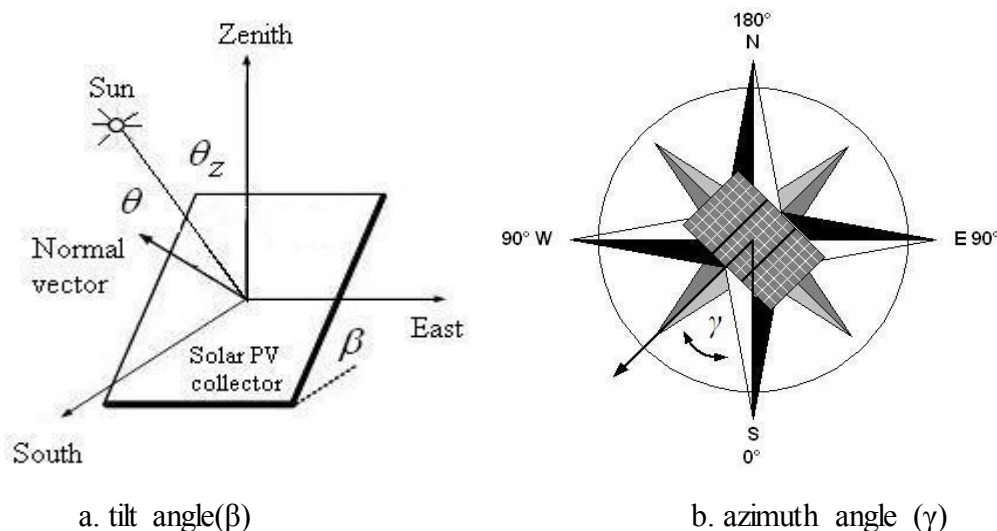


Figure 2.1 definition of surface orientation.

In order to get the optimum surface orientation, several literatures [25] reported that for the Northern hemisphere, the optimum orientation is south facing and the optimum tilt angle depends only on the latitude. It is generally accepted that for low latitudes, the maximum annual output is obtained when the array tilt angle is roughly equal to the latitude angle and the array

faces due south (in the northern hemisphere) or due north (for the southern hemisphere). For higher latitudes, such as those in northern Europe, the maximum output is usually obtained for tilt angles of approximately the latitude angle minus 10-15 degrees.

Many studies have been conducted on the electrical characteristics of solar panels. *Vineet S. et al.*, [26], for example, modeled a photovoltaic module with MATLAB/Simulink software, and presented the implementation of generalized photovoltaic model, which can be representative of a PV cell, module or array; hence can be significant in estimating the electrical behavior of the module with respect to change in environmental parameters.

Hamed Tavasoli, et al., [27] simulated the relation between sun radiation and ambient temperature to that of PV module efficiency. Rodolfo Araneo, et al., [28] investigated the suitability and the accuracy of a methodology aimed at estimating the time profile of the cell temperature of a photovoltaic system on the basis of only the monthly mean values of the daily global irradiation on a horizontal surface.

Kumari and Babu [29] have also carried out mathematical modeling and simulation of PV Cell in matlab/simulink Environment to find the parameters of the nonlinear I-V equation by adjusting the curve at three operating conditions: open circuit, maximum power, and short circuit points .

Richhariya and Pachori [30] have designed a user friendly solar cell model with irradiance and cell temperature as input parameters, by using Matlab/simulink and have verified it with a commercial module.

Ramos-Hernanz et.al. (2012) have compared two PV Simulation Models in time domain by using Matlab/simulink, to achieve an I-V curve similar to the manufacturer's data sheet. However, these models have been developed with a large number of assumptions, some of which are even practically unrealistic [31].

Venkateswarlu and Raju [32] the study of photovoltaic systems in an efficient manner requires a precise knowledge of the IV and PV characteristic curves of photovoltaic modules. A Simulation model for simulation of a single solar cell and two solar cells in series has been developed using sim-electronics (mat lab/simulink) environment and is presented here in this paper. A solar cell block is available in sim electronics, which was used with many other blocks to plot I-V and P-V characteristics under variations of parameters considering one parameter variation at a time.

Effect of two environmental parameters of temperature and irradiance variations could also be observed from simulated characteristics.

Bonkougou et al. (2013) this paper presents a photovoltaic (PV) cell to module simulation model using the single-diode five parameter models. The model was implemented in Matlab software and the results have been compared with the data sheet values and characteristics of the PV module in Standard Test Conditions (STC). Parameters values were extracted using Newton Raphson's method from experimental Current (I)-Voltage (V) characteristics of Solar ex MSX60 module. The results obtained are in good agreement with the experimental data provided by manufacturer. The approach can thus, be very useful for researchers or engineers to quickly and easily determine the performance of any photovoltaic module [33].

In case of directly coupled PV system the electric load has an effect on the performance of the PV array. Perhaps, resistor matching technique is one way of optimizing performance of a PV array. The overall objective of this work is to contribute to the optimum utilization of non-tracking PV panels, in such a way that we can match an electric load to a particular PV panel or vice versa so that it can result an optimum working performance of the PV panel under weather condition of specific site.

CHAPTER THREE

3. Modelling electrical characteristics of a PV device

In the last three decades, solar energy has been used as reliable energy for electric distribution. Use of the solar panel is the key component to convert solar energy into electrical energy. Sometimes the use of solar panels can be more practical than the typical solutions for power generation. An example of the last statement is that the solar panels can supply power for the electronic equipment aboard a satellite over a long period of time, which is a distinct advantage over batteries. Applications of solar panels are not restricted to outer space. It is possible to obtain useful power from the sun in terrestrial applications using solar panels, even though the atmosphere reduces the solar intensity. Some examples are in urban distribution, electric drives, solar cars, etc.

Unfortunately, the actual models to describe solar panel performance are more related to physics, electronics and semiconductors than to power systems. Some of the models require several parameters such as the temperature coefficients, photon current, open circuit voltage, series/shunt resistance of the device, etc. Also, some of the required parameters in those models are not available by the manufacturer data sheets so it is required to find the information in other sources. At the same time, these models can be impractical and too complex for common tasks in power systems such as power flow, harmonic analysis, sensitivity analysis, load matching for maximum power transferred from the source to the load, etc. To solve these problems and to maximize the use of information provided by the manufacturer data sheets, this paper proposes a photovoltaic model based on the electrical characteristics, STC and I-V Curves. This model will be more beneficial and practical for different types of power systems analysis [34].

It can be drawn also that climatic conditions (solar irradiance, G and ambient temperature, T_a) great affected on the whole operation parameters (mostly electrical) of PV module, besides the electric load which directly affected on PV module performance on specific weather parameters.

In case of directly coupled PV system the electric load has also an effect on the performance of the PV system. Perhaps, resistor matching technique is one way of optimizing performance of a PV system. In this study, beside the environmental parameters, the effect of electrical loads on the performance of the PV system is investigated on real environmental parameter.

3.1. Solar cell model

3.1.1 Equivalent Circuit Model

To develop an electrical equivalent circuit of an ideal solar cell, one must take into account two factors. First, a solar cell acts as a diode while not illuminated. Second, while illuminated, a solar cell acts as a current source over a wide range of its operating conditions. To account for these two factors, an ideal model shown in Figure 3.1 has been developed. This ideal model consists of a current source in parallel with a diode.

The following figure shows the equivalent circuit of a theoretical PV cell. And the basic equation from the theory of semiconductors that mathematically describes the I - V characteristic of the ideal PV cell is:

$$I = I_{pv} - I_0 \left[\exp\left(\frac{qV}{aKT}\right) - 1 \right] \quad 3.1$$

$$I_d = I_0 \left[\exp\left(\frac{qV}{aKT}\right) - 1 \right] \quad 3.2$$

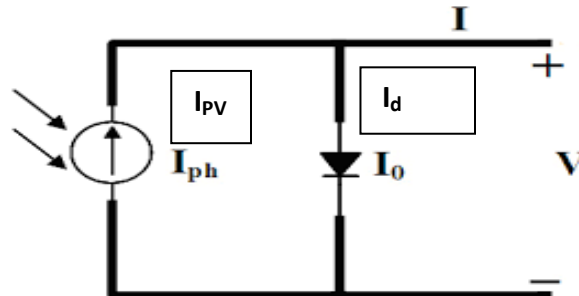


Figure 3.1 Simplified or Ideal equivalent circuit of a PV cell

where I_{pv} is the current generated by the incident light (it is directly proportional to the Sun irradiation), I_d is the Shockley diode equation, I_0 is the reverse saturation or leakage current of the diode, q is the electron charge ($1.60217646 \times 10^{-19}$ C), K is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), T (in Kelvin) is the temperature of the p - n junction, and a is the diode ideality constant.

3.1. 2. Modeling the PV Array

Manufacturers of PV arrays, instead of the $I-V$ equation, provide only a few experimental data about electrical and thermal characteristics. Unfortunately, some of the parameters required for adjusting PV array models cannot be found in the manufacturer’s datasheets, such as the light-generated or PV current, the series and shunt resistances, the diode ideality constant, the diode reverse saturation current, and the band gap energy of the semiconductor. All PV array datasheets bring basically the following information: the nominal open-circuit voltage ($V_{oc,n}$), the nominal short-circuit current ($I_{sc,n}$), the voltage at the Maximum power point (V_{mpp}), the current at Maximum power point (I_{mpp}), the open-circuit voltage/temperature coefficient (K_V), the short circuit current/temperature coefficient (K_I), and the maximum experimental peak output power ($P_{max,e}$). This information is always provided with reference to the nominal condition or standard test conditions (STCs) of temperature and solar irradiation. So, it is necessary to drive the electrical parametric equation (I-V and P-V equation) from the manufacturer’s data sheet.

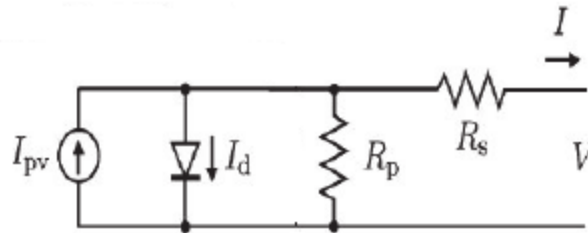


Figure 3.2: Single-diode model of the theoretical of a practical PV device including the series and parallel resistances

The basic equation (3.1) of the elementary PV cell does not represent the $I-V$ characteristic of a practical PV array. Practical arrays are composed of several connected PV cells and the observation of the characteristics at the terminals of the PV array requires the inclusion of additional parameters to the basic equation [26].

$$I = I_{pv} - I_0 \left[\exp\left(\frac{V + R_s I}{V_{ta}}\right) - 1 \right] - \frac{V + R_s I}{R_p} \quad 3.3$$

Where I_{PV} and I_0 are the photovoltaic (PV) and saturation currents, respectively, of the array and $V_t = N_s KT/q$ is the thermal voltage of the array with (N_s) number of cells connected in series.

The diode saturation current I_0 and its dependence on the temperature and expressed as [26].

$$I_0 = I_{0,n} \left(\frac{T_n}{T} \right)^3 \exp \left[\frac{qE_g}{aK} \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \quad 3.4$$

Where E_g is the band gap energy of the semiconductor ($E_g = 1.12$ eV for the polycrystalline Si at 25 °C) and $I_{0,n}$ is the nominal saturation current, the value of diode ideality constant is usually between $1 \leq a \leq 1.5$ and for silicon-poly material is around 1.3 [19]:

$$I_{0,n} = \frac{I_{sc,n}}{\exp(V_{oc,n}/aV_{t,n}) - 1} \quad 3.5$$

With $V_{t,n}$ being the thermal voltage of N_s series-connected cells at the nominal temperature T_n . The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation .

$$I_{pv} = (I_{pv,n} + K_1 \Delta T) \frac{G}{G_n} \quad 3.6$$

Where $I_{pv,n}$ (in amperes) is the light-generated current at the nominal condition (usually 25 °C and 1000 W/m²), $\Delta T = T - T_n$ (T and T_n being the actual and nominal temperatures [in Kelvin], respectively), G (watts per square meters) is the irradiation on the device surface, and G_n is the nominal irradiation. The nominal light generated current $I_{pv,n}$ can be expressed with accurate equation of the following.

$$I_{pv,n} = \frac{R_p + R_s}{R_p} I_{sc,n} \quad 3.7$$

So, equation (3.3) can be expressed with the known values given by the manufacturer's data sheet ($I_{sc,n}$ and $V_{oc,n}$), the constants (a , q , E_g , K), and the external influential factors of radiation and temperature (T , G), but the internal influencing parameters (R_s and R_p) are still unknown.

Marcelo G. et al. [24], proposed an interesting method for adjusting R_s and R_p based on the fact that there is only a pair $\{R_s, R_p\}$ that warranties that $P_{max,m} = P_{max,e} = V_{mpp} I_{mpp}$ at the (V_{mpp}, I_{mpp})

point of the I–V curve, i.e., the maximum power calculated by the I–V model of equation (3.3) ($P_{\max,m}$) is equal to the maximum experimental power from the datasheet ($P_{\max,e}$) at the MPP (where MPP is a maximum power point, which means a point where the power output of the solar panel will be maximum).

The calculated maximum current output of the solar panel at nominal temperature and solar radiation (at 25°C and 1000 W/m²) could be expressed using equation (3.3) as:

$$I_{mpp} = I_{pv,n} - I_{0,n} \left[\exp\left(\frac{V_{mpp} + R_s I_{mpp}}{V_{t,n} a}\right) - 1 \right] - \frac{V_{mpp} + R_s I_{mpp}}{R_p} \quad 3.8$$

Where V_{mpp} is voltage at MPP (maximum power point), the thermal voltage of the array at STC I_{mpp} is current at MPP.

Equation (3.8) is arranged in such a manner to express the shunt resistor with other variables as follows:

$$R_p = \frac{V_{mpp} + R_s I_{mpp}}{I_{pv,n} - I_{0,n} \left[\exp\left(\frac{V_{mpp} + R_s I_{mpp}}{V_{t,n} a}\right) - 1 \right] - I_{mpp}} \quad 3.9$$

Where V_{mpp} is voltage at MPP (maximum power point), the thermal voltage of the array at STC I_{mpp} is current at MPP.

Equation (3.18) is arranged in such a manner to express the shunt resistor with other variables as follows:

Note : From the above equation R_p is expressed not only in terms parameters such as $I_{pv,n}$, $I_{0,n}$, and $V_{t,n}$, but also the nominal maximum power point (i.e. I_{mpp} and V_{mpp}) and the R_s , hence the resulting graph due to the pair values (i.e. R_s and R_p) will surely pass through the nominal maximum power points. A detail numerical algorithm that can determine the electrical characteristic of a PV panel is designed, which is shown in figure 3.3.

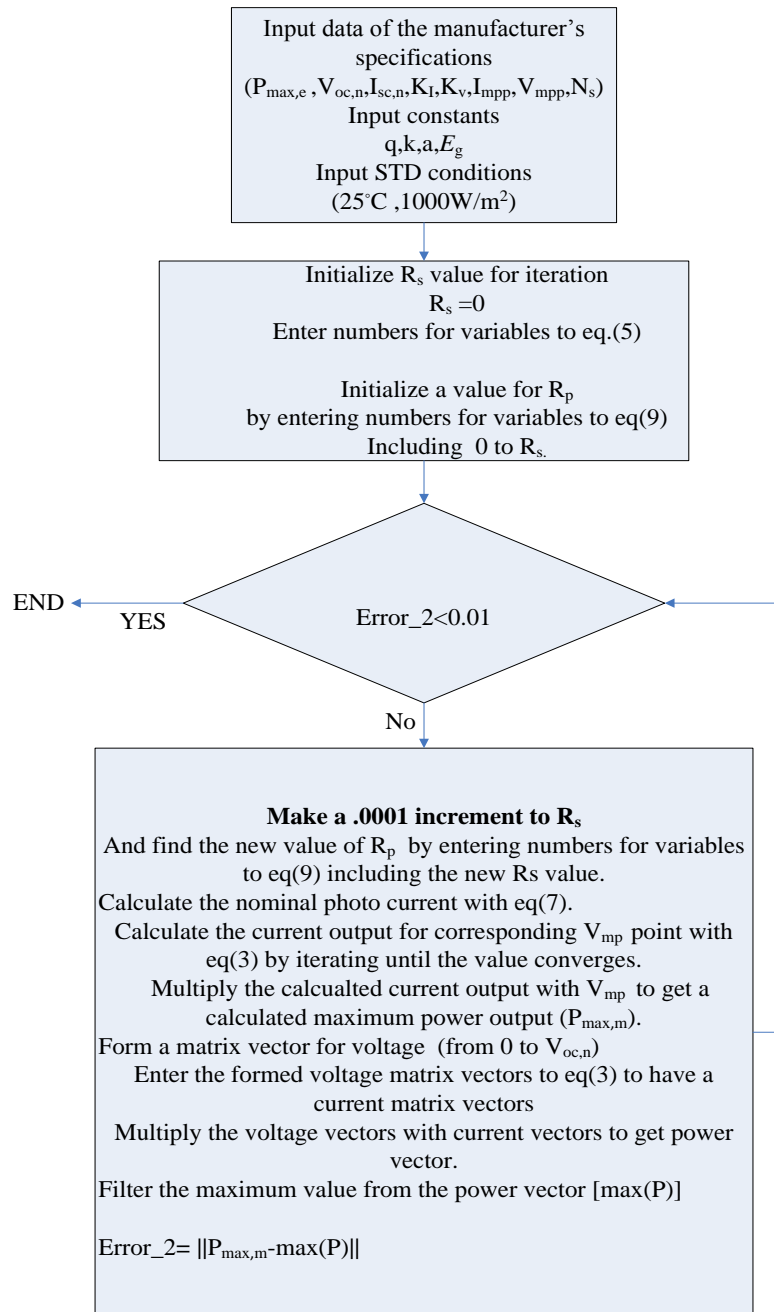


Figure 3.3 : Algorithm of the mat-lab program used to model a PV panel

3.2. Operating temperature and efficiency of PV module

The cell operating temperature T , is also the proper temperature to use in order to predict the electrical performance of the PV array. Because of the internal processes that take place within the cells during their exposure to sun, a large portion of the incident irradiance is degraded and released as heat.

Standard heat transfer mechanisms must be accounted for to compute the appropriate energy balance on the cell array leading to the prediction of cell temperature. At steady-state conditions, only convection and radiation mechanisms are usually considered, since they are prevalent on the conduction mechanism that merely transports heat toward the surfaces of the mounting frame (especially in the case of rack-mounting free-standing arrays). A survey of the explicit and implicit correlations proposed in literature linking cell temperature with standard weather variables and material and system-dependent properties [19].

A large number of empirical correlations exist in a number of literatures whose application appears to be the best and simplest. Hence, it has been chosen an equation that are explicit, depend on easily measurable parameters and, have wide applicability. For variations in ambient temperature and irradiance the cell temperature (in °C) can be estimated quite accurately with the linear approximation [35]:

$$T = T_a + \frac{G}{G_{NOCT}} (T_{NOCT} - T_{a,NOCT}) \quad 3.10$$

where T_{NOCT} is the so-called nominal operating cell temperature, the T_{NOCT} temperature is defined as the temperature of the cell at the conditions of the nominal terrestrial environment (NTE): Solar irradiance $G_{NOCT} = 800 \text{ W/m}^2$, ambient temperature $T_{a,NOCT} = 20^\circ\text{C}$, average wind speed 1 m/s, G is intensity of the solar irradiance.

Hence the above equation can be expressed more simply as follows.

$$T = T_a + \frac{G}{800 \text{ W/m}^2} (T_{NOCT} - 20^\circ) \quad 3.11$$

The solar module power conversion efficiency can be given as

$$\eta = \frac{P_{out}}{G \times A_m} = \frac{I \times V}{G \times A_m} \quad 3.12$$

Where I and V are current and voltage output of the PV module corresponding to solar intensity G and cell temperature, T and A_m is solar panel module area (the dimension of KC200GT solar module can be found on Table 5.1).

3.3. Operating point of a PV panel

A methodology implemented in this paper is a graphical technique, which is used to find an operating point of a PV panel.

When a resistive load is connected to a PV module operating point, that is to say the current and the voltage, is decided by intersection of the I–V characteristics curve of the PV and the I–V characteristics of the load curve, $V=IR$ (Figure 3.4). The slope of this curve is $1/R$ and the operating point will depend on the value of R . Each slope represents a certain resistance [12].

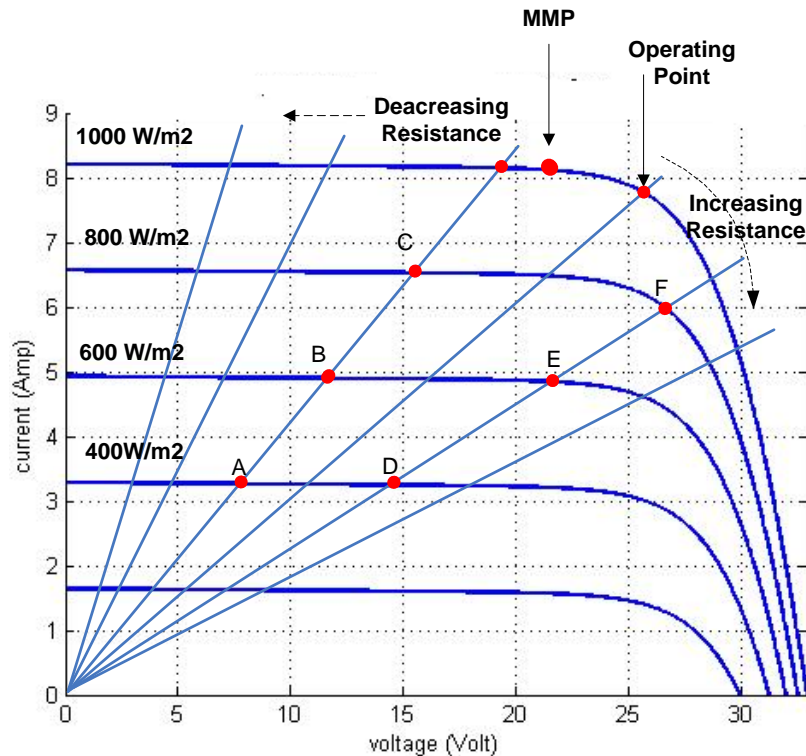


Figure 3.4: Effective resistance load on cell operating point

Figure 3.4 depicts that for smaller resistive load, as radiation intensity increases the operating point will move continuously towards the maximum power point (MMP) of each curve as it is pointed by point A, B and C, hence the efficiency will improve continuously. In the contrary, for higher resistive load the operating point will not move continuously towards the MMP, rather first it moves towards the MMP then it moves away the MMP as pointed by point D, E, and F. Hence the efficiency of the PV panel will first improve then it drops as radiation intensity continuously increases

CHAPTER FOUR

4. Data analysis and interpretation

4.1. Data Analysis

In this study Temperature and Global radiation data is required at least in hourly basis. The Metrology Agency of Ethiopia installed modern equipment that measure and record a metrological data automatically every 15 minutes' difference at Jigjiga.

4.2. Data Structure

The raw data set Temperature and Global Radiation data get from the National Metrology Agency is tabulated in an Excel sheet. The data are presented in 15 minutes' difference for a whole 24-hour time duration of a day in an increasing manner, so we have 96 rows of data of temperature and 96 rows of data of radiation for a single day, temperature and radiation data are presented in separate column. Unfortunately, only data for first 12 days of each month is provided.

4.3. Data Sorting Mechanism for Raw Data Set

The size of data from the National Metrology Agency is too bulky, so there should be a way to sort out the radiation and temperature data to a specific date. A mat-lab program is developed which is capable of sorting out raw data for specific date, which considers the mathematical sequence by which the data is presented.

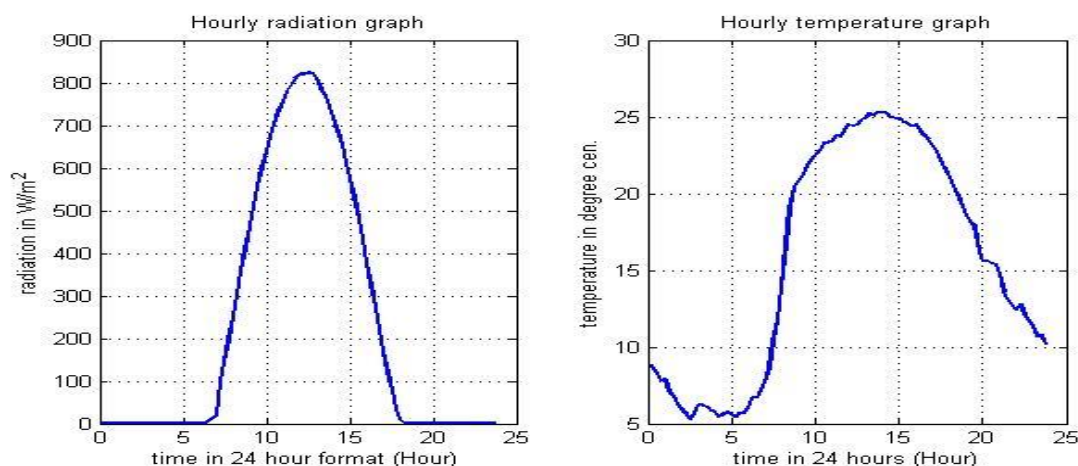


Figure 4.1 Global Radiation and Temperature data for Jan 3rd in 24 hours format

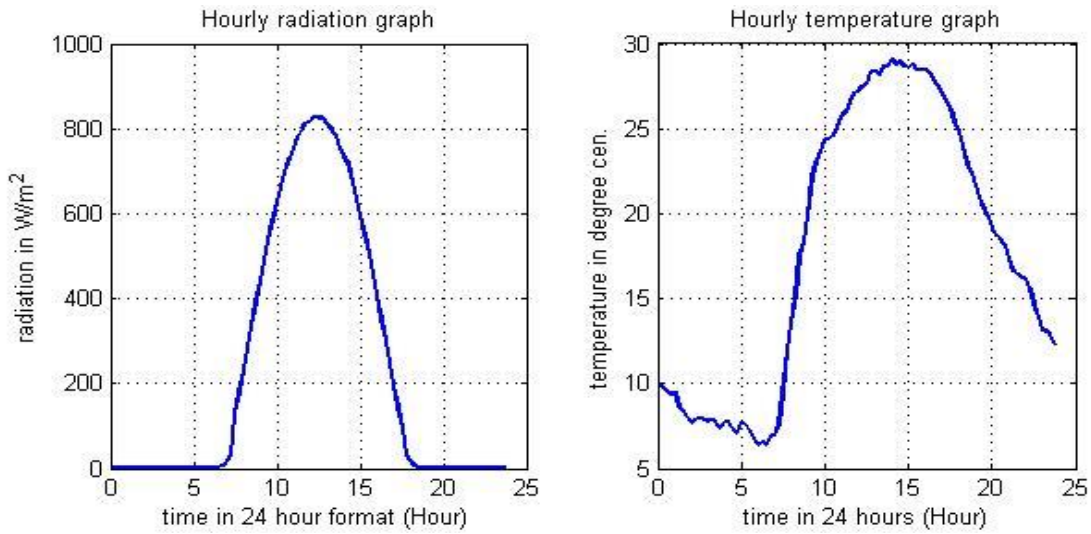


Figure 4.2 Global Radiation and temperature data for Feb 2nd in 24-hour format

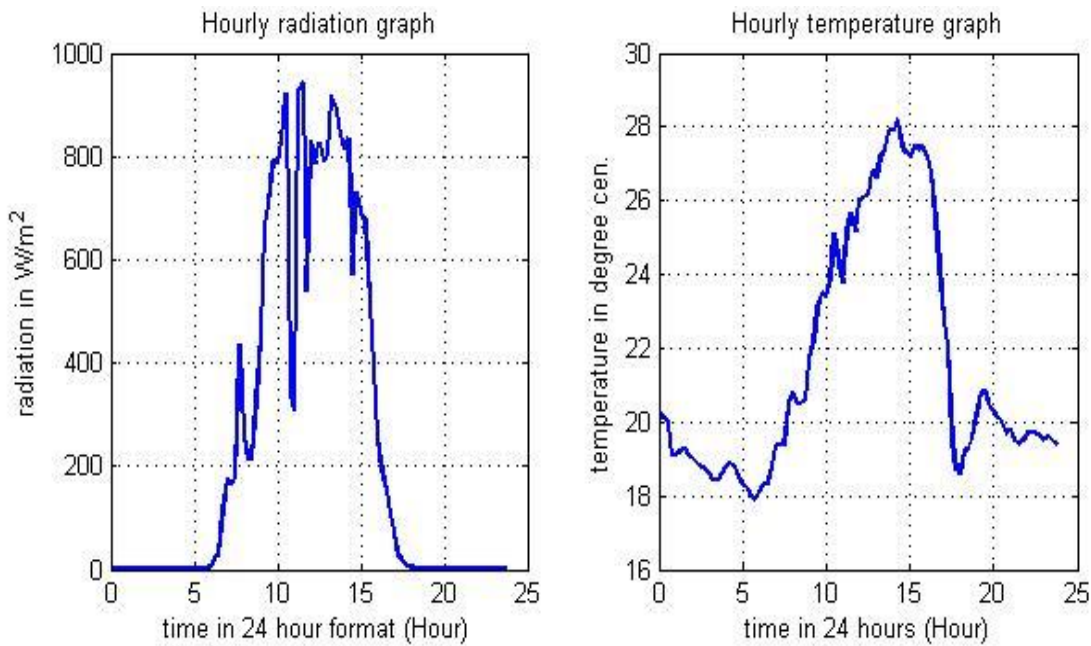


Figure 4.3 Global Radiation and temperature data for May 3rd in 24-hour format

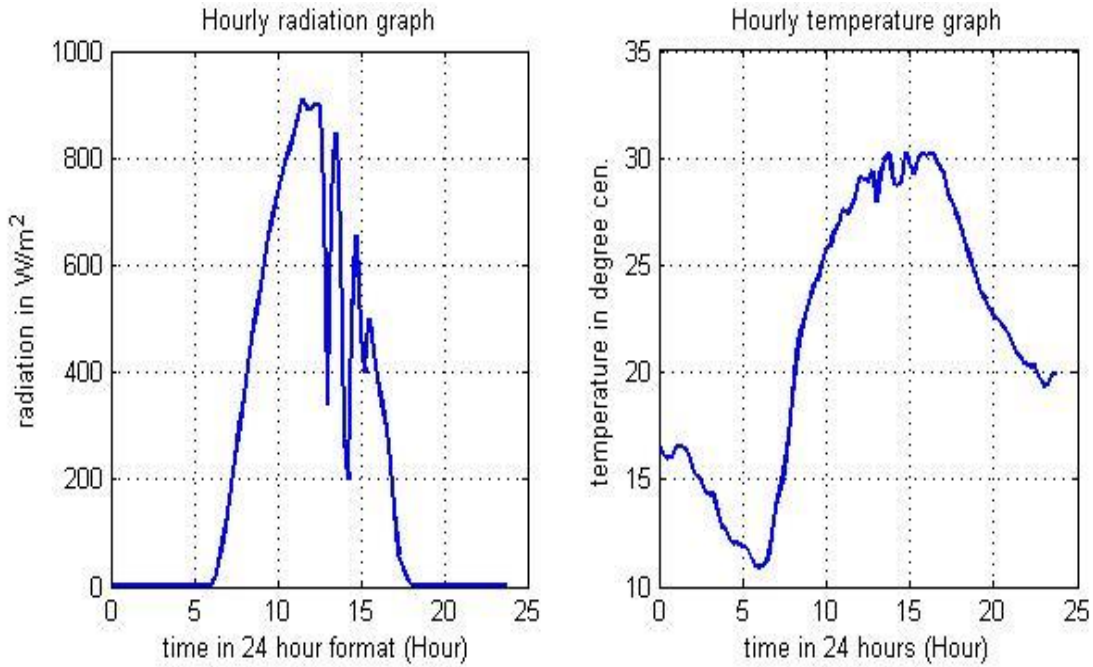


Figure 4.4 Global Radiation and temperature data for Oct.10th in 24-hour format

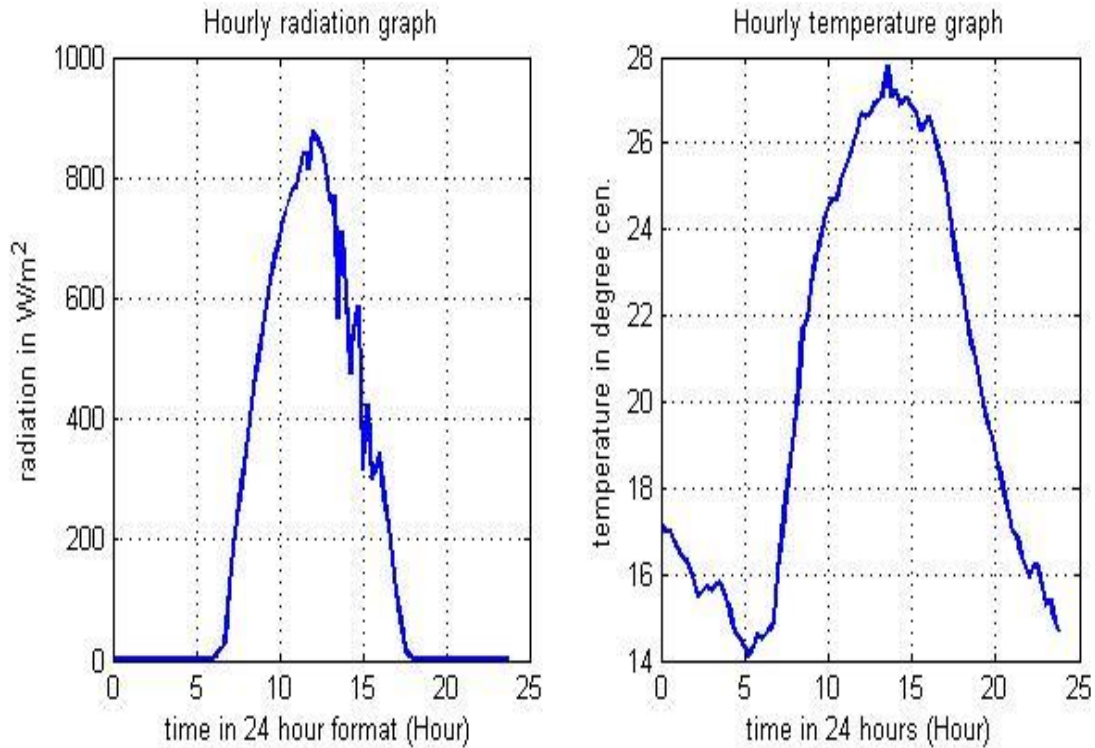


Figure 4.5 Global Radiation and temperature data for Nov 7th in 24-hour format

4.4. Optimum tilt angle of the solar panel

Facing a collector toward the equator for our case, “Jigjiga” is at the Northern Hemisphere, this means facing it south and tilting it up at an angle equal to the local latitude is a good rule-of-thumb for annual performance [14].

To prove the claim first considering the apparent sun path on the sky. The solar radiation reaches pick at solar noon when the sun just becomes at meridian of the point. So, to utilize this pick solar radiation, our solar panel must face south with zero azimuth angle (i.e. no tilting of the panel towards west or east).

For south facing panels incident angle of solar rays is given as [15]:

$$\cos(\theta) = \sin(L - \beta) \sin(\delta) - \cos(L - \beta) \cos(\delta) \cos(H) \quad 4.1$$

Where: θ is incident angle of solar radiation on the PV panel which is tilted by β angle from horizontal surface to south, L is latitude angle of the point, H is hour angle, and δ is declination angle.

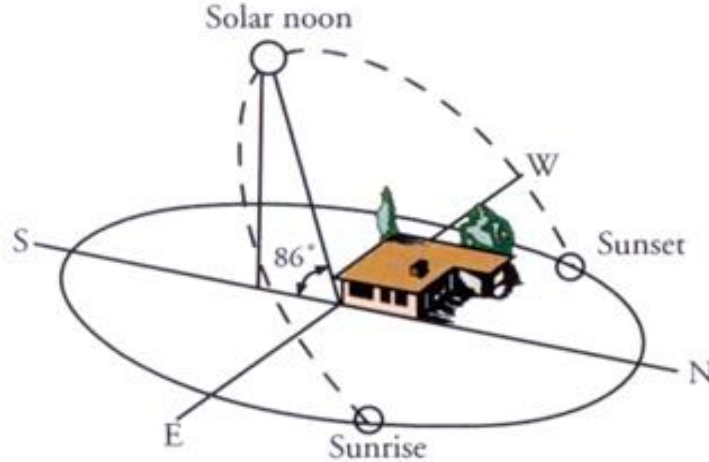


Figure 4.6 Apparent solar path on the sky

At solar noon (as it is important reference for almost all solar calculation [22]) the hour angle (H) will be zero. So, equation (4.1) will be analyzed as follows:

$$\cos(\theta) = \sin(L - \beta) \sin(\delta) - \cos(L - \beta) \cos(\delta) \quad 4.2$$

Which can be further reduced using cosine law

$$\cos(\theta) = -\cos(L - \beta + \delta) \quad 4.3$$

$$\theta = \pi - (L - \beta + \delta) \quad 4.4$$

Taking summer solstice or fall equinox as reference, the declination angle δ will be fixed to zero, and equation (4.3) become.

$$\theta = \pi - (L - \beta) \quad 4.5$$

The incident angle (θ) of equation (4.4) will become optimum when its value is zero. So, does the tilt angle of the panel.

$$0 = \pi - (L - \beta_{optimum}) \quad 4.6$$

$$\beta_{optimum} = L - \pi \quad 4.7$$

Equation (4.7) indicates the need for tilting of the solar panel at the same latitude angle but to opposite direction (i.e. if the latitude position is north to face the panel to south).

In our case, Jijiga is found 9.38° of north. Hence the solar panel should face 9.38° to south. Putting equation (4.7) into equation (4.4).

$$\theta = \delta + 2\pi = \delta \quad 4.8$$

Equation (4.6) shows that adjusting the tilt angle of the solar panel to its optimum position, will result the incident angle (θ) of solar radiation to be equal to declination angle (δ) only at solar noon time. We know that declination angle varies from -23.45° to 23.45° throughout the year, hence we can conclude that incident angle of solar radiation on optimally tilted panel varies from -23.45° to 23.45° throughout the year only at noon time.

4.5. Incidence angle, θ of the optimally tilted PV panel

It has been derived that the incident angle (θ) of the optimally tilted PV panel is equal to the declination angle (δ), but this happens only at noon time where the hour angle (H) is zero. So, we have to visualize the variation of the incident angles at other hour angles.

Putting equation (4.7) to equation (4.1) we got an equation to express for incident angle and derived as follows.

$$\cos(\theta) = \sin(\pi) \sin(\delta) - \cos(\pi) \cos(\delta) \cos(H)$$

$$\cos(\theta) = - \cos(\pi) \cos(\delta) \cos(H)$$

$$\cos(\theta) = \cos(\delta) \cos(H) \quad 4.9$$

Declination Angle (δ)

Declination is the angular distance from the sun north or south to the earth’s equator. The maximum and minimum declination angle values of the earth’s orbit produce seasons. Declination ranges between 23.45⁰ North and 23.45⁰ South. The northern hemisphere is inclined 23.45⁰ far away from the sun sometime around 21 December, which is the summer solstice for the southern hemisphere and the winter solstice for the northern hemisphere. In the northern hemisphere and through 21 June, starting around 21 June, the southern hemisphere is positioned in a way that it is 23.45⁰ away from the sun; meanwhile, it is winter solstice in the northern hemisphere. During the fall and spring equinoxes, which begin on 21 March and 21 September respectively, the sun passes directly over the equator [6].Where the declination angle, δ in degrees for any day of the year (N) can be calculated approximately by the ASHARAE equation.

$$\delta = 23.45 \sin \left[\frac{360}{365} (284 + N) \right] \quad 4.10$$

Table 4-1: Day Number for Each Month

<i>Month</i>	<i>Day Number</i>
January	i
February	31+i
March	59+i
April	90+i
May	120+i
June	151+i
July	181+i
August	212+i
September	243+i
October	273+i
November	304+i
December	334 +i

Hour Angle (ω)

The concept of hour angle is used for describing the rotation of the earth around its polar axis which is equivalent to $+15^0$ per hour during the morning and -15^0 in the afternoon. It is the angular distance between the observer's meridian and the meridian whose plane contains the sun. The following equation can be used to calculate the hour angle in degrees. It should be noted that at noon the hour angle ω is zero .

The hour angle can also be obtained from the Apparent Solar Time (AST); that is, the corrected local solar time [1]:

$$H = (AST - 12)15 \quad 4.11$$

At local solar noon, apparent solar time, $AST=12$ and hour angle, $H = 0^0$. Therefore, the LST (the time shown by our clocks at local solar noon) is:

$$LSN = 12 - ET + 4(SL - LL) \quad 4.12$$

Where LSN is local solar noon which is shown by our clock, SL is standard longitude of the country; LL is local longitude of the region Jigjiga, ET is equation of time whose value can be obtained as a function of the day of the year (N) approximately from the following equations [1]:

$$ET = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \text{ [min]} \quad 4.13$$

and

$$B = (N - 81) \frac{360}{364} \quad 4.14$$

Ethiopia has standard latitude and longitude of 8^000 north and 38^000 east respectively, while Jijiga has 9.35^0N latitude and 42.8^0E longitude.

Incident angle (θ) for a horizontal surface is equal to zenith angle (Φ)

$$\theta = \Phi$$

$$\cos(\Phi) = \sin(L) \sin(\delta) + \cos(L) \cos(\delta) \cos(H) \quad 4.15$$

4.6. Solar radiation on the optimally tilted PV panel

Solar collectors that focus sunlight usually operate on just the beam portion of the incoming radiation since those rays are the only ones that arrive from a consistent direction. Most photovoltaic systems, however, don't use focusing devices, so all three components—beam, diffuse, and reflected—can contribute to energy collected[16].

The global radiation data, which is given by the metrology agency, is a raw data that must be transformed into useful data to design our system, but before doing this; it is customary to investigate the nature of the measured global radiation data and understand what actually the solar radiation equipment, do measure.

4.7. Solar radiation measuring instruments

Solar radiation is measured with radiometers, which absorb solar radiation at its sensor, and transform it into heat and measures the resulting amount of heat to ascertain the level of solar radiation. There are basically two types of solar radiation measuring instruments or radiometers [22]: the pyrheliometer (see Figure 4.7) and the pyranometer (see Figure 4.8).

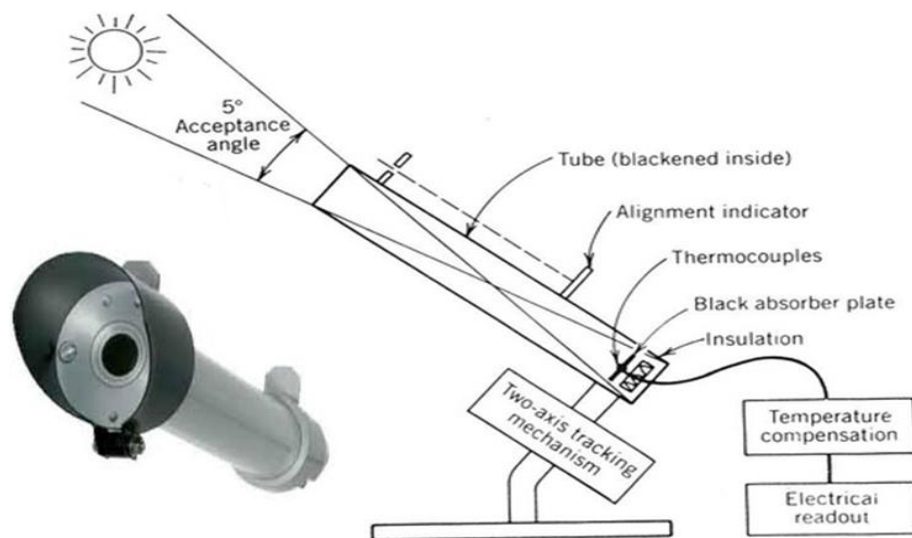


Figure 4.7. Pyrheliometer

A pyrheliometer is used to measure direct solar radiation from the sun and its marginal periphery. To measure direct solar radiation correctly, its receiving surface must be arranged to be normal to the solar direction. For this reason, the instrument is usually mounted on a sun-tracking device called an equatorial mount.

A pyranometer is used to measure global solar radiation falling on a horizontal surface. Its sensor has a horizontal radiation-sensing surface that absorbs solar radiation energy from the whole sky (i.e. a solid angle of $2\pi\text{sr}$) and transforms this energy into heat. Global solar radiation can be ascertained by measuring this heat.

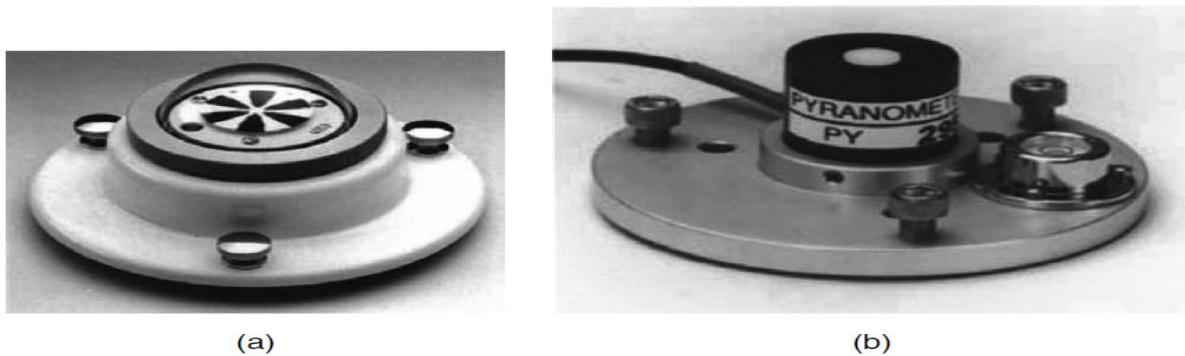


Figure.4.8 (a) A thermopile-type, black-and-white pyranometer and (b) a Li-Cor silicon-cell pyranometer.

As the above paragraph states, global radiation measuring equipment (the pyranometer) measures solar radiation that falls on horizontal surface. So, the provided global radiation data from the Metrology Agency is a radiation measurement carried on a horizontal surface.

4.8. Driving beam and diffuse radiation components from the measured global radiation

In order to determine total radiation on the tilted surface, the global radiation data from metrological agency must be split into its Beam and diffuse component (as the measured data is a global radiation measurement on horizontal surface, it does not contain reflected radiation).

The model developed by Threlkeld and Jordan (1958), which is used in the ASHRAE Clear-Day Solar Flux Model, suggests that diffuse radiation on a horizontal surface G_{DH} is proportional to the direct beam radiation G_B no matter where in the sky the sun happens to be [17]:

$$G_{DH} = C G_B \quad 4.16$$

Where C is a sky diffuse factor and its convenient approximation for any day of the year (N) is expressed as follows [14]:

$$C = 0.095 + 0.04 \sin \left[\frac{360}{365} (N - 100) \right] \quad 4.17$$

but the beam radiation normal to horizontal surface G_{BH} is expressed as:

$$G_{BH} = G_B \cos(\Phi) \quad 4.18$$

Where G_B is beam radiation, and G_{BH} is beam radiation normal to a horizontal surface, and Φ is zenith angle (or incident angle on horizontal surface).

By recalling equation (4.13), zenith angle is expressed as:

$$\cos(\Phi) = \sin(L) \sin(\delta) + \cos(L) \cos(\delta) \cos(H)$$

Putting equation (4.15) to equation (4.17)

$$G_{BH} = \frac{G_{DH} \cos \Phi}{C} \quad 4.19$$

Global radiation on horizontal surface (G_H) is a sum of beam radiation on horizontal surface (G_{BH}) and diffuse radiation on horizontal surface (G_{DH}).

$$G_H = G_{BH} + G_{DH} \quad 4.20$$

Putting equation (4.18) and equation (4.17) all together we get:

$$G_H = G_{DH} + \frac{\cos(\Phi) G_{DH}}{C} \quad 4.21$$

Diffuse Radiation will be expressed in terms of global radiation measured on horizontal surface

$$(G_H) \text{ as: } G_{DH} = \frac{G_H}{1 + \cos(\Phi)/C} \quad 4.22$$

With regard to our previous discussion it is obvious that G_H is a measured radiation data on horizontal surface which is provided by the metrology agency. So, with the help of equation (4.22) it is possible to drive the diffuse component of the measured radiation data.

Beam Radiation component:

After, once we calculated the diffuse radiation, it is possible to get the beam component of the measured data from equation (4.20).

Rearranging equation (4.20) we get an expressive equation to beam component:

$$G_{BH} = G_H - G_{DH} \quad 4.23$$

4.8.1. Total radiation on optimally tilted panel

To optimize solar radiation interception, the panel has been proposed to be tilted at angle equal to the latitude position of the region. However, as it has been mentioned, the provided radiation data was a global radiation measured at horizontal surface. Therefore, we need to generate solar radiation data on the tilted panel, by converting the existing radiation data (on horizontal surface) to radiation on the tilted surface. Beam radiation, G_{Bt} on tilted surface is [15]:

$$G_{Bt} = G_B \cos(\theta) \quad 4.24$$

And on horizontal surface is:

$$G_{BH} = G_B \cos(\Phi) \quad 4.25$$

Where G_B is beam radiation, G_{Bt} is beam radiation on the tilted panel, G_{BH} is beam radiation measured on horizontal surface, and θ is the incident angle, and Φ is azimuth angle.

It follows that,

$$R_B = \frac{G_{Bt}}{G_{BH}} = \frac{\cos(\theta)}{\cos(\Phi)} \quad 4.26$$

Where R_B is called beam radiation tilt factor. In our case the term $\cos(\theta)$ can be calculated with equation (4.9), $\cos(\Phi)$ from equation (4.18), and G_{BH} has been derived from the measured data with equation (4.21). So the beam radiation component for our panel is:

$$GBt = GBH . RB \quad 4.27$$

Diffuse radiation, G_{Dt} on tilted surface is expressed in terms of diffuse radiation on horizontal surface as [16]:

$$G_{Dt} = G_{DH} \frac{1+\cos(\beta)}{2} \quad 4.28$$

Where β is tilt angle of the panel, and G_{DH} is the diffuse radiation which is derived with equation (4.20) from the provided global radiation data.

Reflected radiation can be modeled as the total of horizontal radiation (G_H) times the ground reflectance ρ . The fraction of the ground reflected radiation that will be intercepted by the tilted panel, G_{Rt} depends on the slope of the tilt angle of the panel β , resulting in the following expression for reflected radiation on tilt surface [2]:

$$G_{Rt} = \rho G_H \frac{1-\cos(\beta)}{2} \quad 4.29$$

Estimates of ground reflectance range from about 0.8 for fresh snow to about 0.1 for a bituminous-and-gravel roof, with a typical default value for ordinary ground or grass taken to be about 0.2.

The total (Global) radiation, G_t on the tilted panel is therefore:

$$G_t = G_{Bt} + G_{Rt} + G_{Dt} \quad 4.30$$

4.9. Comparing total radiation on optimally tilted panel and measured global radiation

Using previously derived set of equations, it is possible to compute total radiation flux on optimally tilted panel by taking the measured global radiation data as input (which is measured on horizontal surface), hence it is possible to compare the two set of data (i.e. the measured data to that of the computed data), by doing so we can *directly* judge radiation flux improvement due to the tilting of the PV panel into its optimum angle; or indirectly it is possible to determine the improvement in radiation flux due to the tilting of the PV panel by comparing incident angle to that of zenith angle. Since zenith angle is incident angle of horizontally positioned panel, it determines radiation flux on horizontally positioned panel, while the incident angle determines radiation flux on tilted panel.

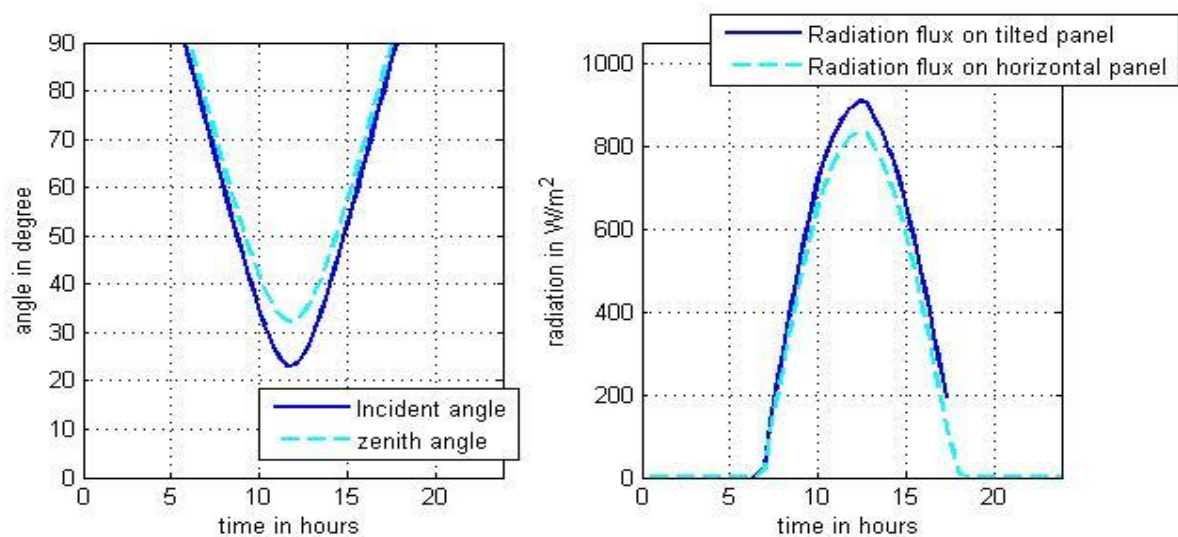


Figure 4.9 Comparison of radiation flux of tilted and horizontally positioned panels at Jan 1st

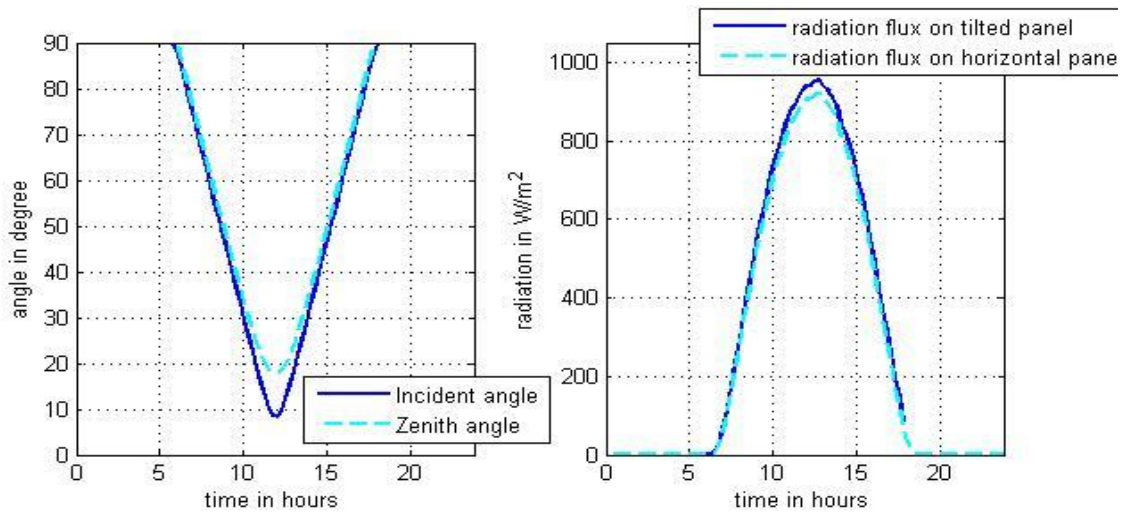


Figure 4.10 Comparison of radiation flux of tilted and horizontally positioned panels at Mar 1st

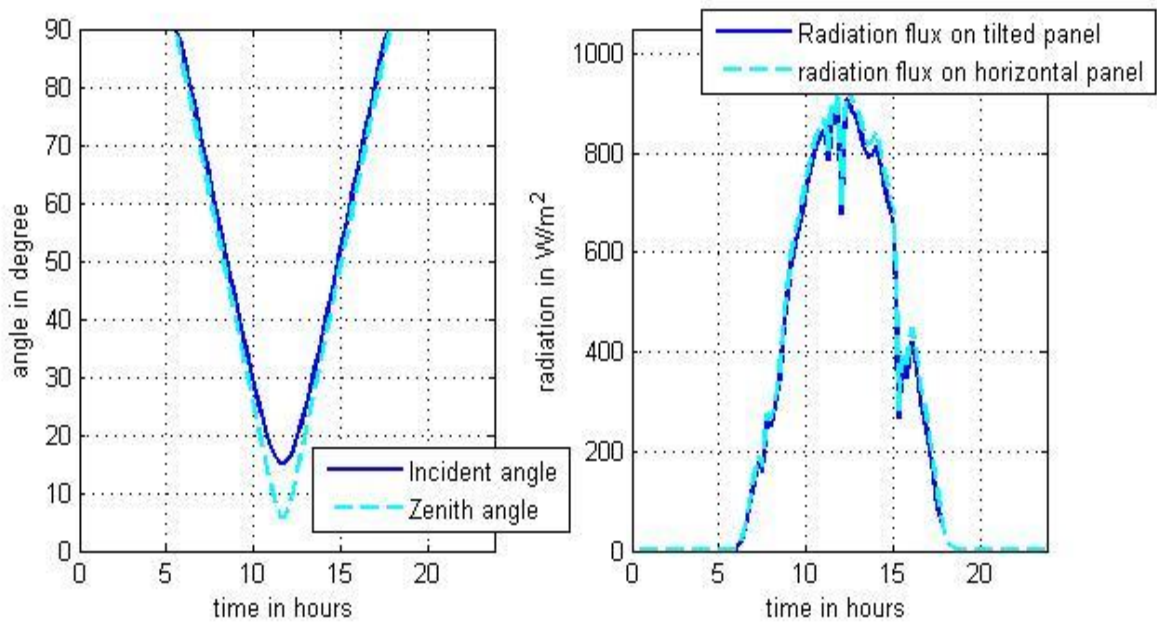


Figure 4.11 Comparison of radiation flux of tilted and horizontally positioned panels at May 1st

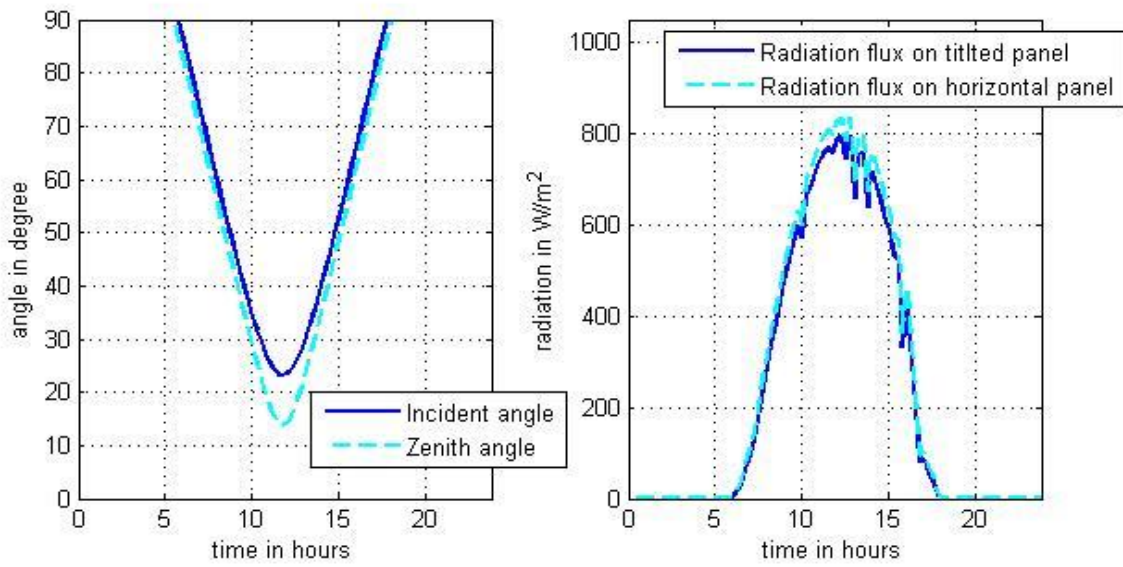


Figure 4.12 Comparison of radiation flux of tilted and horizontally positioned panels at Jul 1st

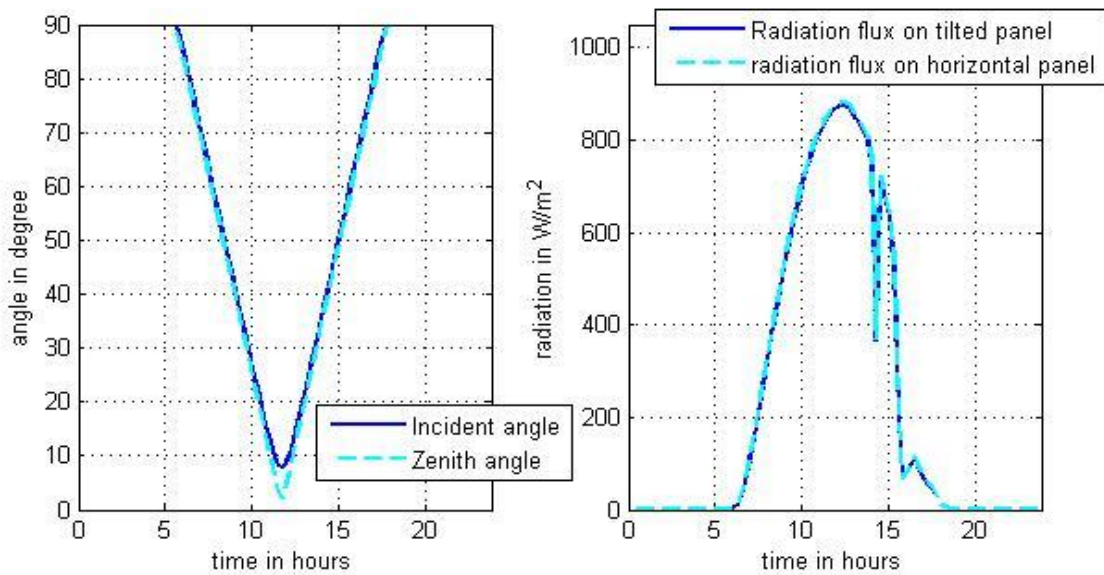


Figure 4.13 Comparison of radiation flux of tilted and horizontally positioned panels at Sept. 1st

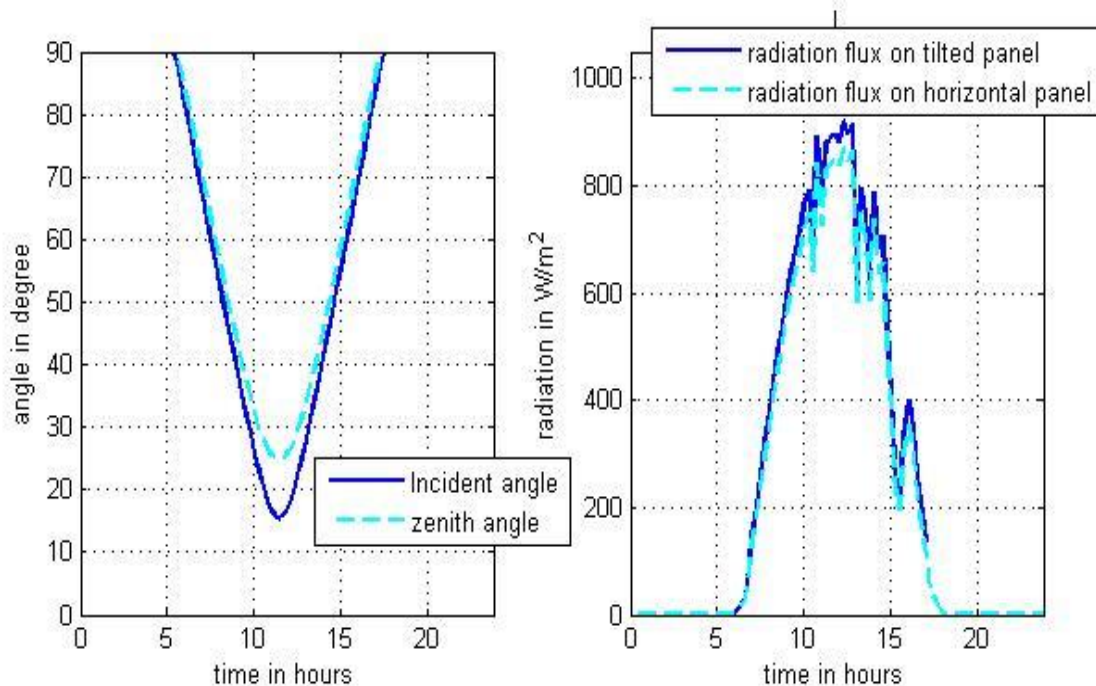


Figure 4.14 Comparison of radiation flux of tilted and horizontally positioned panels at Nov. 1st

The first two graphs i.e. graphs for January 1st and March 1st show an improvement in radiation flux due to the tilting of the panel into its optimum angle. As it is depicted on the graphs, the incident angles are traced below the zenith angles, since a lower angle means a higher radiation flux; it indirectly shows the improvement of radiation flux due to tilting it rather than positioning horizontally. Another option is to directly compare the computed radiation flux on the tilted panel to that of the measured radiation flux on horizontal panel, as it is depicted on the right side of each figure, still we see an improvement of the radiation flux on the first two figures.

In the next three graphs (i.e. May 1st, July 1st, and Sept 1st), the radiation flux on the tilted panel is not improved rather it is lower than horizontally positioned panel, i.e. from May 1st to Sept 1st, the panel will have better performance if it is positioned horizontally rather than tilting it to its optimum angle.

Finally, at November 1st, radiation flux of tilted panel has improved, hence we can conclude that, tilting a PV panel will result a general improvement in its performance, but it will not give a better performance all the time.

CHAPTER FIVE

5.0. Results and discussion

Here in this paper we are modeling a particular PV module (which is Kyocera 200 GT) under constant electric load, and weather condition of Jijiga. Hence annual temperature and global radiation (i.e. pyranometer) data from Ethiopian National Metrology Agency is provided which is measured in 15 minutes difference.

Table 5.1 Specification of KC200GT Solar Array

Electrical Performance Under Standard Test Conditions (STC)	
Maximum Power (Pmax)	200 Watt
Maximum Power Voltage (Vmpp)	26.3 V
Maximum Power Current (Impp)	7.61 A
Open Circuit Voltage (Voc)	32.9 V
Short Circuit Current (Isc)	8.21 A
Temperature Coefficient of Voc	$-1.23 \times 10^{-1} V/o_c$
Temperature Coefficient of Isc	$3.18 \times 10^{-3} A/o_c$
CELLS	
Number per module	54
MODULE CHARACTERISTICS	
Length ×Width ×Depth	(1425×990×36) mm
NOCT	47 C ⁰

5.1. Output Result of the Computer Program for Selected PV Modules

PV module is chosen as reference example for modeling, because they are well-suited to traditional applications of photovoltaic, which are KC200GT.

The proposed model was tested using manufacturer data sheets. The following figures show different simulations for the Kyocera family solar modules using the information provided by the manufacturer KYOCERA. For the products KC200GT (see table 5-1).

The I-V curves (which is shown in figure 5.1) depict the simulation results for current versus voltage characteristics of the photovoltaic modules with the operating cell temperature of 25°C and the effective irradiance level changing (i.e. 200W/m², 400W/m², 600W/m², 800W/m², and 1000W/m²).

Based on characteristics in Figure 5-1, it's clear that at constant module temperature, increasing of irradiation give big affect (proportional) on a short circuit current (I_{sc}) value but small effect on the open circuit voltage (V_{oc}) value. In other side, it can be observed that increasing of module temperature at constant irradiation will increase a short circuit current (I_{sc}) slightly and decrease the open circuit voltage (V_{oc}) proportional.

Based on Figure 5-2, it can be seen also that at constant module temperature, increasing of irradiation give significant affect on the output power of PV module (P).

The figure showed the increase in short circuit current of the PV panel with increase in radiation intensity. Similarly, the P-V curve (of figure 5.2) show power versus voltage characteristics at different effective irradiance level and 25°C cell temperature. It showed the increase in maximum power output of the PV panel with increase in radiation intensity. Higher is the solar irradiation, higher would be the solar input to the solar cell and hence power magnitude would increase for the same voltage value. With increase in the solar irradiation the open circuit voltage (V_{oc}) increases. This is due to the fact that, when more sunlight incidents on to the solar cell, the electrons are supplied with higher excitation energy, thereby increasing the electron mobility and thus more power is generated.

It can be validated that I-V curve on figure 5.1 and P-V curve of figure 5.2 are very similar to the I-V and P-V curve plotted by Marcelo G. et al. [19].

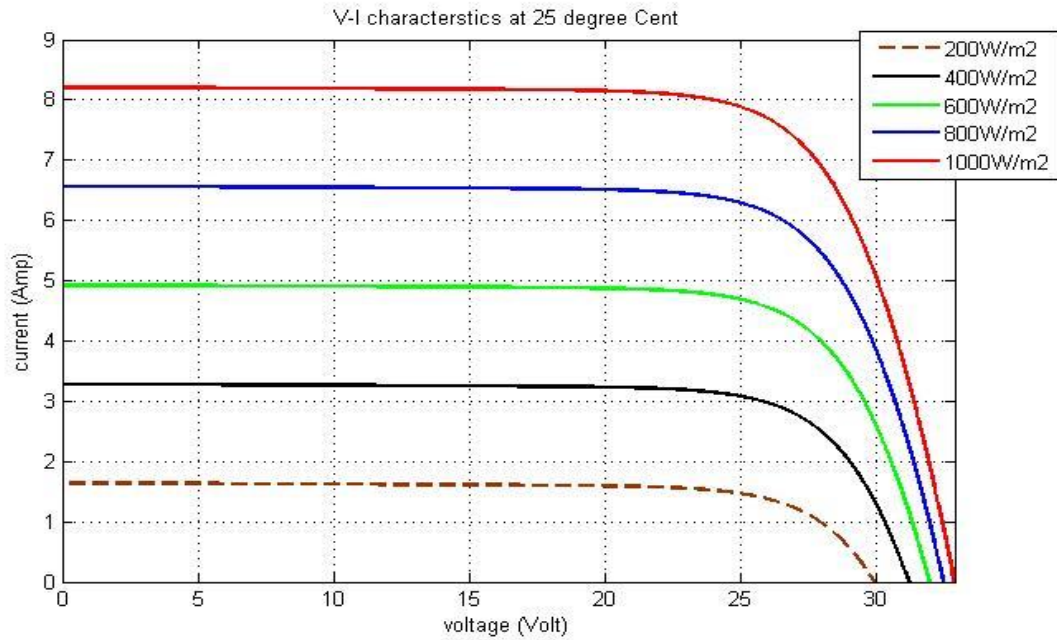


Figure 5.1: I–V model curves of the KC200GT solar array at different irradianations, 25 °C

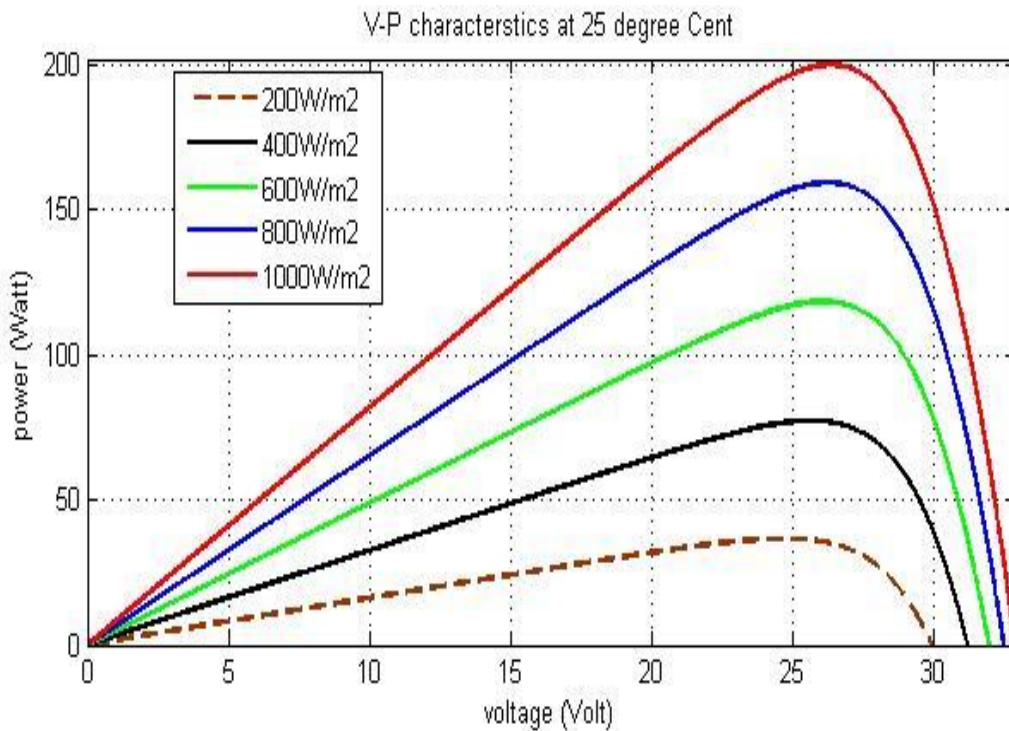


Figure 5.2 : P–V model curves of the KC200GT solar array at different irradianations, 25 °C

I-V curve of the photovoltaic module KC200GT under different temperatures of operation (i.e. 25°C, 50°C and 75°C) with the irradiation level at 1000W/m². The figure 5-3 depicts insignificant rise in short circuit current while a significant drop in open circuit voltage of the PV panel with increase in cell temperature. Figure 5.4 shows the adverse effect of temperature to the maximum power supplied by the photovoltaic module under a constant irradiance level of 1000W/m².

As the working temperature increases, the ISC also increases. This is expected because the photocurrent described by equation is linearly dependent on temperature.

Also, as the working temperature decreases, one can see that VOC increases. Unlike the other cell parameters, changing the working temperature does not affect the slopes of either the current source or voltage source segments of the IV curve.

Meanwhile, increasing of module temperature at constant irradiation will great affect on decreasing of output power (*P*) PV module. This phenomenon illustrated that output power (*P*) PV module is affected indirectly by ambient temperature, *T_a*.

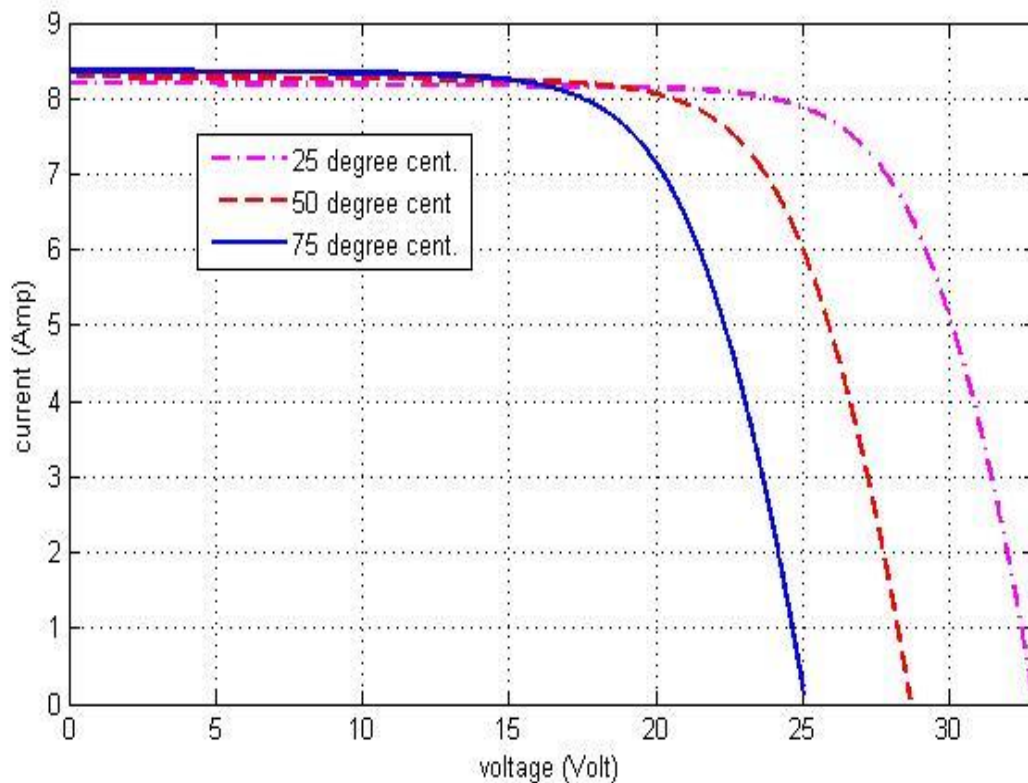


Figure 5.3 I-V model curves of the KC200GT solar array at different temperature, 1000W/m²

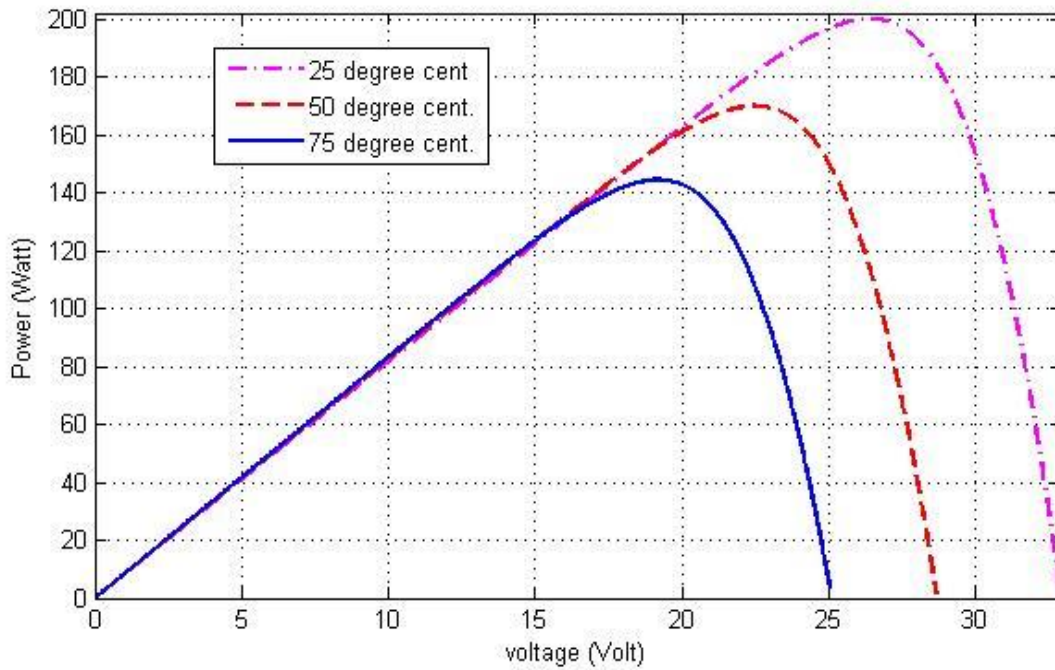


Figure 5.4 P-V model curves of the KC200GT solar array at different temperature, 1000W/m²

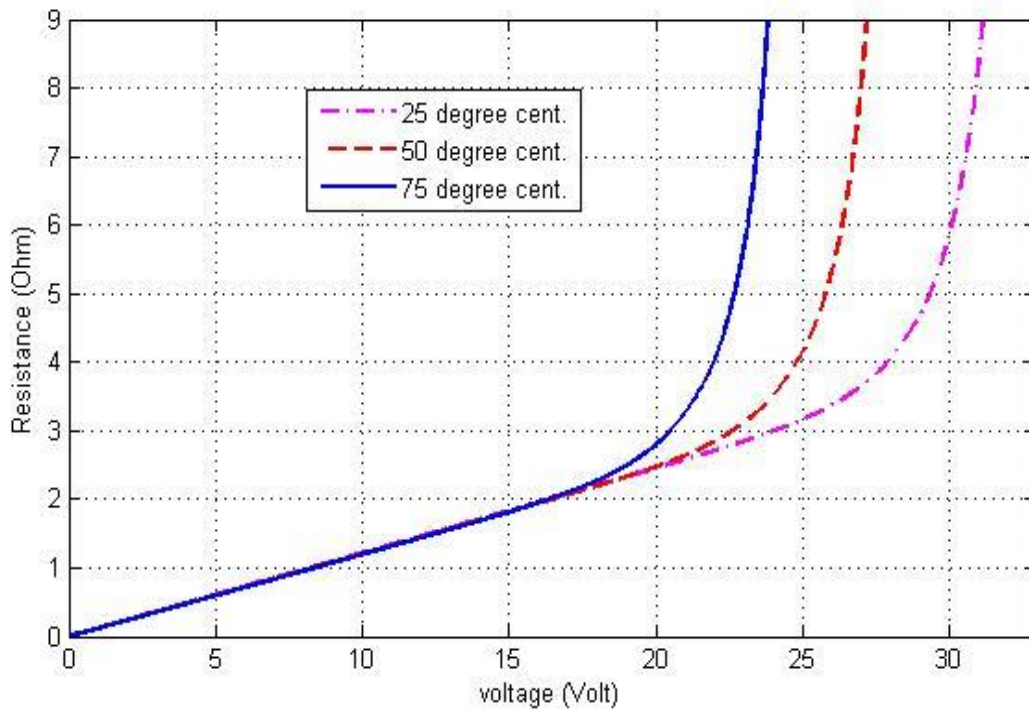


Figure 5.5 R-V model curves of the KC200GT solar array at different temperature, 1000W/m²

5.2. Hourly variation of global radiation on a tilted panel

Flat plate photovoltaic systems (like KC200GT), don't use focusing devices, so all three components—beam, diffuse, and reflected—can contribute to energy collected, hence we have to use the global radiation in the analysis of module temperature as well as power generation.

Total radiation intensity (i.e. global radiation) is measured with pyranometer, which measures radiation intensity on horizontal surface. However, facing a collector toward the equator (for our case, Jigjiga is at the Northern Hemisphere, this means facing it south) and tilting it up at an angle equal to the local latitude is a good rule-of-thumb for annual performance[31], hence it will be convincing to tilt our system to its optimum angle (i.e. at angle equal to the local latitude), and to perform the analysis based on the tilting angle.

Figure 5.6 indicates that the tilt angle has very significant effect on the hourly variation of summer season July1st, winter season January1st and rest of season April1st, October1st considered to perform analysis based on tilting angle.

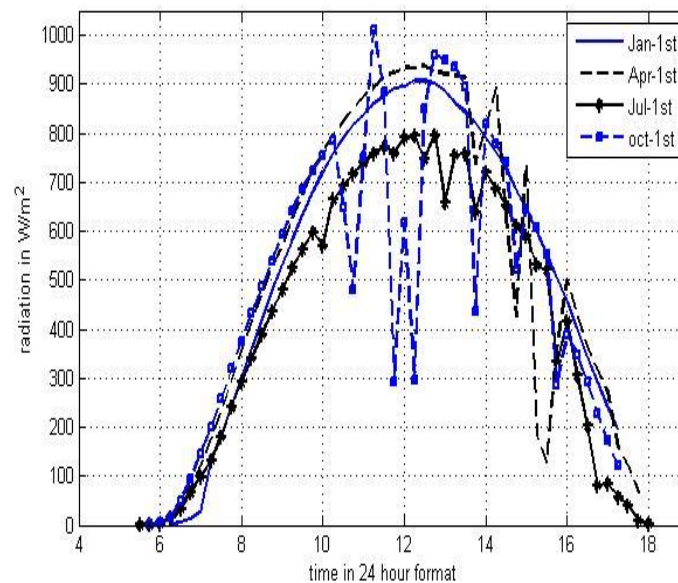


Figure 5.6: Hourly variation of global radiation on optimally tilted panel.

5.3. Hourly variation of PV module operating temperature

Equation (3.11) can model operating temperature of a PV module from NOCT and environmental variables (i.e. ambient temperature and radiation intensity).

Figure 5. 7 show variation in operating temperature of the PV module for the first days of selected months. (i.e. January, April, July, and October).

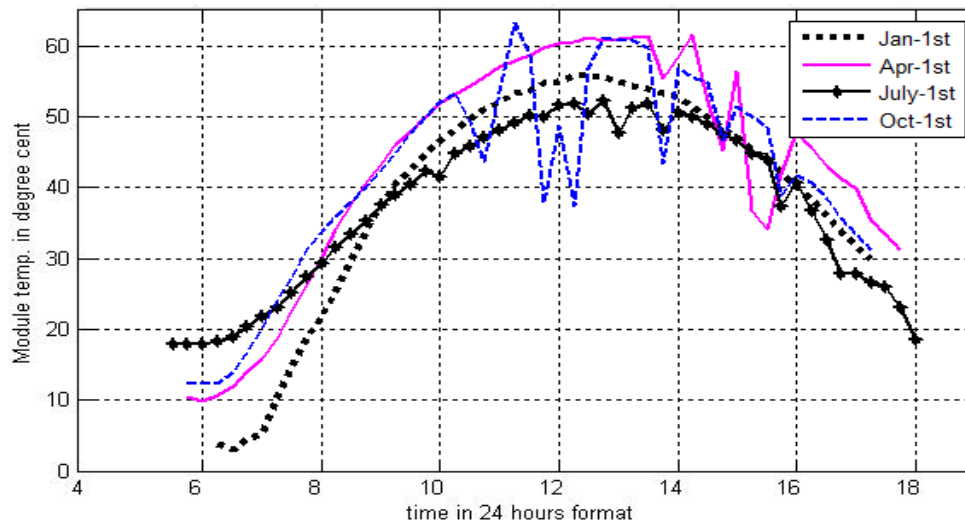


Figure 5.7 Hourly variation of PV module operating temperature

5.4. Hourly variation of electric performance of the PV module

This paper is concerned on modelling of a typical PV module (i.e. Kyocera 200GT), at constant electric load and under weather condition of Jigjiga. Figure 5.8, figure 5.9, figure 5.10, and figure 5. 11 depict hourly variation in voltage, current, power output, and conversion efficiency of the PV module for the first dates of selected months under 2Ω electric load.

For the 2Ω electric load as radiation increases, all the electrical characteristics (i.e. voltage, current, and power output as well as efficiency) will increase continuously, and decrease when radiation intensity decreases. Because as radiation increases the operating point jumps from smaller I-V curve to higher I-V. Also, as it is mentioned in section 3.3, for smaller electric loads the operating point will continuously move towards maximum power point, hence the efficiency will improve continuously (refer to figure 3.4).

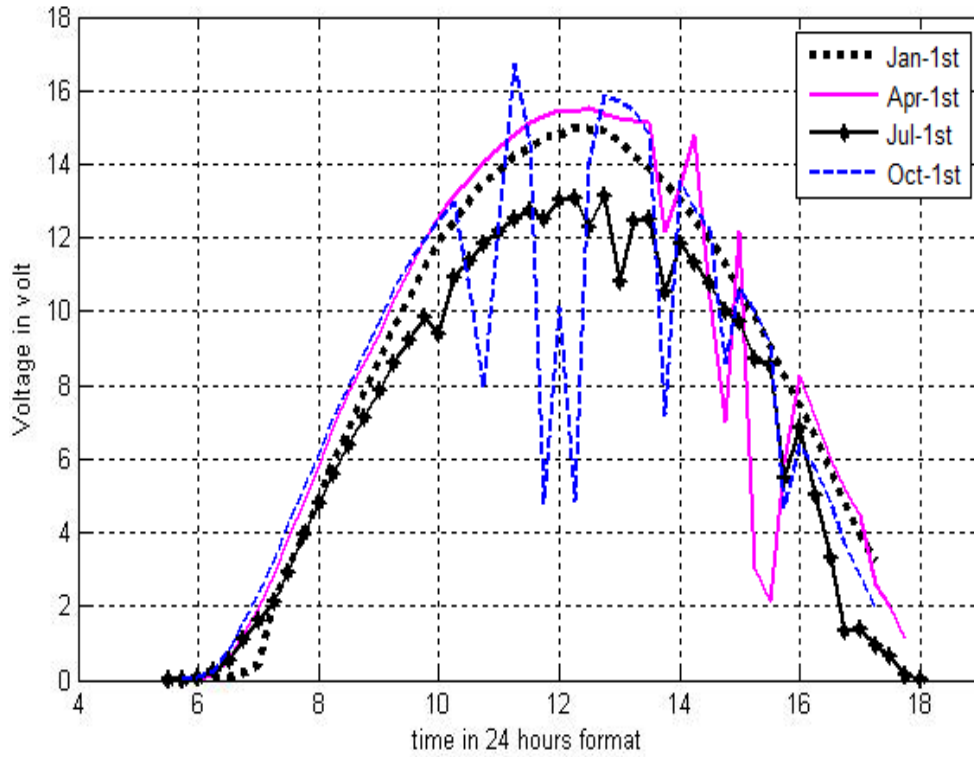


Figure 5.8 Hourly variation of voltage output of Kyocera 200GT PV module for 2Ω resistance.

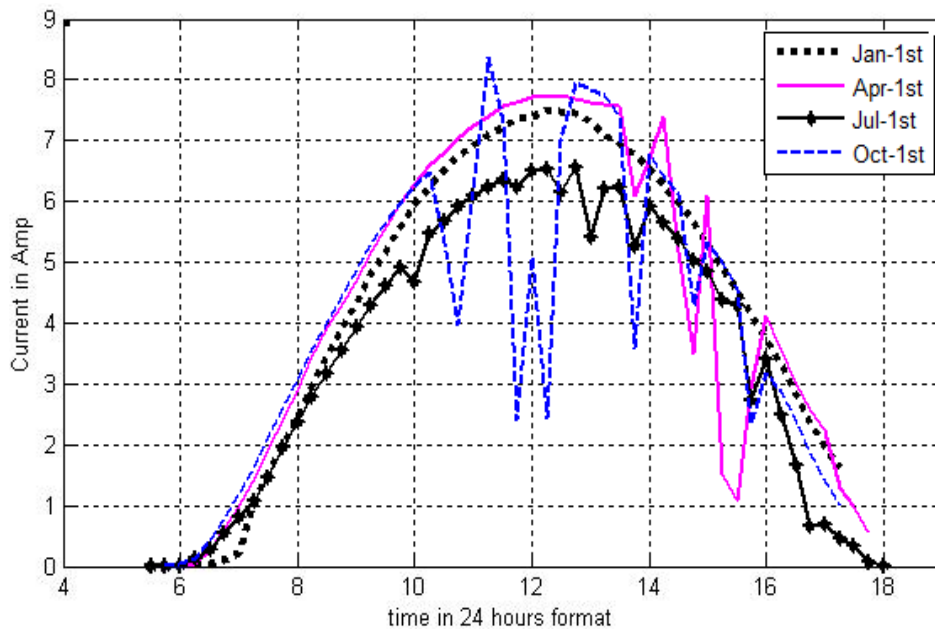


Figure 5.9. Hourly variation of current output of Kyocera 200GT PV module for 2Ω resistance.

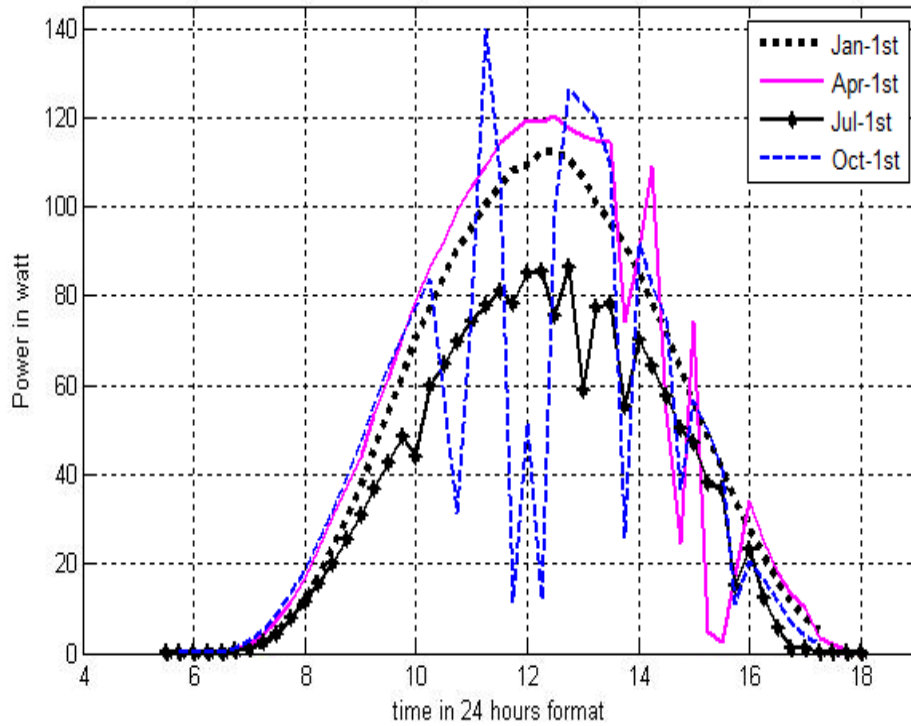


Figure 5.10. Hourly variation of power output of Kyocera 200GT PV module for 2Ω resistance.

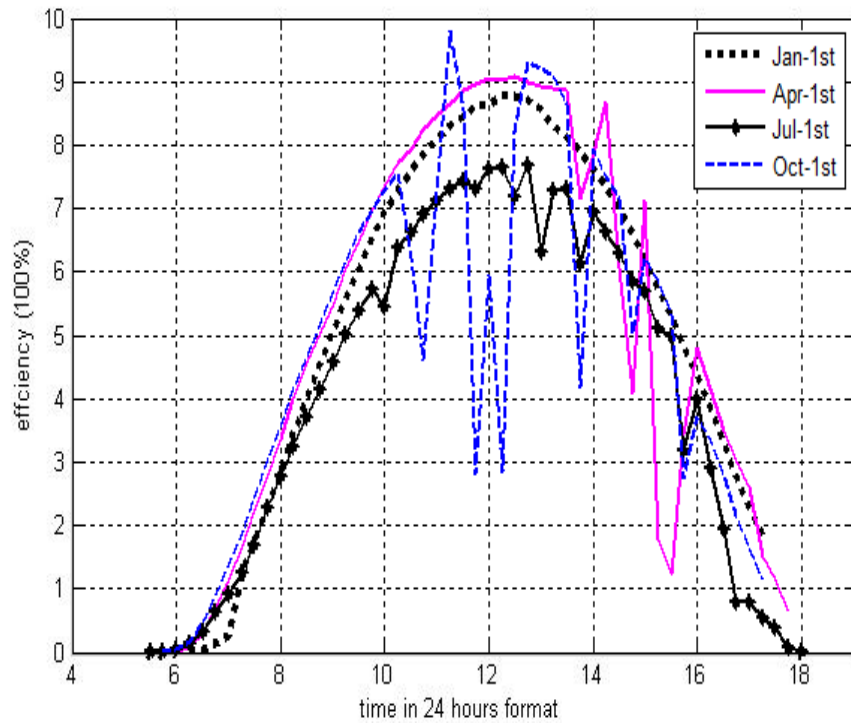


Figure 5.11. Hourly variation of efficiency of Kyocera 200GT PV module for 2Ω resistance.

5.5. Effect of electric load on performance of the PV panel

Figure 5.12 and figure 5. 13 depict variation in electric performance of KC 200GT PV module for different electric load (i.e. 2Ω, 4Ω, 6Ω, and 8Ω electric resistance) and under weather condition of January 1st.

According to the figure 5.12, the 4Ω electric load caused a desirable efficiency. It resulted a higher operating efficiency of the PV module for duration of the time at which the solar radiation intensity is the highest. This claim can be further inspected with figure 5. 13 (which shows hourly variation in power output of the PV module for different electric load). As it is depicted with the figure, the 4Ω electric load resulted a highest power output from 10AM to 3PM time interval than other electric loads, the reason behind the scenario is that the PV panel operates relatively nearer to its maximum power point in the time interval when it is connected to the 4Ω. Then the 6Ω electric load has a better power output in the time interval next to the 4Ω electric load.

In addition, figure 5.12 shows a U- shape efficiency curve for 6Ω and 8Ω electric load for the time interval where radiation intensity is highest.

This result asserts the concept stated in section 3. 3, that for higher resistive load the efficiency of the PV panel drops as the operating point moves beyond the maximum power point.

To judge the better performance of the PV module on the basis of electric load, the power output does not give us a clear picture. If an electric load gave as a better power output at some time interval, it does not mean that it performed better through all the time. Hence to have a clear picture, we have to compare the energy output of the PV module for each electric load. The following formula can help in the analysis of the daily energy output of the PV module. It calculates the areas under the curves of figure 5. 14.

$$E_{\text{output}} = \sum_{0:00}^{23:45} P_{\text{out}} \times \Delta t \quad 5.1$$

Where E_{output} is daily energy output of the PV panel under an electric load, P_{out} is calculated power output, Δt time interval at which calculations are performed.

Since environmental measurements are taken with 15 minutes differences, Δt will be taken as 15 minutes, and the last measurement is taken at 23:45 time of a day.

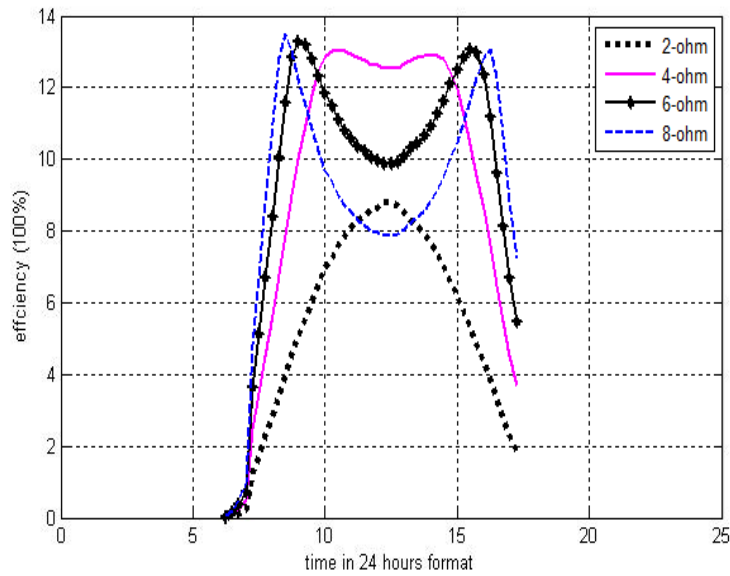


Figure 5. 12: Hourly variation of efficiency of Kyocera 200GT PV module for different electric load under weather condition of January 1st.

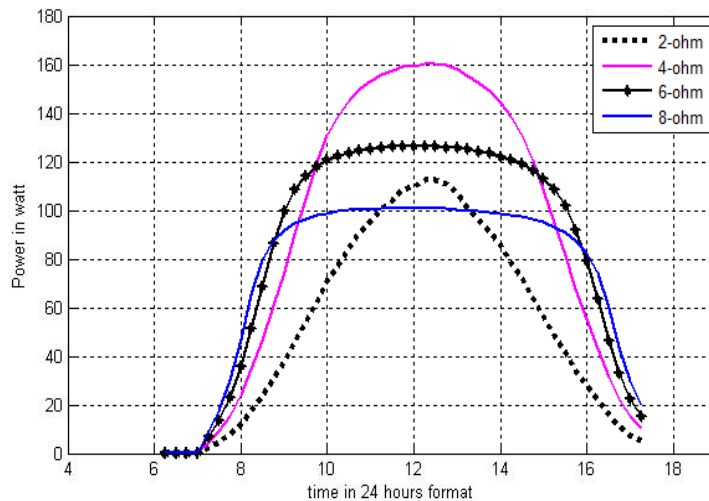


Figure 5.13: Hourly variation in power output of Kyocera 200GT PV module for different electric load under weather condition of January 1st.

Figure 5. 14 depict daily energy output of the PV module for the first 12 days of the month of January under 2Ω , 4Ω , 6Ω , and 8Ω electric loads. According to the figure the 4Ω electric load resulted the highest energy output among all other electric load for the first 10 days of the month. In January 11th, it had the same amount of energy output as that of the 6Ω electric load, but in January 12th it is over taken by both 6Ω and 8Ω electric load. The 2Ω electric load had the lowest energy output than all other electric load for all mentioned days of the month.

NOTE: From this result it can be concluded that all environmental condition will not favor a single electric load, but we can compare the annual performance of the PV module to judge which electric load will optimize the operation of the PV panel.

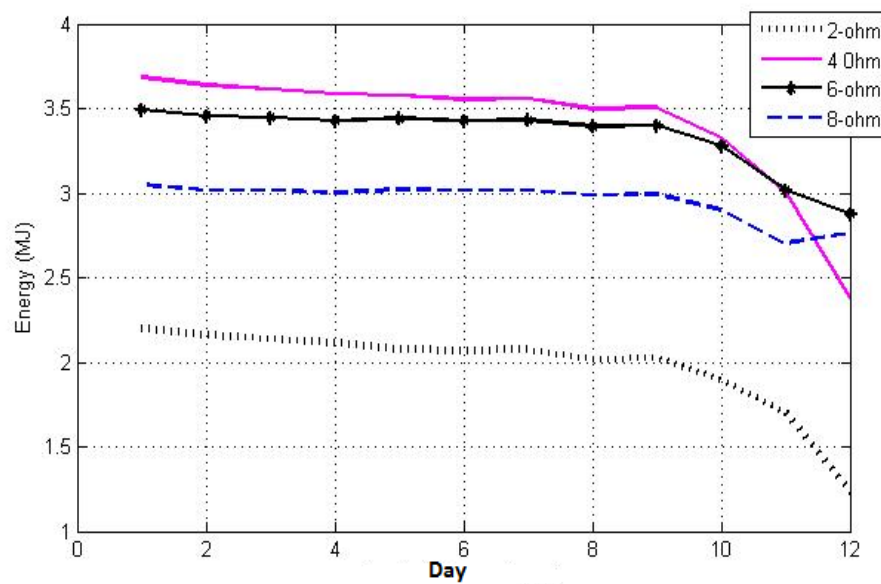


Figure 5.14: Variation in daily Energy output of Kyocera 200GT PV module for the first 12 days of January under different electric load.

CHAPTER SIX

6. Conclusions and Recommendations

Most of previous research papers on solar PV system are concerned only on modelling the electrical characteristics of the PV system using a single diode electrical model, and investigates the effect of environmental parameters, which are radiation intensity and cell temperature on the performance of PV systems. In case of directly coupled PV system the electric load has also an effect on the performance of the PV system. Perhaps, resistor matching technique is one way of optimizing performance of a PV system. In this study, beside the environmental parameters, the effect of electrical loads on the performance of the PV system is investigated on real environmental parameter.

The following conclusions are drawn:

- A detailed mathematical model is developed to calculate the performance parameters of a PV module.
- The developed model is capable of predicting the output parameters such as cell temperature, maximum power point current, voltage, power and efficiency.
- The values computed from the mathematical model are found in good agreement with the experimental data recorded.
- Increase in the solar irradiance provides higher power output but at the cost of reduction in the module efficiency. Absorption of solar radiation increases the temperature of PV cells resulting in a drop of electrical efficiency.
- The increase in the temperature of the PV module is always associated with the reduction in the efficiency.
- The hourly variation in electrical performance of a typical PV panel is simulated under real weather conditions.
- The performance of the PV panel is compared for different electrical loads. The 4 Ω electric load resulted daily energy output of the PV panel for 11 days of the month of January (out of 12 considered days), but in the last day it resulted a poorer performance with respect to the other two electrical loads (i.e. 6 Ω and 8 Ω electric loads). Hence it is concluded that every weather condition doesn't favor a single load all the time, hence to

select a single electric load for a PV panel for its optimized operation at a specific weather condition or site, the same type of analysis shall be done on annual basis.

- With the outcome of this thesis and further development of the overall model, on PV is expected to predict the electrical characteristics of the new PV cells and assess their electrical performance in the overall system from source to the sink (electrical load).
- Full year's data and a computer with a high computing performance will use for best modeling PV solar panel for modeling PV panel for constant load under real parameter is required.
- Modeling of photo voltaic solar panel for constant electric load with storage device coupling effect at specific whether condition for future work.

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Appendix : Specification of solar panels

KC200GT

HIGH EFFICIENCY MULTICRYSTAL
PHOTOVOLTAIC MODULE



HIGHLIGHTS OF KYOCERA PHOTOVOLTAIC MODULES

Kyocera's advanced cell processing technology and automated production facilities produce a highly efficient multicrystal photovoltaic module.

The conversion efficiency of the Kyocera solar cell is over 16%.

These cells are encapsulated between a tempered glass cover

and a pottant with back sheet to provide efficient protection from the severest environmental conditions.

The entire laminate is installed in an anodized aluminum frame to provide structural strength and ease of installation. Equipped with plug-in connectors.



APPLICATIONS

KC200GT Is Ideal for grid tie system applications.

- Residential roof top systems
- Large commercial grid tie systems
- Water Pumping systems
- High Voltage stand alone systems
- etc.

QUALIFICATIONS

- MODULE : UL1703 certified
- FACTORY : ISO9001 and ISO 14001

QUALITY ASSURANCE

Kyocera multicrystal photovoltaic modules have passed the following tests.

- Thermal cycling test
- Thermal shock test
- Thermal / Freezing and high humidity cycling test
- Electrical isolation test
- Hail impact test
- Mechanical, wind and twist loading test
- Salt mist test
- Light and water-exposure test
- Field exposure test

LIMITED WARRANTY

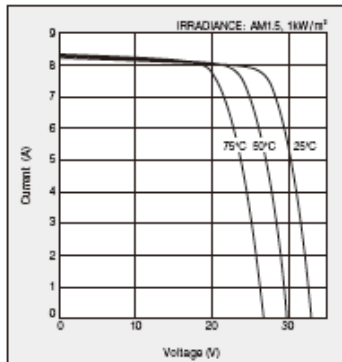
※ 1 year limited warranty on material and workmanship

※ 20 years limited warranty on power output: For detail, please refer to "category IV" in Warranty issued by Kyocera

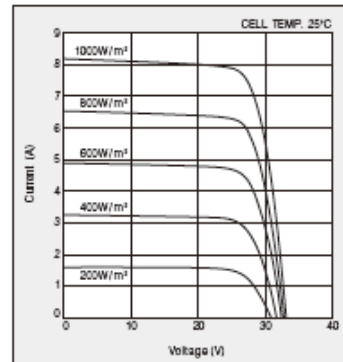
(Long term output warranty shall warrant if PV Module(s) exhibits power output of less than 90% of the original minimum rated power specified at the time of sale within 10 years and less than 80% within 20 years after the date of sale to the Customer. The power output values shall be those measured under Kyocera's standard measurement conditions. Regarding the warranty conditions in detail, please refer to Warranty issued by Kyocera)

ELECTRICAL CHARACTERISTICS

Current-Voltage characteristics of Photovoltaic Module KC200GT at various cell temperatures



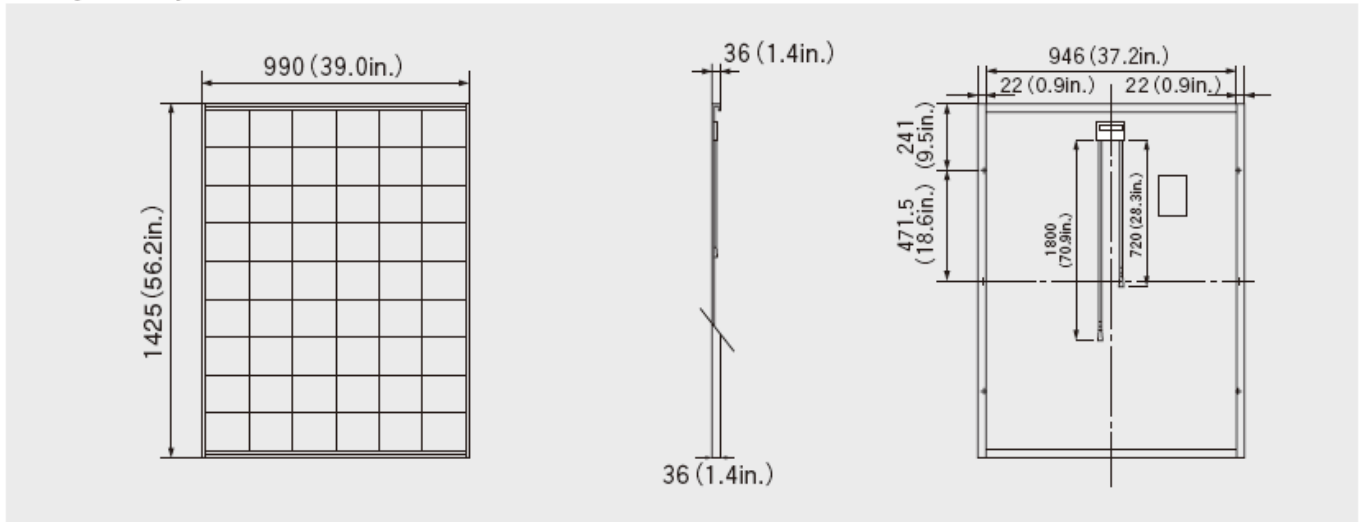
Current-Voltage characteristics of Photovoltaic Module KC200GT at various irradiance levels



KC200GT

Physical Specifications

Unit : mm (in.)



■ Specifications

■ Electrical Performance under Standard Test Conditions (*STC)

Maximum Power (Pmax)	200W (+10%/−5%)
Maximum Power Voltage (Vmpp)	26.3V
Maximum Power Current (Impp)	7.61A
Open Circuit Voltage (Voc)	32.9V
Short Circuit Current (Isc)	8.21A
Max System Voltage	600V
Temperature Coefficient of Voc	$-1.23 \times 10^{-1} \text{ V/}^\circ\text{C}$
Temperature Coefficient of Isc	$3.18 \times 10^{-3} \text{ A/}^\circ\text{C}$

*STC: Irradiance 1000W/m², AM1.5 spectrum, module temperature 25°C

■ Electrical Performance at 800W/m², NOCT, AM1.5

Maximum Power (Pmax)	142W
Maximum Power Voltage (Vmpp)	23.2V
Maximum Power Current (Impp)	6.13A
Open Circuit Voltage (Voc)	29.9V
Short Circuit Current (Isc)	6.62A

NOCT (Nominal Operating Cell Temperature): 47°C

■ Cells

Number per Module	54
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■ Module Characteristics

Length × Width × Depth	1425mm(56.2in)×990mm(39.0in)×36mm(1.4in)
Weight	18.5kg(40.7lbs.)
Cable	(+)720mm(28.3in), (-)1800mm(70.9in)

■ Junction Box Characteristics

Length × Width × Depth	113.6mm(4.5in)×76mm(3.0in)×9mm(0.4in)
IP Code	IP65

■ Reduction of Efficiency under Low Irradiance

Reduction	7.8%
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Reduction of efficiency from an irradiance of 1000W/m² to 200W/m² (module temperature 25°C)