# Techno–Framework of Photovoltaic (PV) and Photovoltaic Thermal (PV/T) Systems

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***Abstract:*** **The swift rise of the average global temperature, as a result of the increasing rates of greenhouse gas emission, is an issue that most countries around the world are pooling in large amounts of resources to solve. In addition, countries all over the world, especially those south of the Sahara Desert have load shedding problem because electricity demand grows faster than the rate at which power plant capacities are increased. In order to ensure high power system stability and reliability with the added benefit of low running cost, while curbing climate change, some of these countries including Ghana are developing their power system around renewable energy resources such as solar. Countries in the tropical zone, specifically, African States have high solar energy potential across the entire region all over the year. However, the usage of solar energy for electricity generation is very low. One way to improve the efficiency of solar PV panels is to increase the energy density of the equipment by combining solar photovoltaic and solar thermal system in a technology known as Photovoltaic Solar Thermal (PV/T) Collector. The study focused on observing the performance of the PV/T system in terms of electrical energy efficiency, and total energy conversion efficiency using MATLAB software. This paper used climatic condition data for Navrongo Solar Power Plant in Ghana as a case study information for the work. The research established that, photovoltaic thermal system has a higher electrical efficiency than an ordinary PV panel (solar photovoltaic system) irrespective of the prevailing weather conditions. However, the thermal energy extracted contributed less than 1% to the overall energy conversation efficiency as a result of a very low flow rate of the working fluid (water).**

***Key Words*: Global Temperature, Greenhouse Gas, Emission, Energy, Solar Photovoltaic System, power, technology**

## I. INTRODUCTION

The demand for electricity increases rapidly as a result of rapid global population growth, urbanization and industrialization. Currently, almost 60 percent of all electricity generated in the world is from fossil fuel sources [1]**.** Fossil fuels such as coal, crude oil and natural gas are non-renewable energies and are therefore exhaustible. These energy sources cannot consequently provide the long-term energy security required to meet future electricity demands. In order to improve energy security and to curb global warming caused by anthropogenic burning of fossil fuels, large investments are being made in the field of solar energy. Solar energy technologies rely on energy sources that are infinite or energy sources that can readily be replenished. Solar Photovoltaic technologies have the fastest growth rate but it is unable to reach its full potential because of high initial capital cost and low energy conversion efficiency.

Developing countries especially those in Africa have periodically been plagued with the problem of shortage of electricity and had resulted to load shedding since the 1980s. For instance, Ghana in 1983, had a fair share of shortage of electricity when her most important source of electricity generation, Akosombo Hydroelectric Dam experienced severe drought. As a result, water level of the Volta Lake that supply the dam with water drop below minimum operating level [2].The severity and frequency of electricity shortage and its attendance load shedding have continued to reduce since then as Ghana diversifies its power generation options. Currently, Ghana’s energy mix consists of hydroelectricity, thermal power (fossil fuel based) and solar power [3].

The demand for electricity grows faster than the rate at which power plant capacities are increased in developing countries hence load shedding still occurs in most of these countries today. As at today, 70% of gross grid generation is obtained from thermal power plants which rely on non-renewable energy for their operation [4]. The price of fossil fuels on the world market is always changing and this translates to fluctuating end – user tariffs. In order to ensure high power system stability and reliability with the added benefit of low running cost, Africa has to develop its power system around resources that are abundant in the continent. By virtue of the location of the continent in the world, Africa has comparative advantage in using solar energy to generate electricity. Two techniques are used in this endeavour; they are Solar Photovoltaic (PV) system and Solar Thermal System.

The main aim of this paper is to combine Solar Photovoltaic (PV) and Solar Thermal Systems to obtain solar power generating system known as Photovoltaic Thermal (PV/T) System; and how their combination would improve the performance and electrical energy efficiency of generating electricity from solar source. In this vein, the authors would focus on non – concentrating solar collector to operate the Photovoltaic Thermal (PV/T) System.

*1.1 Solar Energy*

The sun is the ultimate source of energy for the Earth, without which life on the planet could not be possible. The sun is an inexhaustible power source as a result of the fusion reactions occurring constantly in its core. The sun supplies the upper atmosphere of the Earth with 174 Petawatts (PW) of energy but a maximum of 1 kW reaches every square meter of the ground; this is due to the Earth's atmosphere, reflective objects on the surface of the Earth among other factors [5]**.** Even though a large percentage of the energy supplied by the sun is lost, solar energy reaching the Earth's surface is enough to produce 50 – 1500 TW of power (depending on location and land fraction) assuming 10% solar-to-electricity conversion efficiency [6]**.** In addition to the sun's high electrical power potential, the sun is the driver of other renewable energy sources. These sources include: wind energy, hydropower, ocean thermal energy, bioenergy and wave energy. These are possible as a result of the following functions performed by solar radiation:

1. Sensible heating – this brings about ocean thermal energy, solar heating, solar drying among others;
2. Latent heat of water evaporation – this drives the water cycle and hence the sun is the indirect source of hydropower;
3. Kinetic energy – this brings about wind energy and waves; and
4. Photon processes – this drives photosynthesis and hence the sun is the source of bioenergy.

Photovoltaic technologies also rely on the visible light produced by the sun. Solar energy is an invaluable energy source that is more evenly distributed than any other energy source in the world. As a result of the fact that solar energy reaches every part of the world (at different intensities), solar energy technologies are the fastest growing renewable energy technology today [7].

Solar radiation interacts with the atmosphere (which contains clouds and aerosols) before reaching the ground. The atmosphere consists of elements which reflect, refract and scatter solar radiation. The interaction of solar radiation with the atmosphere changes its nature and hence solar radiation reaching the ground has three main forms. These forms are:

1. Beam or direct solar radiation: is the radiation received without being scattered by the atmosphere;
2. Diffused solar radiation: is the radiation received after its direction has been changed by refraction and scattering by the atmosphere; and
3. Albedo or reflected solar radiation: is the solar radiation received from the ground or the environment and is zero for a horizontal surface.

The sum of all the forms of solar radiation reaching the Earth is known as global solar radiation but as diffuse radiation increases, the energy contents of global radiation reduces**.** Figure 1.1 shows the journey of solar radiation from the sun to the surface of Earth as well as the components of global radiation.

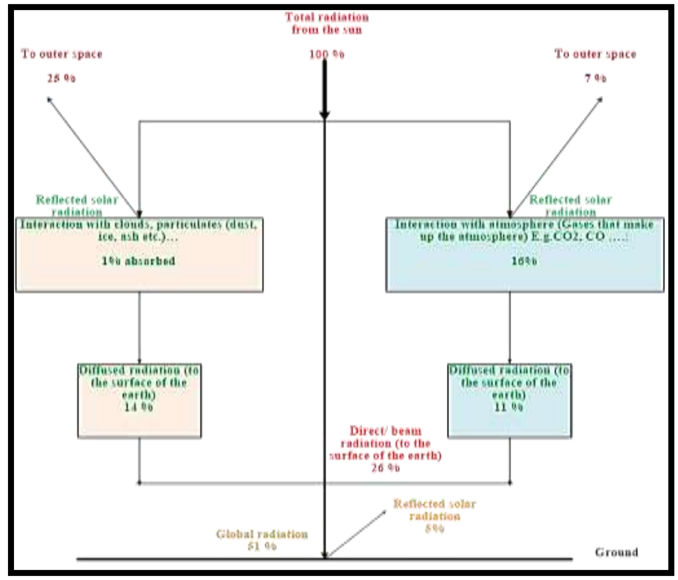


Fig 1.1: Components of Global Radiation

*1.2 Solar Energy Measuring Instruments*

In siting solar energy technologies, it is important to have data on solar radiation in order to determine the best location to site the system. There are three main instruments used in measuring solar radiation. These instruments are: pyrheliometer, pyranometer and albedo meter. The pyrheliometer has a restricted view and thus it is used to measure beam radiation by pointing the instrument towards the sun. It is always assembled on a sun tracker. Figure 1.2 shows a pyrheliometer.

Fig 1.2: Pyrheliometer

The pyranometer has a hemispherical view and thus measures global radiation. In order to measure diffused radiation using the pyranometer, a shade ring is fitted on the instrument to block beam radiation (the method needs a correction factor since the shade ring also blocks diffused radiation). Figure 1.3 shows a pyranometer.

Fig 1.3: Pyranometer

The albedo meter is made up of two identical pyranometers, one facing up and the other facing down. Figure 1.4 shows an albedo meter.

Fig 1.4: Albedo Meter

The pyranometer facing the sky measures the global radiation while the pyranometer facing the ground measures the radiation reflected by the Earth (albedo radiation).

*1.3 Solar Energy Technologies*

Solar energy technologies are a class of renewable energy technologies that convert solar radiation into other forms of energy (i.e. electricity and heat). The two main solar energy technologies currently available are:

1. Solar Photovoltaic (PV) systems (converts the visible light spectrum of solar radiation into electrical energy directly).
2. Solar Thermal systems (converts the infrared spectrum of solar radiation into heat).

Solar power is non – dispatchable and cannot be used on demand due to its high intermittency and variability and this is the biggest limitation on the use of solar energy technologies. The intensity of solar radiation reaching the Earth's surface depends on factors such as weather condition, time of day, location, the nature of the environment among others and therefore solar energy technologies (especially solar thermal systems) cannot be both technically viable and cost – effective in all parts of the world. The advantage these technologies have over most power systems is its wide array of applications and because of their nature, they can be used for both centralised and decentralised electrical and/or heat energy productions.

*1.4 Solar Collector Orientation*

The performance of a solar collector (both solar thermal and solar PV collectors) is dependent on the solar radiation reaching the surface of the collector. To obtain a high amount of solar radiation hitting the surface of a solar collector, the tilt angle (the angle the collector makes with the horizontal surface or ground) of the collector is the most important determining factor [8]. A tracking system is an automated device that tracks the sun to ensure that the collector faces the sun at the optimal tilt angle throughout the day, and using this device ensures the solar collector receives maximum solar radiation. The solar tracker is however expensive and may not be a technically and economically feasible for all solar power projects, therefore it is practical to orient the solar collector at a fixed optimum tilt angle and to correct the tilt seasonally. For a solar collector without a tracking device, the collector surface should be oriented such that the collector surface faces the equator (Earth). That is, solar collectors should face south in the Northern hemisphere, and north in the Southern hemisphere. Figure 1.5 shows the tilt angle of a solar collector.

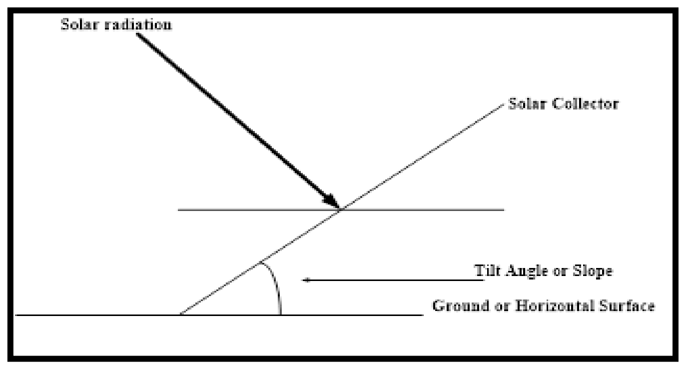


Fig: 1.5 Tilt Angle of a Solar Collector

The optimal tilt angle for a particular location can be derived using complex equations that estimate the angle based on the coordinates of the location (longitude and latitude), the day of the year, the solar noon of the location (the time of day that the sun is positioned directly overhead) among many other factors. The conclusion is that the optimal tilt angle for any location for a fixed solar collector is the latitude of that location [9], [10].

It is argued that basing the estimation of the optimal tilt angle solely on the geometry of the Earth and the sun will not yield a very precise result since the tilt angle is also dependent on factors such as weather conditions (cloud cover characteristics of the location) and the altitude above sea level [11]. Global climate model, GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model) as well as existing optimal tilt data by country and by latitude, is then used to estimate a more accurate optimal tilt angle for all countries of the world, examining a futuristic 2050 scenario, where aerosol, cloud, temperature, and wind speed properties differ from today's.

### *1.5 Solar Photovoltaic System*

Photovoltaic System is a structure that converts radiation of the sun in the form of light into electricity. It composes of the solar array and balance of system (BOS) components such as: inverters, racking, wiring, solar combiner, solar disconnects, circuit breakers and electric meters. The arrangement of these components to generate electricity is as shown in figure 1.6.

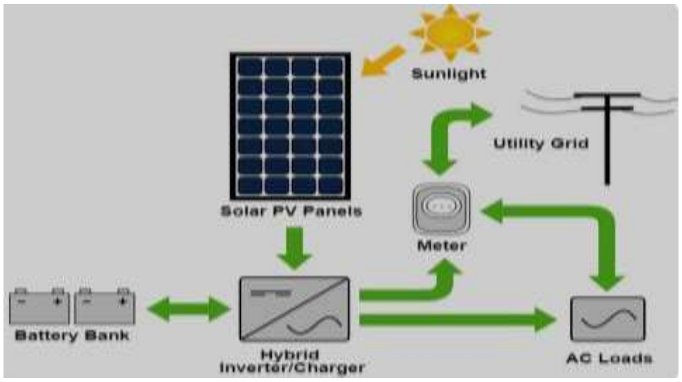


Fig 1.6: Photovoltaic System

The function of the system is such that light energy from the sun known as photons drops on the solar PV array (solar panels) creating electric current in a process called photovoltaic effect. This electricity so generated from the solar array is in the form of direct current (DC). Even though, the direct current can be used to operate many electronic devices such as mobile phones and laptop computers directly; for grid utility or grid-tied PV system seek, this current is converted to alternating current (AC) by inverter. The AC electricity from the inverter can be used at home locally to run electronic appliances or sent onto the national electricity grid for usage elsewhere. This PV system can be grid connected or off-grid connected (standalone PV system) where storage mechanism such as battery bank will be required.

The racking which is a mounting apparatus is used to fix the solar array firmly to the ground or rooftop as the case may be. The solar combiner is used to aggregate or combine two or more electrical cables into one larger one; this combiner includes fuses for protection. The solar disconnects are switches or electrical gates that are used to disconnect electrical wire manually and serve as electrical isolation when an inverter needs to be installed or replaced. The solar disconnect before the inverter is called DC disconnect and the one after is AC disconnect. The circuit breakers are used to protect the electrical systems from over current or surges. The electric meter measures the quantity of electricity that passes through it. This measurement device is used by electric utility companies to measure and charge customers. For solar PV systems, a special bi-directional electric meter is used to measure both the incoming electricity from the utility, and the outgoing electricity from the solar PV system. The wiring or electrical cables convey the electrical energy from one component to another.

A solar cell is a semi – conductor device that converts the visible light from solar radiation into electrical energy directly. The solar cell operates on the photovoltaic effect which was discovered by French Scientist Alexander-Edmond Becquerel in 1839, when he experimented with an electrolytic cell and noticed that electricity generation increased when the cell was exposed to light [12]. The first solar cell did not produce substantial amount of electrical current and hence it was not considered as a power source until 1954 when Daryl Chapin, Calvin Fuller and Gerald Pearson developed a new solar cell using doped semiconductor silicon [13]. The solar cell has evolved significantly since then and currently there are three (3) generations of solar cells. The first-generation solar cells are crystalline silicon types (monocrystalline and polycrystalline solar cells). The second-generation solar cells are thin film types ($CuInGaSe_2$ (CIGS), amorphous Si, and CdTe) and the third-generation solar cells are the nanostructures, dyes and organic materials types which has not been commercialized yet [14]. A comparison of the common types of solar cells is made in Table 2.1.

Table I: Comparison of the Common Types of Solar Cells

| | First Generation Solar Cells | | Second Generation Solar Cells (Thin films) | | |
|---|---|---|---|---|---|
| Property | Mono – crystalline | Poly – crystalline | Amorphous Silicon | Cadmium Telluride (CdTe) | Copper Indium Diselenide (CIS) |
| Efficiency | 15% and above | 12% | 6% | 8 or 9% | 10-13% |
| Cost | Highest | Moderate | Lowest | | |
| Energy density | Highest | Moderate | Lowest | | |
| High Temperature Performance | Lowest | Lowest | Better | | |
| Generation in Diffused Light | Average | Average | Better | | |

### *1.5.1 Working Principle of the First-Generation Solar* Cell

A solar cell or photovoltaic cell is a device that converts light particles in DC current and voltage. The first-generation solar cells are silicon – based and they are produced using $SiO_2$ as raw material. Silicon is an atom with four valence electrons therefore, it is a semiconductor. The photovoltaic effect occurs in semiconductor materials and it involves the release of electrons from a material when in contact with photons (light particles). The flow of electrons creates electric current but electrons are usually tied up in the valence band (low energy level) of an atom (semiconductor). The electrons have to be in the conduction band (high energy level) in order to flow and produce current. An energy barrier (or band-gap energy) separates the valence band from the conduction band and has to be overcome in order for electrons to move from the low energy level to a high energy level. Photons provide the energy needed to overcome the band-gap, when the photons strike the surface of the semiconductor, some of the valence electrons are ejected into the conduction band and thus electrons are available for conduction of electricity. Figure 1.7 illustrates the photovoltaic effect.

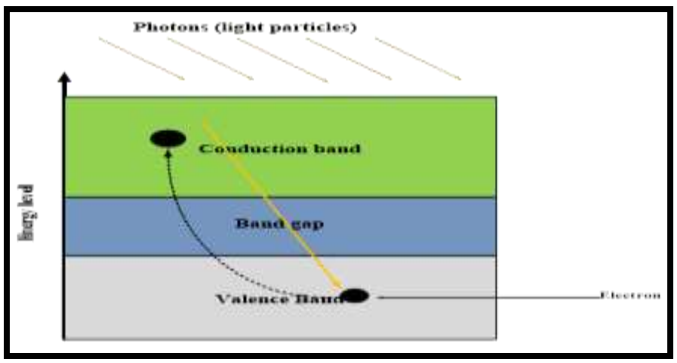


Fig 1.7: Photovoltaic Effect

### *1.5.2 Structure of a Silicon based Solar Cell*

The valence electrons in the silicon atom are held in the valence band by the nucleus (positively charged) of the silicon atom. After the photovoltaic effect occurs and electrons are released into the conduction band, they are easily pulled back into the valence band by the nucleus before electric current can be produced.

In order to produce power, the solar cell is made up of two thin sheets of silicon crystal, each doped (addition of impurities) with a different substance. One silicon sheet is doped with a small quantity of an element that has five valence electrons (to create additional electrons) such as phosphorus or arsenic to create an n-type semiconductor. The other sheet is doped with an element that has three valence electrons typically boron or gallium (to create positive holes – absence of electrons) to form a p-type semiconductor. Detached, both the n-type and p-type semiconductors are electrically neutral (that is, in the n-type material the negative charge of the extra electrons is balanced by the higher positive charge of the dopant nuclei, and in the p-type material the extra holes are balanced by the lower positive charge of the dopant nuclei).

A P-N junction is formed when the p-type and n-type semiconductors are joined. When joined, extra electrons from the n-type semiconductor move to the positive holes in p-type semiconductor. This makes the portion of n-type material close to the PN junction positively charged while the p-type material becomes negatively charged in the vicinity of the junction. An electric field is created across the junction but no electricity is produced because of the equal flow of electrons in both directions across the junction.

In a solar cell, the n-type semiconductor faces the incoming solar radiation. When solar radiation strikes the solar cell, excess electrons flow from the n-type material through the external circuit to the p-type material. This makes the p-type material more negatively charged and with the help of the electric field across the junction, excess electrons are conducted across the junction back to the more positively charged n-type material. This creates a closed loop of electron flow thereby producing electricity. Figure 1.8 shows the flow of electron within a solar cell.

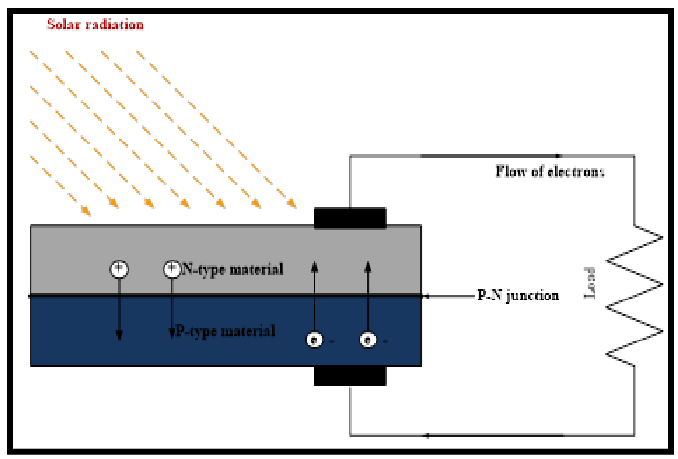


Fig 1.8: Production of Electricity from a Solar Cell

### *1.5.3 Building Blocks of a Solar Photovoltaic (PV) Collector*

A single solar cell produces a voltage of about 0.5 V and current density of 400 A/m$^2$ at standard test condition (operating at a temperature of 298 K, with an insolation of 1000 W/m$^2$ and air mass of 1.5)**.** In order to produce more power, solar cells are collected in series and parallel depending on the power requirement of the load. Solar cells connected in series are called strings. Strings are connected in parallel to form a solar PV module (solar PV panel). Solar PV modules can also be connected in series and parallel (based on the power requirement of the load) to form a PV array so as to produce even more power. Figure 1.9 shows the building blocks of the solar photovoltaic collector system.

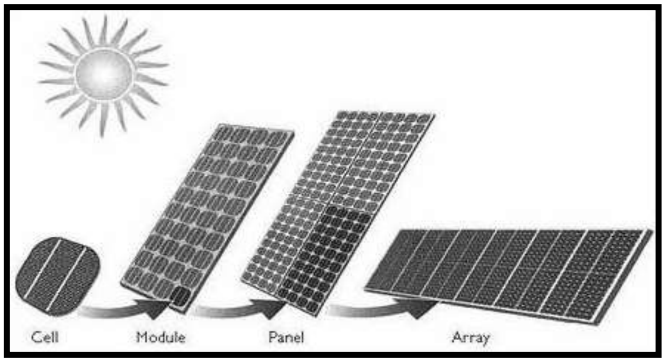


Fig 1.9: Building Blocks of the Solar Photovoltaic Collector System

*1.6 Solar Thermal System*

The solar thermal collector is the core of a solar thermal system and it is a special heat exchanger that converts solar radiation into heat. It is electricity generating method where mirrors or lenses (collectors) are used to concentrate the sun's rays or energy to heat fluid (water, oil etc) often using conventional steam turbine. The first solar thermal collector was constructed in 1767 by Swiss scientist Horace de Saussure (which were called “Hot Boxes” at the time) and was used in the 1830s by Sir John Herschel to cook food during his tour of South Africa (U.S. Department of Energy, 2002). Unlike conventional heat exchangers, heat is transferred to the working fluid predominantly by radiation heat transfer. The solar thermal collectors are classified based on the type of working fluid (air, water, thermal oils), the type of mechanism used (solar tracker), the operating temperature and whether or not mirrors or lenses are used to concentrate solar radiation (main types). They are selected based on the field of application of the captured heat. There are six main solar thermal market areas, namely:

1. Solar water heating;
2. Space heating;
3. Industrial process heat;
4. Solar cooling;
5. Thermal power generation; and
6. Solar ponds.

Non – concentrating solar collectors are used for low temperature applications (such as water and space heating) and are the most widely used type currently. These solar collectors convert global radiation into heat while the concentrating types rely solely on direct radiation and hence the concentrating types cannot operate properly on overcast days [15]. For high temperature applications (such as thermal power generation and industrial process heat), the concentrating solar collectors are used since direct solar radiation cannot raise the temperature of the working fluid above 100℃. The concentrating solar collectors that are commercially available are:

1. Parabolic Trough (working fluid is heated to 150 – 390 ℃) [16]
2. Linear Fresnel (working fluid is heated to 150 – 300 ℃).
3. Parabolic Dish System (working fluid is heated to 250–700 ℃) 17]; and
4. Solar Tower (working fluid is heated to 500 – 1000 ℃.

*1.6.1 Non – Concentrating Solar Collectors*

There are two main types of non – concentrating solar collectors. They are Flat Plate Collectors and Evacuated Tube Collectors. These collectors can be further classified based on whether or not their means of energy collection is active or passive. Active energy collection involves the use of pumps, valves and controllers to circulate the working fluid through the collector for more efficient heat collection. The passive energy collection technique relies on the thermosiphon phenomenon. That is water flows through the collector because of the difference in density of the warm water in the collector and the cool water in storage tank. The aim of this technique is to circulate the working fluid through the collectors and as a result, these systems are cheaper to construct and have low maintenance costs.

*Flat Plate Solar Collectors:*

There are two main types of flat plate solar collectors. They are glazed and unglazed flat solar collector. The glazed flat plate collector generally consists of:

1. Sealed heat enclosure holds all the collector components in place and keep them safe from dust, moisture and other external factors which may damage these components.
2. Manifold or header collection tubes: There are two and they are normally installed at the top and bottom of the collector for draining the heat transfer fluid into and out of the collector system.
3. Heat absorbing riser tubes which are tube embedded in the absorber sheet (or plate) through which the heat transfer fluid flows.
4. Absorber plate is a dark coloured metal surface to which the heat absorbing riser tubes are attached and it absorbs solar energy and transfers heat to the riser tubes.
5. Glazing sheet that may include one or more layers of glass or transparent plastic and traps solar energy within the system and prevents heat loss from the absorber.
6. Insulation (the insulation material is usually aluminium, glass wool, wood or foam) reduces heat loss from the back of the collector, the tubes and along the side walls of the frame [18].

The main difference between the glazed and the unglazed flat plate collector is the absence of a glazing sheet and insulation materials (in the unglazed flat plate collector). The unglazed flat plate collector significantly cheaper than the glazed flat plate collector and is suitable for heat applications where temperatures must be slightly higher than the ambient temperature. Figure 1.10 shows a schematic of a glazed flat plate solar collector.

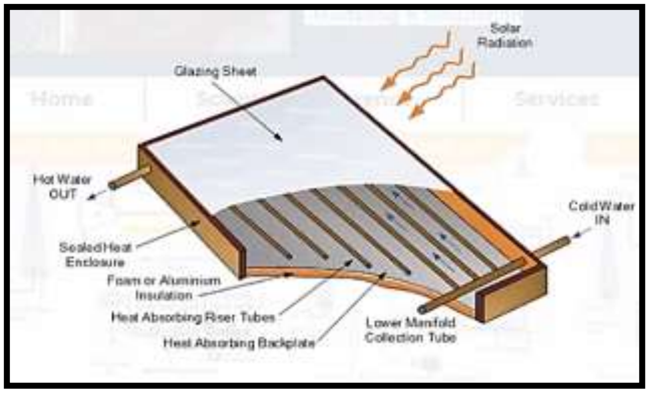


Fig 1.10: Glazed Flat Plate Solar Collector

*Evacuated Tube Solar Collector:*

The Evacuated Tube Solar Collector presents a more efficient method of solar energy capture (as compared to the flat plate collector). This collector is made up of multiple columns of transparent cylindrical evacuated tubes which replaces the heat absorber in the flat plate collector. The cylindrical nature of the glass tubes aids the Evacuated Tube Solar Collector to passively track the sun throughout the day and therefore has very high performance even on periods of the day when solar radiation is low. The evacuated tubes of this collector is devoid of air, therefore conductive and convective heat losses from the tube is very low. Generally, an evacuated tube solar collector consists of the following components:

1. Evacuated glass tubes are usually made from borosilicate glass (which has high chemical and thermal shock resistance) and consists of two glass tubes with a vacuum between the walls. The outer tube is transparent allowing light rays to pass through with minimal reflection while the inner tube is coated with a selective coating which ensures maximum solar radiation absorption and minimal light reflection properties [19].
2. The Barium Getter removes air between the two glass tubes and forms a layer at the bottom of the outer glass tube. The barium layer also provides a clear visual indicator of the vacuum status since it changes into a milky colour when exposed to air.
3. Storage tank stores the water and mainly consists of two tank (an inner tank and an outer tank). The gap between the two tanks is filled by insulating materials (such as mineral wool) to reduce the heat losses from the solar heated working fluid inside the inner tank.
4. Mounting frame is the structure on which the components of the thermal collector is mounted.
5. External water supply source; it supplies the water to the storage tank of evacuated tube solar water heater. Figure 1.11 shows an evacuated tube solar collector.

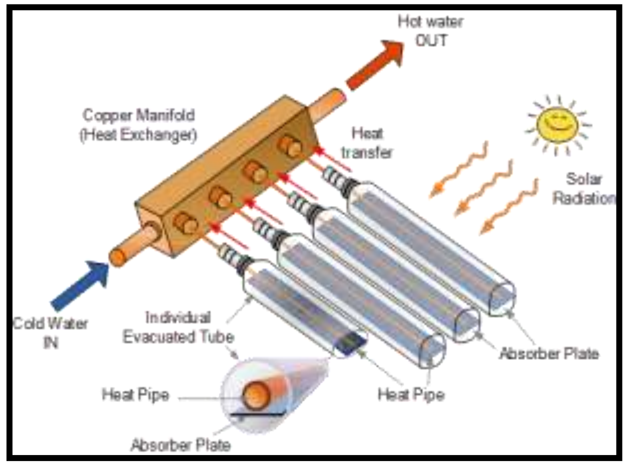


Fig 1.11: Evacuated Tube Solar Collector

The Evacuated Tube Solar Collector is significantly more expensive than the conventional flat plate solar collectors. It is designed to operate within a temperature range of 77 – 177 ℃ and is more suitable to non – tropical climates. The function of solar thermal system is such that a concentrated sun energy is used to heat water or any other fluid in a boiler to a very high temperature. The steam emanating from the boiler is converted into mechanical energy to turn a turbine. This turbine then powers a generator to produce electricity. For optimized concentration of the sun energy on the reflectors (mirrors) of the solar thermal system, tracking structures are employed to keep sunlight focused on the mirrors throughout the day as the sun changes position in the sky. A schematic diagram of Solar Thermal System is as shown in figure 1.12.

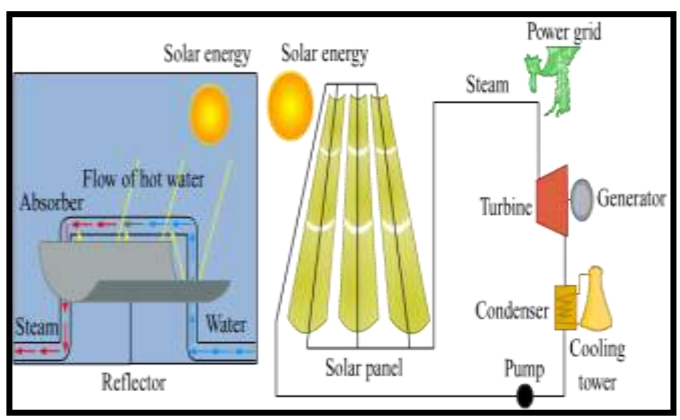


Fig. 1.12: Schematic Diagram of Solar Thermal System

*1.7 Photovoltaic Thermal (PV/T) System*

Photovoltaic Solar Thermal (PV/T) Collector is a system developed by the combination of the Photovoltaic System and Solar Thermal System. This combination enables the production of electricity and heat concurrently. The photovoltaic collector is the heat absorber and it serves as the source of heat to the solar thermal collector in this system. Photovoltaic Solar Thermal (PV/T) Collector system research started in the 1970s, the system was designed mainly to improve the overall efficiency of both the Solar Photovoltaic System and Solar Thermal System [20]. Most research conducted during that time, on PV/T systems used both theoretical analysis and experimentation to study the system, and a comparison between the simulated results and experimental data were made. There are many configurations of the PV/T collectors and in recent times, research focuses on the analysis of their configurations. A schematic diagram of the constituents of the PV/T system is shown in Figure 1.13. The performance of photovoltaic system or collector decreases with increase in the solar PV array or modules.

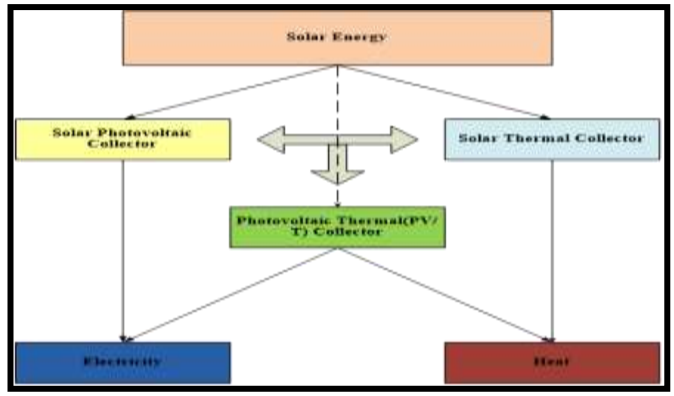


Fig 1.13: Schematic Diagram of the constituents of PV/T system

The PV/T system therefore improves the efficiency of the PV array by extracting heat from the PV modules, thereby decreasing the temperature of the modules and improving the performance. The heat extracted from the PV modules could be used for several heating purposes, including feed-in-water for boilers and room heating. A schematic illustration of Photovoltaic Thermal (PV/T) System is depicted in figure 1.14.

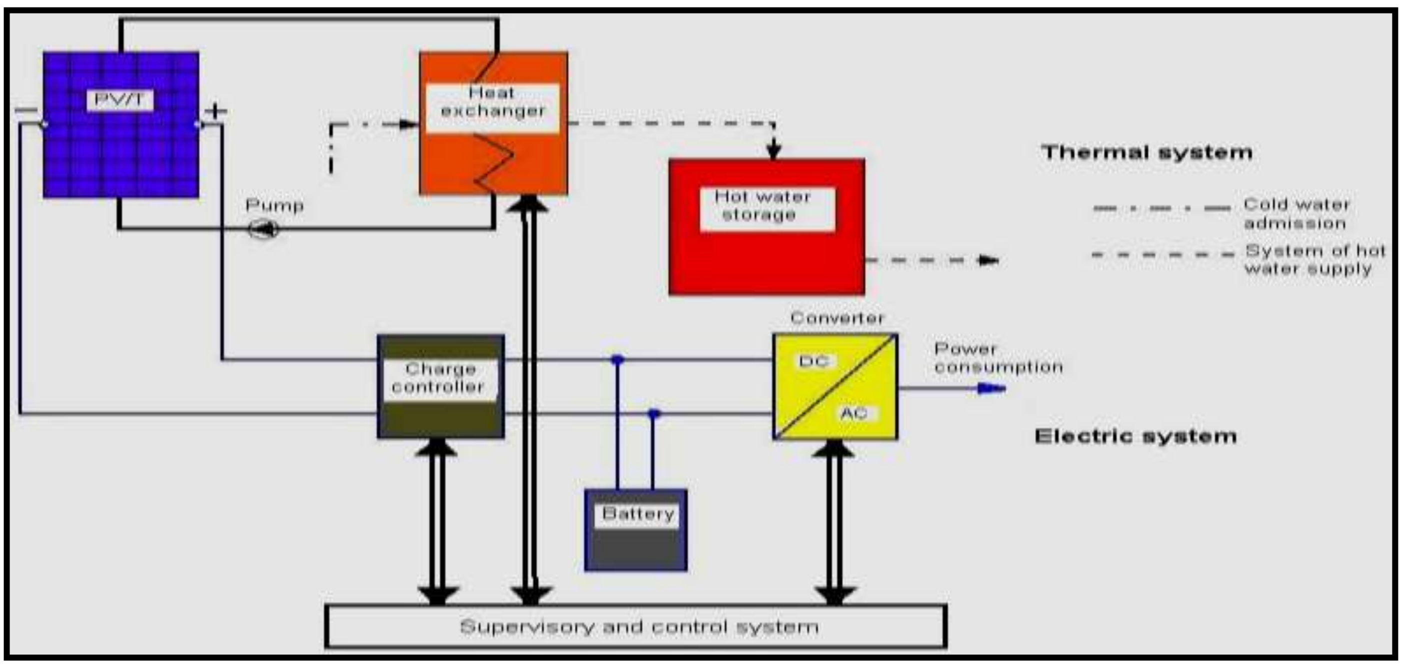


Fig. 1.14: Schematic Illustration of PV/T System

*1.8 Navrongo Solar Power Plant in Ghana: Case Study*

This paper is limited ONLY to the climatic conditions prevailing in Navrongo Solar Power Plant and NOT the plant itself. This solar power plant is purely grid-tied solar photovoltaic system. Navrongo is among the areas in Ghana with the highest solar radiation of about 5.5 kWh/m²/day.

This Solar Power Plant is owned by Volta River Authority (VRA) and was the first large-scale or utility-scale power plant in Ghana. The 9 million US dollar solar power plant has an installed capacity of 2.5 MW and capable of generating up to 3.8GWh of electricity per annum [21]**.** This plant is located in Navrongo, Northern part of Ghana and about 10km from Ghana-Burkina Faso border. The Navrongo solar power plant was commissioned in June 2013. The solar plant was built by a Chinese company known as China Wind Power (CWP). Electricity from the plant is integrated into the national grid through an off-taker company by name Northern Electricity Distribution Company (NEDCo).

## II. RESEARCH METHODOLOGY

The research methodology of this paper presents the modelling of photovoltaic system and photovoltaic thermal system using MATLAB based on solar and weather data from Navrongo, Ghana. The main constituents of the system are a 350 W monocrystalline solar PV panel, a water tank, a water pump and a solar thermal collector. The performance of the solar PV panel model would be compared to the performance of PV/T model. To achieve this, in these two scenarios (PV System Only and PV/T System). We would use mathematical equations to simulate the output performance of these systems.

### *2.1 Average Hourly Solar Radiation Data for Navrongo (May and August)*

Navrongo receives the highest solar radiation in May and the lowest in August [22]. The optimal angle of inclination for solar collectors in Ghana is 5°, facing south however, the solar collector is required to be tilted 10° for self-cleaning of the solar collector surface [23]. Solar radiation reaching an inclined surface is given by

*Equation 2.1.*

$$G_T = G_b \cos\theta + G_d \qquad \textbf{(2.1)}$$

Where:

$G_T$ = the total solar radiation reaching the surface of the solar collector
$G_b$ = beam radiation
$G_d$ = diffuse radiation
$\theta$ = the angle of inclination of the PV/T collector

*Equation 2.2* gives the effective absorbance of the solar cell.

$$G = G_T \cdot \left(\frac{\alpha_{pv}\cdot\tau}{1-(1-\alpha_{pv})\times p_{drr}}\right) \qquad \textbf{(2.2)}$$

Where:

$G$ = the solar radiation absorbed by the solar cell
$\alpha_{PV}$ = the absorbance of the solar cell.
$\tau$ = transmittance of the glass cover
$p_{drr}$ = diffuse radiation reflectance = 0.16

The solar insolation (solar energy per unit area) is used for modelling of the PV/T system. Solar radiation (solar power per unit area) data is recorded at one-hour intervals which is equivalent to 3600 seconds. The relation that converts solar power to solar energy is given by

*Equation 2.3:*

$$E_T = G_T \cdot 3600 \qquad \textbf{(2.3)}$$

Where:

$E_T$= the total solar insolation reaching the surface of the solar collector.

### *2.2 Mathematical Modelling of a Solar Cell*

The solar cell is the basic building block of a solar PV panel; because solar cells are connected in series and/or parallel to form a solar PV module. The output power characteristic of a solar cell mainly depends on solar radiation and the cell temperature. A solar cell has non-linear power output power characteristics and can be modelled using a diode, a series resistor, a shunt resistor and a current source connected together in an electrical circuit [24]. Figure 2.4 shows the equivalent electrical circuit of a solar cell.

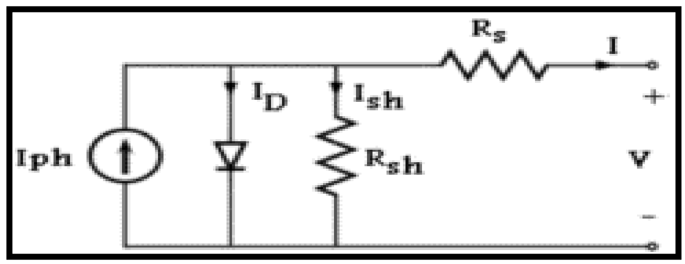


Fig 2.1: Equivalent Electrical Circuit of a Solar Cell

From Kirchhoff's junction rule, the total current produced by a solar cell is given by:

*Equation 2.4.*

$$I = I_{ph} - I_D - I_{sh} \qquad \textbf{(2.4)}$$

Where:

$I$ = the output current of the solar cell.
$I_{ph}$= photo-current produced by the solar cell.
$I_D$= diode current (current passing through the diode).
$I_{sh}$= shunt current (current passing through the shunt resistor).

The photocurrent produced by the solar cell is dependent on solar radiation and operating temperature and is mathematically represented by

*Equation 2.5.*

$$I_{ph} = \left[I_{sc} + \left(K_{is}(T-298)\right)\right]\cdot\frac{G}{1000} \qquad \textbf{(2.5)}$$

Where:

$I_{sc}$ = the short-circuit current.
$K_{is}$ = the short-circuit current of the cell at standard testing conditions.
$T$ = the solar cell operating temperature.

The diode current can be mathematically represented using the Shockley equation which is given by

*Equation 2.6.*

$$I_D = I_o \cdot \left[exp\left(\frac{(V+IR_S)}{n\cdot N_S\cdot V_t}\right) - 1\right] \qquad \textbf{(2.6)}$$

Where:

$I_o$= reverse saturation current of the diode.
$V$ = the voltage across the diode.
$R_s$ = the series resistance (it has a very small value; 0.01 ohms).
$n$ = the ideality factor of the diode.
$N_s$ = the number of solar cells in the PV module connected in series.
$V_t$ = the diode thermal voltage.

The diode thermal voltage is given by

*Equation 2.7.*

$$V_t = \frac{k \cdot T}{q} \quad \textbf{(2.7)}$$

Where:

$k$ = Boltzmann's constant
$q$ = the charge of an electron

The current passing through the shunt resistor (shunt current) is very small because the shunt resistor has a very high resistance (1000 ohms). The shunt current of the solar cell is given by

*Equation 2.8.*

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \quad \textbf{(2.8)}$$

Where:

$I_{sh}$ = the shunt current
$R_{sh}$ = the shunt resistance

Putting equations 2.2, 2.3, 2.4 and 2.5 into equation 2.1 will yield the overall mathematical model of the solar cell as shown in

*Equation 2.9.*

$$I = \left[\left[I_{sc} + \left(K_{is}(T - 298)\right)\right] \cdot \frac{G}{1000}\right] - I_0 \times \left[exp\left(\frac{q \cdot (V + IR_s)}{n \cdot k \cdot N_s \cdot T}\right) - 1\right] - \left[\frac{V + IR_s}{R_{sh}}\right]$$
**(2.9)**

A diode is a device that allows current to flow in only one direction. When a diode is forward bias, current flows from the anode to the cathode. Reverse saturation current in a solar cell (also known as dark current) is the small amount of current that flows in the opposite direction, that is, this current flows from the cathode to the anode [25]**.** The reverse saturation current in large amounts can damage the solar and should be taken into consideration when modelling a solar cell to avoid undesired operation. The reverse saturation current is given by

*Equation 2.10.*

$$I_0 = I_{oref} \cdot \left[\frac{T}{T_{ref}}\right]^3 \cdot exp\left[\frac{q \cdot E_{go} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}{n \cdot k}\right] \quad \textbf{(2.10)}$$

Where:

$T_{ref}$ = the reference temperature.
$E_{go}$= the band gap energy of silicon.
$I_{oref}$ = the reverse saturation current at the reference temperature.

The reverse saturation current at the reference temperature is given by

*Equation 2.11.*

$$I_{oref} = \frac{I_{sc}}{\left[exp\left(\frac{(q \cdot V_{oc})}{n \cdot N_s \cdot k \cdot T}\right) - 1\right]} \quad \textbf{(2.11)}$$

Where:

$V_{oc}$ = the open-circuit voltage.

*2.3 Design Specifications of the Solar PV Panel used in PV/T Model*

The solar panel used for the PV/T modelling is a 96 cell 350 W rated monocrystalline solar PV panel manufactured by Solare Ben solar panel manufacturing company. Standard Testing Conditions (STC) of the solar panel are a solar irradiance of 1000 W/m$^2$, 298 K cell temperature and an air mass of 1.5. Figure 2.2 shows the dimensions of solar PV panel.

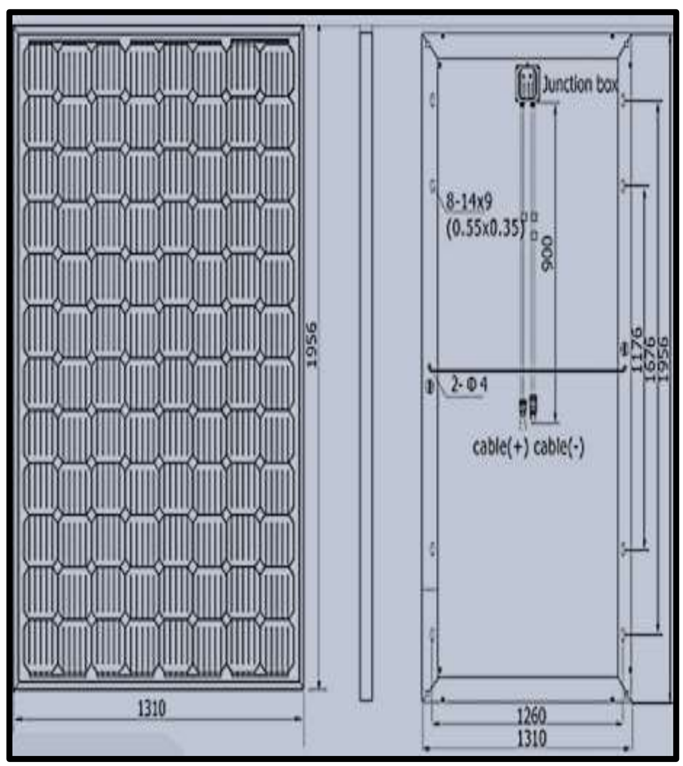


Fig 2.2: Dimensions of the Solare Ben 350 W Solar PV Panel

Table I displays the design specifications of the solar PV panel used in the PV/T simulation.

Table I: Solar PV Panel Design Specifications

| Solare Ben PV Module Properties | Values |
|---|---|
| Rated power | 350W |
| I-rated | 9.48 A |
| V-rated | 36.9 V |
| VOC | 43.80 V |
| ISC | 10.43 A |
| Cell Efficiency | 19.97% |
| Module Efficiency | 18.13% |
| Power Tolerance | 0~+5% |
| Number of series connected cells | 96 |
| Number of parallel connected cells | 1 |
| Short-circuit current of cell at STC | 0.0032 A/K |

The mathematical model of the solar cell is mainly dependent on the cell temperature, T. The solar cell temperature as a function of ambient temperature is given by

*Equation 2.12.*

$$T = T_e + \left(T_{ref} - 20\right) \cdot \frac{G}{800} \quad \textbf{(2.12)}$$

Where:

$T_e$ = the temperature of air surrounding the panel (air temperature).

With the mathematical model developed, the hourly output power of the Solare Ben solar PV panel can be determined. The performance of the PV only system would be a baseline on which the performance of the PV/T system can be compared. To determine the performance of the PV/T system, a thermal model of the system is required. This was achieved through energy balance equation.

*2.4 Thermal Modelling of the Photovoltaic Thermal Collector*

The thermal modelling of the photovoltaic thermal collector is done on the basis of the energy balance equation which is given by

*Equation 2.13:*

Heat in an area = Heat leaving the area + Heat stored by the area **(2.13)**

Assumptions are required for thermal modelling to reduce the scope of the model and make computation easy. The assumptions made for modelling the PV/T system is as follows:

1. No heat loss occurs at the edges of the PV/T system;
2. The thermal and optical properties of the layers of the PV/T system are constant;
3. Heat transfer is one dimensional.
4. Thermal resistance between the layers is negligible;
5. PV/T shading or dust on the glass surface is not considered;
6. The ambient temperature is equal around the PV/T collector; and
7. Wind speed at the back of the PV/T collector, inclined at 10 degrees, is close to zero.

The modelling of the PV/T system would be divided into six different layers namely:

1. Energy balance of the glass cover;
2. Energy balance of the solar PV module;
3. Energy balance of the absorber;
4. Energy balance of the insulator;
5. Energy balance of the tubes; and
6. Energy balance of the fluid in the tubes.

The energy flow from the sun to the water tubes of thermal collector is shown by Figure 2.3.

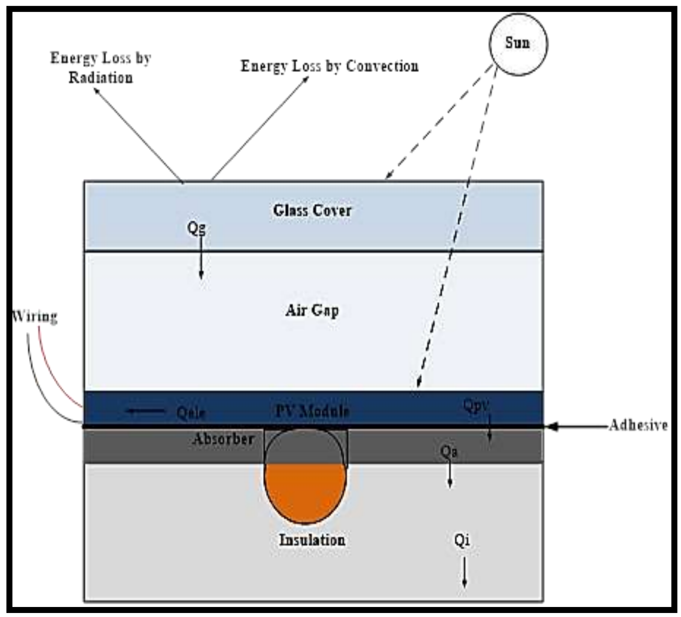


Fig 2.3: Flow of Energy from the Sun to the Thermal Collector

*2.4.1 Energy Balance of the Glass Cover*

Part of the energy reaching the glass cover ($E_T$) is lost by forced convection caused by wind ($Q_{gec}$), radiative heat transfer to the environment ($Q_{ger}$), convective heat transfer from the glass to the PV module through the air gap ($Q_{gpvc}$), radiative heat transfer from the glass to the PV module ($Q_{gpvr}$) and heat stored by the glass cover ($Q_g$). The heat balance of the glass is given by

*Equation 2.14;*

$$m_g c_g \frac{dT_g}{dt} = Q_{gec} + Q_{ger} + Q_{gpvc} + Q_{gpvr} + Q_g = h_{gec}A\left(T_e - T_g\right) + h_{ger}A\left(T_{sky} - T_g\right) + h_{gpvc}A_{pv}\left(T_{pv} - T_g\right) + h_{gpvr}A_{pv}\left(T_{pv} - T_g\right)A\alpha_g E_T \quad \textbf{(2.14)}$$

Where:

$m_g$ = mass of the glass cover
$c_g$ = specific heat of the glass cover

$T_g$,$T_{sky}$, $T_{pv}$ = the temperature of the glass cover, sky and PV module respectively

$A$ and $A_{pv}$= area of the whole PV/T system and PV module respectively

$\alpha_g$ = absorbance of the glass

$h_{gec}$ , $h_{gpvc}$ = the convective heat transfer coefficients for the heat lost to the environment and PV module respectively (from glass cover).

$h_{ger}$, $h_{gpvr}$ = the radiative heat transfer coefficients for the heat lost to the environment and PV module respectively (from glass cover).

$$h_{gec} = \{2.8 + 3V_w\} \quad \textbf{(2.15)}$$

Where:

$V_w$ = wind speed

$$h_{gpvc} = \frac{Nu_{air} \cdot K_{air}}{H_{gap}} \quad \textbf{(2.16)}$$

Where:

$Nu_{air}$ = Nusselt number of air (inclined air layer) (Nu = 1 – conductive heat transfer).

$K_{air}$ = thermal conductivity of the air layer.

$H_{gap}$ = thickness of air.

$$h_{ger} = \varepsilon_g \cdot \sigma\left(T_g{}^2 + T_{sky}{}^2\right)\left(T_g + T_{sky}\right) \quad \textbf{(2.17)}$$

Where:

$\varepsilon_g$ = emissivity of the glass cover

$\sigma$ = Stefan Boltzmann’s constant

$$T_{sky} = 0.0552T_e{}^{1.5} \quad \textbf{(2.18)}$$

$$h_{gpvr} = \frac{1}{\frac{1}{\varepsilon_{pv}}+\frac{1}{\varepsilon_g}-1} \cdot \sigma \cdot \left(T_g{}^2 + T_{sky}{}^2\right)\left(T_g + T_{sky}\right) \quad \textbf{(2.19)}$$

Where:

$\varepsilon_{pv}$ = emissivity of the PV module.

*2.4.2 Energy Balance of the PV module*

The thermal balance of the PV module studies the convective and radiative heat transfer from the glass cover to the PV module ($Q_{gpvc}, Q_{gpvr}$), heat conduction from the PV module through the layer of adhesive (glue) to the absorber ($Q_{pva,cd}$) and the conductive heat transfer through the adhesive layer to the tubes ($Q_{pvt,cd}$), the heat absorbed by the PV layer ($Q_{pv}$), and electricity production ($E_{ele}$). The energy balance of the PV module is given by

*Equation 2.20.*

$$m_{pv}c_{pv}\frac{dT_{pv}}{dt} = Q_{gpvc} + Q_{gpvr} + Q_{pva,cd} + Q_{pvt,cd} + Q_{pv} - E = h_{gpvc}A_{pv}\left(T_g - T_{pv}\right) + h_{gpvr}A_{pv}\left(T_g - T_{pv}\right) + h_{pvacd}A_{pva}\left(T_a - T_{pv}\right) + h_{pvtcd}A_{pvt}\left(T_t - T_{pv}\right) + \left(E_T \cdot \alpha_{PV} \cdot \tau\right) - E_{ele} \quad \textbf{(2.20)}$$

Where:

$h_{pva,cd}$ = the heat transfer coefficient for glue between the PV module and absorber.

$A_{pva}$ = area of the absorber in contact with the PV module.

$T_a$, $T_t$ = temperature of the absorber and tube respectively.

$h_{pvt,cd}$ = the heat transfer coefficient for the tubes in contact with the PV module.

$$h_{pva,cd} = \frac{K_{adh}}{H_{adh}} \quad \textbf{(2.21)}$$

$$A_{pva} = A\left(1 - \frac{D_o}{t_{space}}\right) \quad \textbf{(2.22)}$$

Where:

$D_o$ = outer diameter of the tube

$t_{space}$ = tube spacing

$h_{pvt,cd}$ . $A_{pvt}$ is given by

*Equation 2.23.*

$$h_{pvt,cd}A_{pvt} = \frac{H_{pv}L}{\frac{X_{pv}}{2K_{pv}} \cdot \frac{H_{adh}}{K_{adh}} \cdot \frac{H_{pv}}{D_o}} \quad \textbf{(2.23)}$$

Where:

$H_{adh}$, $H_{pv}$ = thickness of the adhesive and the PV module respectively

$K_{adh}$, $K_{pv}$ = heat conductivity of the adhesive and PV module respectively

$$X_{pv} = \frac{t_{space}}{4}$$

$$E_{ele} = (I \cdot V) \times 3600 \quad \textbf{(2.24)}$$

*2.4.3 Energy Balance of the Absorber*

The energy balance of the absorber considers the conductive heat transfer from the PV module to the absorber ($Q_{pva,cd}$), heat conduction from the absorber ($Q_{at,cd}$) to the tubes and the conductive heat transfer from the absorber to the surroundings through the insulation. The energy balance of the absorber is given by

*Equation 2.25.*

$$m_a c_a \frac{dT_a}{dt} = Q_{pva,cd} + Q_{at,cd} + Q_{ai,cd} = h_{pva,cd}A_{pva}\left(T_{pv} - T_a\right) + h_{at,cd}A_{at}\left(T_t - T_a\right) + h_{ai,cd}A_{ai}\left(T_i - T_a\right) \quad \textbf{(2.25)}$$

Where:

$h_{at,cd}$, $h_{ai,cd}$ = the heat transfer coefficient for tube and insulation respectively.

$A_{ai}, A_{at}$ = area of the absorber in contact with the insulation and tube respectively.

$T_i$= temperature of the insulation.

$$A_{pva} = A\left(\frac{t_{space}-D_o}{t_{space}}\right) \quad \textbf{(2.26)}$$

$$A_{at} = H_a \cdot L \quad \textbf{(2.27)}$$

$$h_{at,cd} = \frac{2K_a}{Y_a} \quad \textbf{(2.28)}$$

$$h_{ai,cd} = \frac{2K_i}{H_i} \quad \textbf{(2.29)}$$

Where:

$H_a$, $H_i$ and $H_t$ = thickness of the absorber, insulation and tubes respectively.

$L$ = length of the tubes.

$K_i$, $K_a$ and $K_t$= thermal conductivity of the insulation, absorber and tubes respectively.

$$Y_a = \frac{t_{space}-D_o}{4}$$

*2.4.4 Energy Balance of the Tubes*

The energy balance of the tubes considers the conductive heat transfer from the PV module to the tube ($Q_{pvt,cd}$), heat conduction from the absorber ($Q_{at,cd}$) to the tubes, the conductive heat transfer from the tubes to insulation ($Q_{ti,cd}$) and heat transfer to the water within the tubes ($Q_{tw}$). The energy balance of the tubes is given by

*Equation 2.30*

$$m_t c_t \frac{dT_t}{dt} = Q_{pvt,cd} + Q_{at,cd} + Q_{ti,cd} + Q_{tw} = h_{pvtcd}A_{pvt}(T_{pv} - T_a) + h_{atcd}A_{at}(T_a - T_t) + h_{ticd}A_{ti}(T_i - T_t) + h_{tw}A_{tw}(T_w - T_t) \quad \textbf{(2.30)}$$

Where:

$h_{ti,cd}, h_{tw}$ = the heat transfer coefficient for tubes in contact with the insulation and water respectively.

$A_{tw}, A_{ti}$area of the tube in contact with the water and insulation respectively.

$T_i$= temperature of the insulation

$$A_{tw} = \pi D_i L \quad \textbf{(2.31)}$$

Where:

$D_i$ = inner diameter of the tubes

$$A_{ti} = \left(\frac{\pi}{2} - 1\right) D_o L \quad \textbf{(2.32)}$$

$$h_{tw} = \left\{4.36 \times \frac{K_w}{D_H}\right\} \quad \textbf{(2.33)}$$

Where:

$K_w$ = thermal conductivity of water

$D_H$ = hydraulic diameter = $D_o$

*2.4.5 Energy Balance of the Insulator*

The energy balance of the insulator considers the conductive heat transfer from the absorber to the insulator ($Q_{ai,cd}$), heat conduction from the tubes to the insulator ($Q_{ti,cd}$) and the conductive and convective heat transfer from the insulation to the environment ($Q_{ie,cd+cv}$). The energy balance of the insulator is given by

*Equation 2.34.*

$$m_i c_i \frac{dT_i}{dt} = Q_{ai,cd} + Q_{ti,cd} + Q_{ie,cd+cv} = h_{ai,cd}A_{ai}(T_a - T_i) + h_{ti,cd}A_{ti}(T_t - T_i) + h_{ie,cd+cv}A(T_e - T_i) \quad \textbf{(2.34)}$$

Where:

$h_{ie,cd+cv}$ = the conductive and convective heat transfer coefficient for the insulation in contact with the surrounding.

$$h_{iec} = 2.8$$

$$h_{ie,cd} = \frac{K_i}{H_i} \quad \textbf{(2.35)}$$

$$h_{ti,cd} = \frac{2K_t}{Y_a} \quad \textbf{(2.36)}$$

*2.4.6 Energy Balance of the Coolant*

The energy balance of water considers the heat transfer from the tubes to the water ($Q_{tw}$) and heat accumulated by the water ($Q_w$). The energy balance is given by

*Equation 2.37*. The mass flow rate of water flowing through the tubes is 0.05kg/s.

$$m_w c_w \frac{dT_w}{dt} = Q_{tw} + Q_w = h_{tw}A_{tw}(T_t - T_w) + \dot{m}C_p(T_{win} - T_{wout}) \quad \textbf{(2.37)}$$

$$T_w = 0.5T_{win} + 0.5T_{wout} \quad \textbf{(2.38)}$$

*2.5 Electrical and Thermal Efficiency of the Solar Systems*

The efficiency of solar system (PV-only or PV/T) shows the percentage of solar power reaching the surface of the collector that is converted into useful energy. The PV/T system produces both heat and electricity hence the overall efficiency of this system is the sum of the electrical and thermal efficiency. The electrical efficiency of a solar system is given by

*Equation 2.39.*

$$\eta_{ele} = \frac{I \cdot V}{A \cdot G_T} \times 100\ \% \qquad \textbf{(2.39)}$$

Where:

$\eta_{ele}$= electrical efficiency of the solar system

The thermal efficiency is given by

*Equation 2.40.*

$$\eta_{th} = \frac{Q_W}{A \cdot E_T} \times 100\ \% \qquad \textbf{(2.40)}$$

Where:

$\eta_{th}$= thermal efficiency of the solar system.

The overall efficiency of the PV/T system is given by

*Equation 2.41.*

$$\eta_{oet} = \eta_{ele} + \eta_{th} \qquad \textbf{(2.41)}$$

Where:

$\eta_{oet}$= overall efficiency of the PV/T system.

### *2.6 Solar and Weather Data for an Average Day in May and August for Navrongo*

The thermal modelling of PV/T system is largely dependent on solar data, temperature data and wind speed data.

*Solar data: May and August for Navrongo*

The amount of solar energy reaching a surface of the earth is dependent on the inclination of the surface. Solar collectors in Ghana are inclined at an angle of 10° for optimal solar energy extraction and self-cleaning. The solar collector installed at Navrongo for the PV/T system model therefore has 10° angle inclination. The average solar radiation (solar energy) recording taken for this system in May and August in 2021 from 6:30 am to 5:30 pm daily is as shown in figure 2.4.

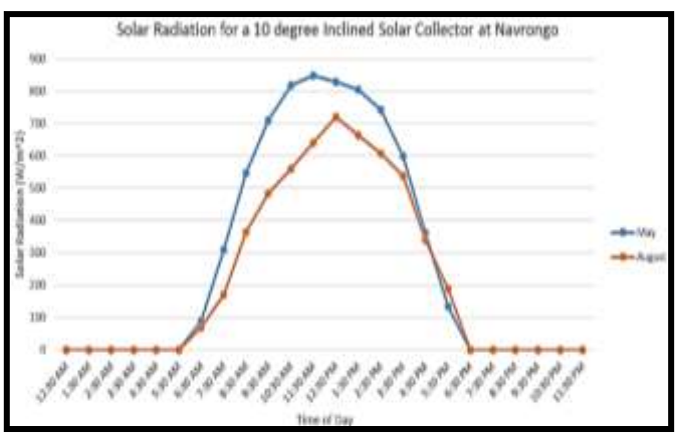


Fig 2.4: Solar Data for a Monthly Average Day in May and August for Navrongo

*Temperature Data: May and August for Navrongo*

The heat collected by the PV/T system is dependent on ambient temperature and wind speed. The temperature recording for this period under study is depicted in figure 2.5.

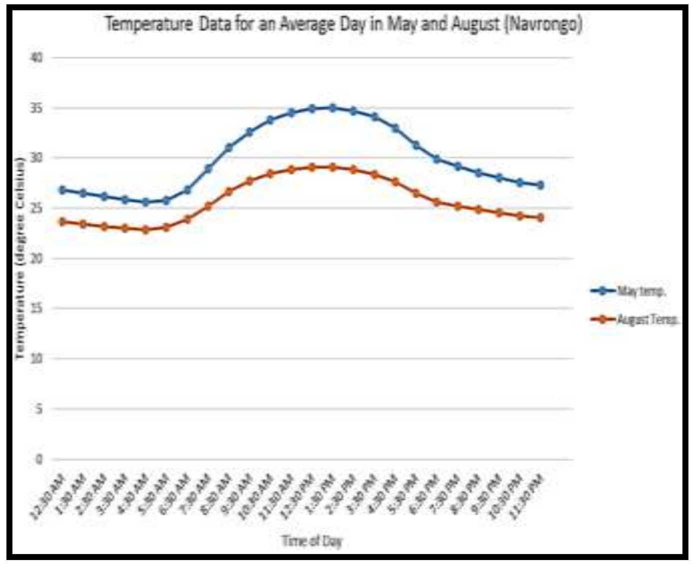


Fig 2.5 Graph of the Monthly Average Daily Temperature for May and August

*Wind Speed Data May and August for Navrongo*

The wind speed recording for this period under study is also demonstrated and depicted in figure 2.6.

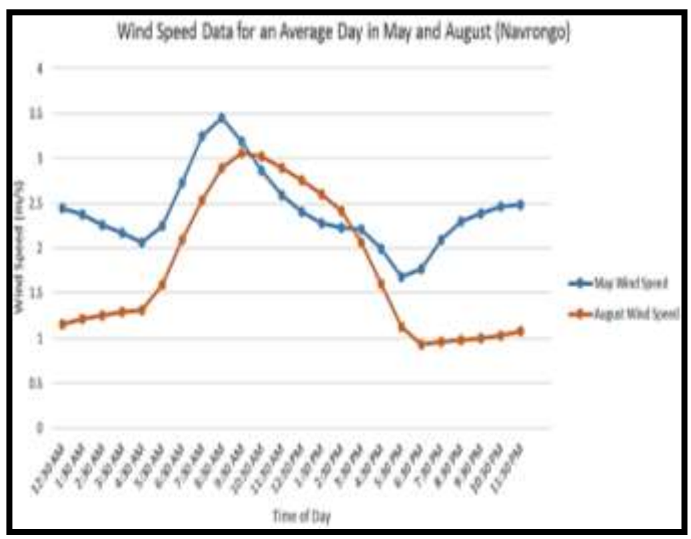


Fig 2.6: Graph of Monthly Average Daily Wind Speed for May and August

### *2.7 PV/T System Material Properties and Geometric Characteristics*

The physical properties of the glass cover, air gap, PV module, tubes, absorber, insulation and adhesive used for the thermal modelling of the PV/T system is shown in Table II.

Table II: Physical Properties of the Materials used for the PV/T System Modelling

| Material | Area (A) | Thickness (H) | Volume $v = A \cdot H$ | Density $\rho$ | Mass $m = v \cdot \rho$ | Total units |
|---|---|---|---|---|---|---|
| Glass Cover | 2.60000 | 0.00400 | 0.01040 | 2200 | 22.88000 | 1 |
| Air Gap | 2.60000 | 0.02000 | - | - | - | - |
| PV module | 2.08000 | 0.00035 | 0.00074 | 2330 | 1.71255 | 1 |
| Tubes (Cu) | 1.206367 (L=1.92000) | 0.00200 $D_o$ =0.02000 $D_i$= 0.018000 | 0.00241 | 8940 | 21.56984 | 10 |
| Absorber | 1.96666 | 0.00020 | 0.00039 | 2702 | 1.06278 | 1 |
| Insulation | 1.42379 | 0.02000 | 0.02848 | 20 | 0.56952 | 1 |
| Adhesive | 2.60000 | 0.00005 | 0.00013 | - | - | - |
| S.I. Units | $m^2$ | m | $m^3$ | kg/ $m^3$ | kg | |

Table III shows the thermal and optical properties of the selected materials. The space between the tubes in the PV/T system is 0.12 m.

Table III: Thermal and Optical Properties of Materials used in the PV/T System

| | Optical Properties | | | Thermal Properties | |
|---|---|---|---|---|---|
| Material | Emissivity $\varepsilon$ | Absorptivity $\alpha$ | Transmittance, $\tau$ | Thermal conductivity, (K) | Specific Heat (c) |
| Glass Cover | 0.880 | 0.100 | 0.930 | 1.100 | 670 |
| Air Gap | - | - | - | 0.025 | - |
| PV module | 0.960 | 0.900 | - | 140.000 | 900 |
| Tubes (Cu) | - | - | - | 400.000 | 389 |
| Absorber | - | - | - | 310.000 | 800 |
| Insulation | - | - | - | 0.034 | 670 |
| Water | - | - | - | 0.598 | 4184 |
| Adhesive | - | - | - | 0.850 | - |
| S.I. Units | - | - | - | W/ m· K | J/kg· K |

## III. RESULTS AND DISCUSSION

This section of the paper delves into the results and discussion from the simulation of the PV-only and the PV/T system as well as a comparison of the electrical efficiency of the two systems.

### *3.1 Simulation of the PV- Only System*

The PV-only system functions as a baseline on which the improved electrical performance of the PV/T system can be measured. Figures 3.1 to 3.5 show the MATLAB model of the PV-only system (with the use of signal routing tools).

The PV current part of the simulation shown in figure 3.1 was achieved using equations 2.4 and 2.5.

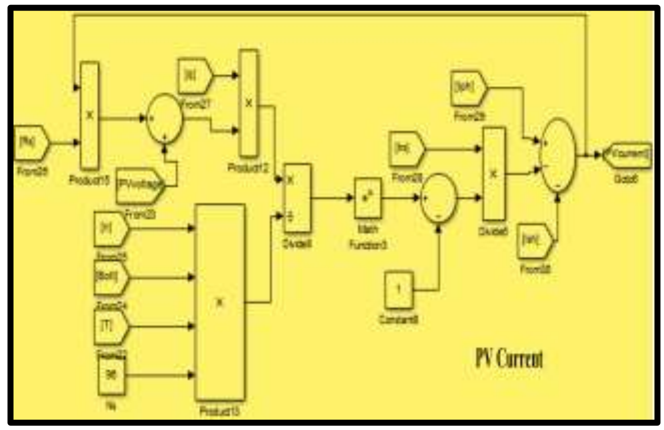


Fig. 3.1: PV Current Section

The reverse saturation current at the cell temperature section shown in figure 3.2 was modelled using equation 2.9.

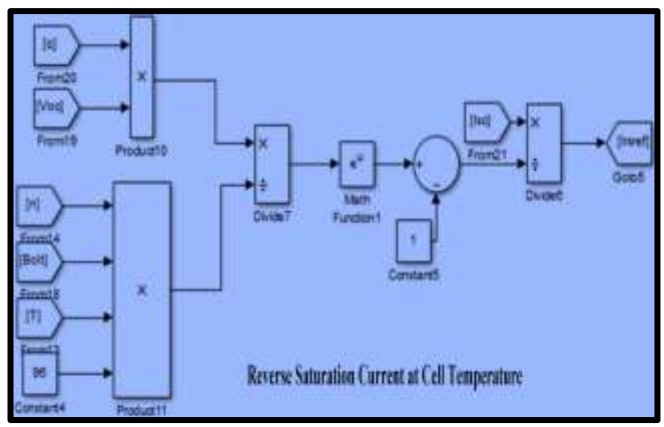


Fig. 3.2: Reverse Saturation Current at the cell temperature Section

The reverse saturation current at the section shown in figure 3.3 was modelled using equations 2.10 and 2.11.

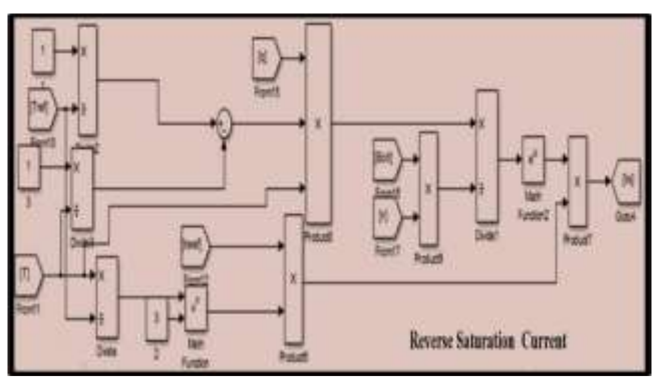


Fig. 3.3: Reverse Saturation Current Section

The Photo current and shunt current sections as shown in figure 3.4 were simulated using equations 2.4, 2.7 and 2.8.

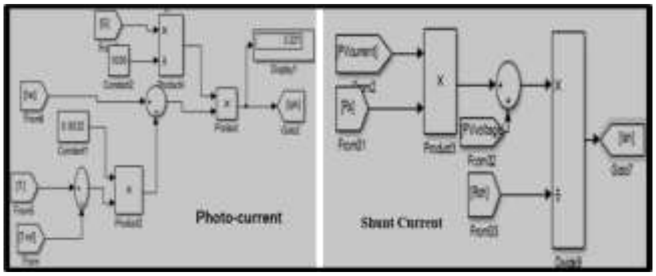


Fig. 3.4: Photo Current and Shunt Current Sections

The PV cell temperature section as shown in figure 3.5 was simulated using equations 2.12.

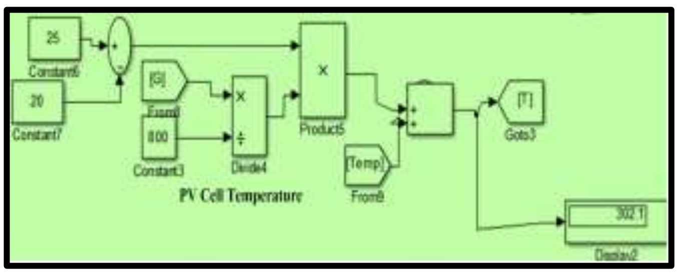


Fig. 3.5: PV Cell Temperature Section

The combination of the various sections of the simulation is as shown in figure 3.6. This was done in order to portray the coordination between the sections in the PV-Only system.

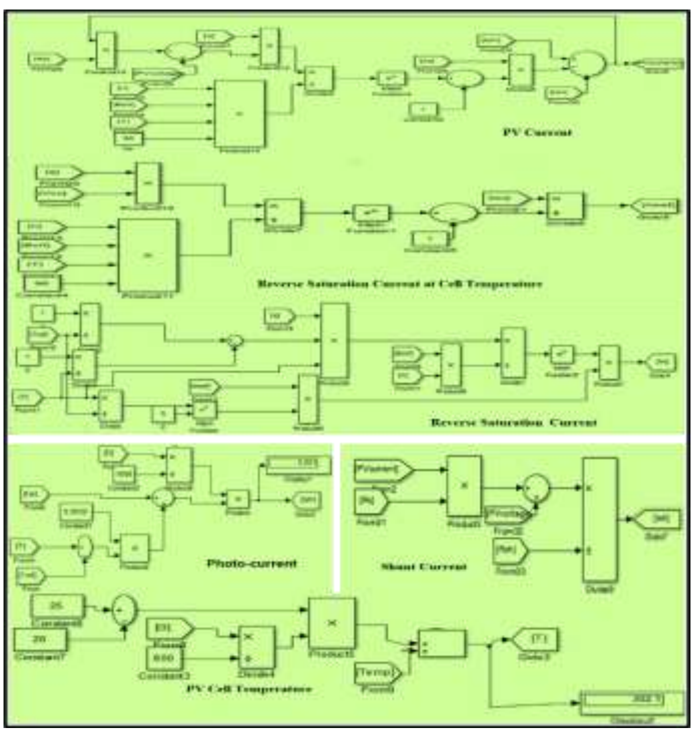


Fig. 3.6: The Combined Sections of the MATLAB Model for the PV-Only System

Solar radiation and temperature data for an average day in the months of May and August for Navrongo were applied to the MATLAB PV-only system model. The total current, voltage and electrical energy produced on an average day in May was 60.4952 A, 157.6835V and 871.0468 Wh respectively. Figure 3.7 shows this assertion, where the hourly distribution of current, voltage and power for May were demonstrated.

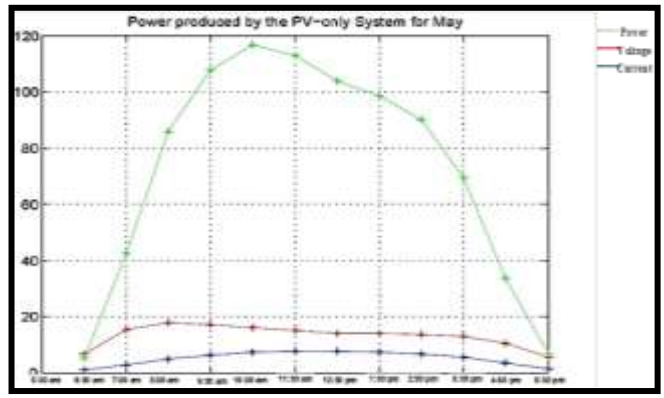


Fig. 3.7: Hourly Distribution of Current, Voltage and Power in May

In August, the PV-only system produced a total current, voltage and energy of 47.542 A, 252.402 V and 1118.3Wh respectively. This hourly distribution was depicted in figure 3.8.

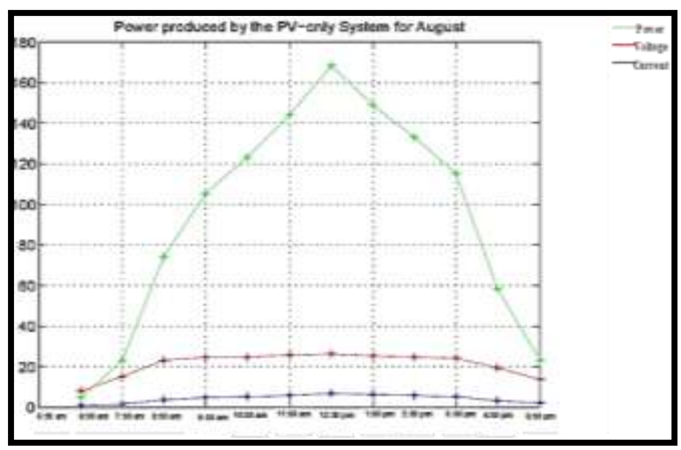


Fig. 3.8: Hourly Distribution of Current, Voltage and Power in August

In Navrongo, the highest amount of solar radiation is recorded in May and the lowest in August. The results of the simulation showed that a PV panel produces more power in August than in May even though the panel receives more solar radiation in May. Voltage and current (hence power) increase as the amount of solar radiation reaching the surface of the panel increases provided temperature is constant**.** As temperature increases, current increases marginally while voltage decreases rapidly therefore power produced also decreases with increasing temperature. From temperature data for Navrongo, the average atmospheric temperatures for May and August are 29.9 ℃ and 25.75 ℃ respectively. As shown in figures 3.7 and 3.8, slightly more current was produced in May than in August but voltage produced in August was drastically higher than that produced in May. Therefore, more power is produced in August than in May. The power produced by the PV-only system for May and August corresponded to an electrical efficiency of 7.247 % and 11.93 % respectively.

*3.2 Simulation of the PV/T System*

The MATLAB PV/T system model consists of an electrical section and a thermal section. The electrical section is identical to the PV-only system while the thermal section was modelled using equations 2.13 to 2.41. Figure 3.9 shows the MATLAB PV/T system model.

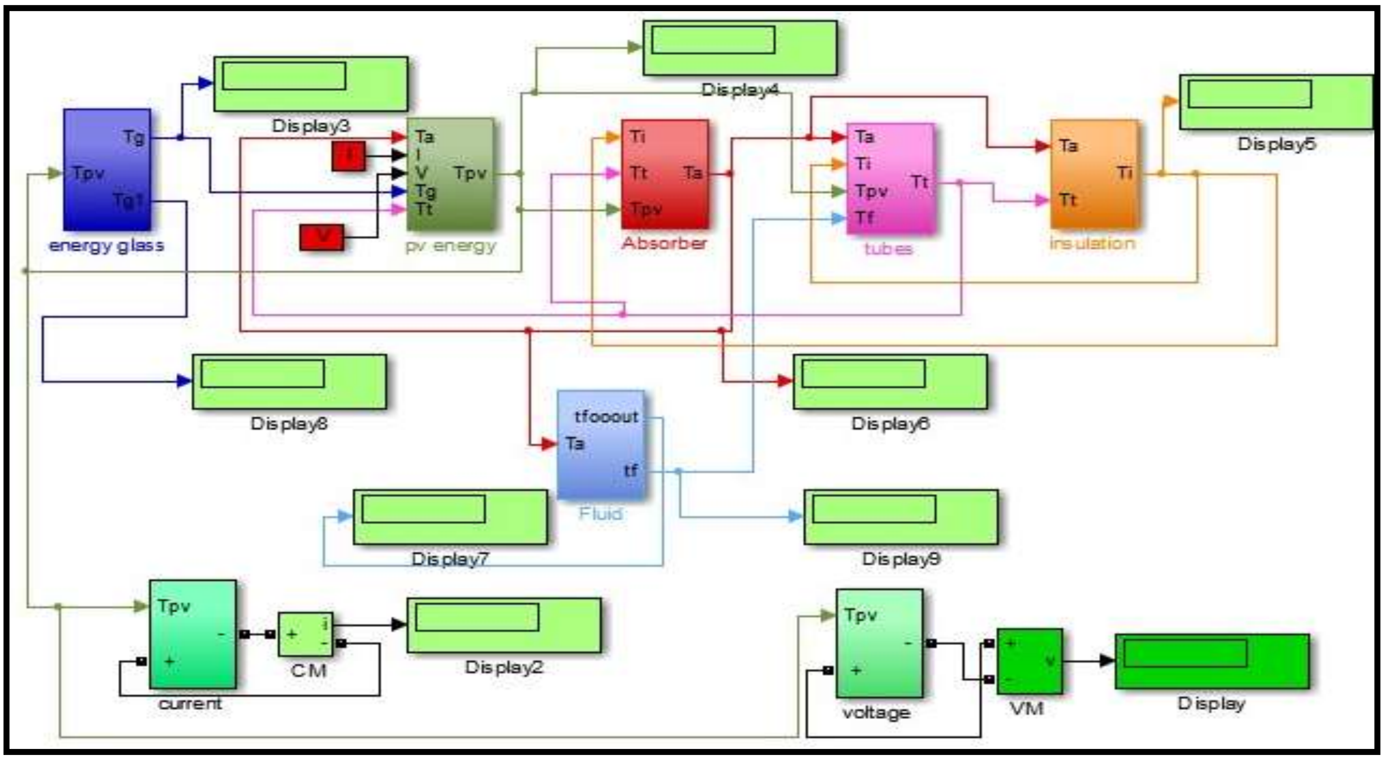


Fig. 3.9: MATLAB PV/T System Model

Solar radiation, wind and temperature data for an average day in the months of May and August for Navrongo were applied to the MATLAB PV/T system model. Heat collection was carried out with the help of a solar powered 20W rated water pump delivering 0.05 kg of water to the copper tubes every second.

For the month of May, the modelled PV/T system produced a total of current, voltage, electrical power and thermal energies of 60.3807 A, 362.8100 V, 1840.3 Wh and 40390 J respectively. The PV/T system produced slightly less current but significantly higher voltage and power than the PV-only system for the month of May. The water pump consumes 240 Wh daily to circulate water through the system, therefore the effective electrical energy produced by the PV/T system was 1600.3 Wh. The electrical, thermal energies and overall efficiency of the PV/T system was 13.315 %, 0.0746 % and 13.389 % respectively. Figure 3.10 shows the hourly distribution of current, voltage, power, solar cell temperature and thermal energy collected for May.

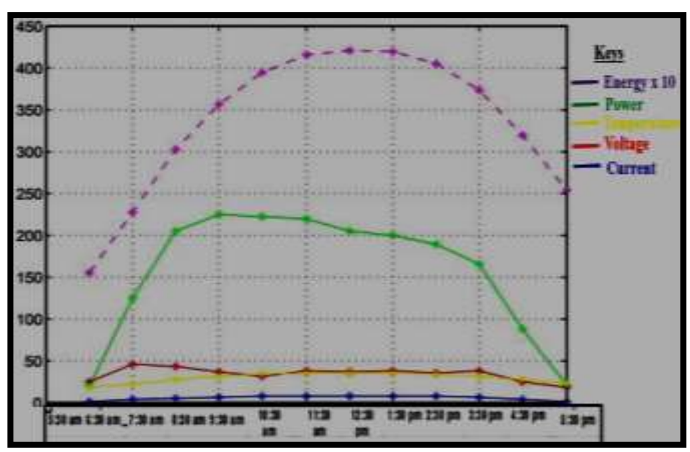


Fig. 3.10 Hourly Distribution of Current, Voltage, Power, Temperature and Thermal Energy Collected for the Modelled PV/T for May

In August, the modelled PV/T system produced a total current, voltage, electrical power and thermal energies of 47.4378 A, 646.6400 V, 26817Wh and 25871 J respectively. The PV/T system produced slightly less current but significantly higher voltage (above the rated voltage) and power than the PV-only system for the month of August. The effective electrical energy produced by the PV/T system was 2441 Wh taking into consideration energy used by the pump. The electrical, thermal energies and overall efficiency of the PV/T system were 26.044 %, 0.061 % and 26.105 % respectively. Figure 3.11 shows the hourly distribution of current, voltage, power, solar cell temperature and thermal energy collected for August.

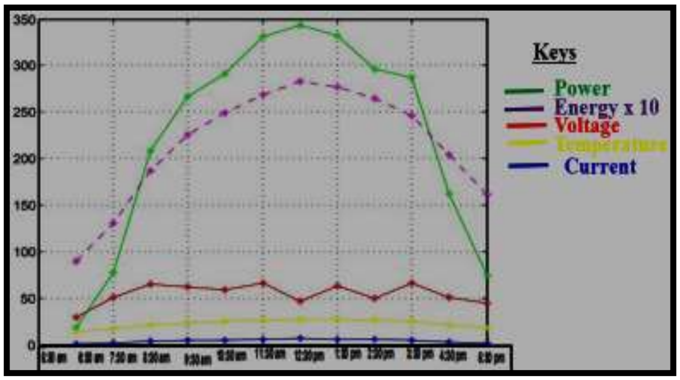


Fig. 3.11 Hourly Distribution of Current, Voltage, Power, Temperature and Thermal Energy Collected for the Modelled PV/T for August.

In May, the overall efficiency of the electrical power produced by the PV-Only System in percentage terms was 7.247% that of PV/T System was 13.389%. The difference in the overall efficiency was 6.149% (13.389% - 7.24% = 6.149%) approximately 6% in favour of PV/T System. In August, the overall efficiency for PV-Only System was 11.93 %, PV/T System had 26.105 %. The difference between the two efficiencies was 14.175%, (i.e. 26.105 % − 11.93 % =14.175 %); more than 14% still in favour of PV/T System. The study therefore established that the photovoltaic thermal system (PV/T System) has a higher electrical efficiency than an ordinary photovoltaic panel system (PV-Only System) irrespective of the prevailing weather conditions. These results were collaborated by other researchers as indicated in the following statement "under the environmental conditions of higher ambient temperature and stronger solar radiation intensity, the electro-thermal efficiency and primary energy saving efficiency of PVT system will be higher than that of PV-system" [26]. Other researchers also concluded on their work on PV/T and PV systems that the overall efficiency of the PV/T system was higher than PV system by 21.4% [27]. Hence, the simulation in this paper concluded that, the PV/T System had an electrical energy efficiency improvement of 6% and 14% for May and August respectively. The PV/T system also produced lukewarm water which could be used for domestic heating purposes. The thermal energy extracted contributed less than 1% (Equation 2.41**)** to the overall energy conversation efficiency as a result of a very low flow rate of the working fluid (water).

## IV. CONCLUSION

In this paper, it is noted that about 60% of the world's electricity comes from fossil fuel sources. The fluctuating price of fossil fuel in the world market confines the end-user to uncertain electricity tariff. The Russia-Ukraine conflict and the sanctions imposed on the former (Russia) have compound this volatility in price. This paper discussed the needs to use solar energy to generate electricity in order to reduce the over reliance on fossil fuel. One of the generating technologies to employ in this endeavour, in the view of this article is Photovoltaic Thermal (PV/T) System. The paper also discussed other solar generating technologies such as Solar Photovoltaic and Solar Thermal Systems.

The paper adopted weather condition data prevailing in Navrongo Solar Power Plant, Ghana to simulate the efficiency of electricity generation from PV-Only and PV/T Systems. The researchers in this paper used MATLAB based techniques to simulate several mathematical equations to design output models for PV-Only and PV/T Systems. Weather condition data in May and August prevalent in Navrongo were also used to model graphs for PV-Only and PV/T Systems. The paper demonstrated that, the overall efficiency of electrical power produced by PV/T System in May and August was more than PV-Only System.

The researchers of this paper came to the firm conclusion that, the PV/T system by its nature would contribute to achieving the 13th sustainable development goal (climate action) because of its very low carbon footprint. When proper material selection is done, taking into consideration cost reduction, the PV/T system will provide viable means of achieving the 7th sustainable development goal (affordable and clean energy) as well. For residential power consumption, the replacement of centralized fossil fuel – based power systems with decentralized PV/T systems would be beneficial in securing a sustainable future.

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