Building integration photovoltaic module with reference to Ghana: using triple junction amorphous silicon

BUILDING INTEGRATION PHOTOVOLTAIC MODULE WITH REFERENCE TO GHANA: USING TRIPLE-JUNCTION AMORPHOUS SILICON

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This paper assesses the potential for using building integrated photovoltaic (BIPV) roof shingles made from triple-junction amorphous silicon (3a-Si) for electrification and as a roofing material in tropical countries, such as Accra, Ghana. A model roof was constructed using triple-junction amorphous (3a-Si) PV on one section and conventional roofing tiles on the other. The performance of the PV module and tiles were measured, over a range of ambient temperatures and solar irradiance. PVSyst (a computer design software) was used to determine the most appropriate angle of tilt. It was observed that 3a-Si performs well in conditions such as Accra, because it is insensitive to high temperatures. Building integration gives security benefits, and reduces construction costs and embodied energy, compared to freestanding PV systems. Again, it serves as a means of protection from salt spray from the oceans and works well even when shaded. However, compared to conventional roofing materials, 3a-Si would increase the indoor temperature by 1 – 2 °C depending on the surface area of the roof covered with the PV modules. The results presented in this research enhance the understanding of varying factors involved in the selection of an appropriate method of PV installation to offset the short falls of the conventional roofing material in Ghana.

Keywords: Building Integrated Photovoltaic (BIPV), Triple-junction Amorphous (3a-Si), performance, PVSyst

INTRODUCTION

Renewable energy technologies have been in use in Ghana for many years, and account for about 89% of electricity generation, although solar photovoltaic (PV) accounts for a small percentage. Ghana has installed a total electric generation capacity of more than 1.7 Gigawatts, from which it is estimated that PV installation totals up to 1.0MW (www.ghanaef.org) approximately 0.01% of the total Electricity supply (www.hedon.info). However, more than one-third of the population are still without power. Though these areas are mostly rural, parts of the capital city (Accra) are constantly under load shedding to enable industries to operate, while other parts are in total darkness.

Ghana like all the countries in the Sub-Sahara region (West Africa) have a good solar energy resource, receiving daily solar irradiation of between 4 and 6 kWh/m^2 and a corresponding annual sunshine duration of 1800 - 3000 hours. In Ghana, solar radiation levels are higher in the northern regions which include a large portion of the rural areas of the country (www.areed.org). With respect to PV, it is estimated that

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amongst 90% of installation is in the Northern part of the country due to its scattered settlements (houses) and hence grid-electrification would not be viable. Most of these installations are standalone systems (off-grid) (www.areed.org). The only building integrated photovoltaic (BIPV) system known in Ghana is a 50 kWp system installed on the roof of the Ministry of Energy. This is serving a dual purpose: (a) for workshop demonstration and (b) generating power to the grid (www.energycom.gov.gh).

Terminologies and Glossary

Solar Energy: The solar energy definition is quite simple to understand, see below for additional information on this form of energy (www.solarbuzz.com).

Photovoltaics (PV): this is the direct conversion of light into electrical energy through a solar cell.

PV Module: several PV cells interconnected to form an assembled package.

Array(s): two or more PV modules connected in series and/or in parallel (www.solarbuzz.com).

Building Integrated Photovoltaic (BIPV): it is a system that consists of integrating photovoltaics modules into the building envelope, such as the roof or the façade. The system simultaneously serves as a building envelope material and a power generator (www.wbdg.org).

Stand-alone PV System (off-grid**):** An independent solar PV system that operates without connection to a grid but capable to supply electricity. They are normally used in remote or isolated places where the electric supply from the power-grid is unavailable or not available at a reasonable cost www.solarenergyhome.co.uk). It is also known as autonomous PV systems

Watt peak (Wp): The power output when a Solar module is illuminated under standard conditions of 1000 Wm^{-2} intensity, 25°C ambient temperature and a spectrum that relates to Air Mass 1.5.

Irradiance: The solar power incident on a surface, usually expressed in kilowatts per square meter (kWm^{-2}) (www.solarbuzz.com). It is also a solar flux density incident on a surface in $W\ m^{-2}$. Irradiance multiplied by time gives insolation.

Irradiation: this is the solar energy incident on a surface over a specified period, often expressed in Jm^{-2} per day or $kWhm^{-2}$ per day.

Conventional Roofing and Adverse Effects

The main roofing materials used in Ghana are; aluminium and asbestos roofing sheets, concrete roofs and tiles (in the minority), except for some rural areas where straw and/or grass are used. The most common of these is aluminium, basically because it is less costly. However, for a city such as Accra, the Atlantic Ocean which borders the south of the country has a strong adverse effect on such roofing materials as they tend to corrode due to the salt spray from the ocean .As a result, it requires replacement after about 15 years. Also, in some extreme weather conditions this roofing material tends to blow off rendering it unsafe for occupants. Considering the economy of Ghana this option may be just right but for a brief period. Building Integrated Photovoltaic (BIPV) modules could be a viable alternative for most roofing materials in Ghana. It would not only serve as a roofing material but would also be a source of electrification, security and it would also resist the effect of corrosion from the salt spray.

Research Purpose: Choice of Method

The abundance of sunlight makes PV systems a solution to solve some, if not all of Ghana's energy crisis. Until now, a number of the PV systems installed have fallen in a state of disrepair due to lack of maintenance, or available accessories (especially storage systems) rendering the entire project a white elephant. This may be attributed to the fact that most of the PV installations (standalone systems) are owned by communities or individuals who know very little or nothing about the system and how it works. As a result, using PV systems integrated into the building structure (roof) instead of roofing materials is considered to be the most robust approach to avert these shortfalls. In this research, triple-junction amorphous silicon (3a-Si), SHR-17, is investigated as a potential BIPV. This is because, according to manufacturers, it works better in high temperature conditions (www.uni-solar.com) and it is easy to integrate into building façades. It is envisaged that the 3a-Si shingles could replace the conventional roofing material and serve in the following capacities;

- ❖ As a roofing material-security
- ❖ Power generation.

To be able to verify these, several tests; to assess the temperature, and shading effects, characteristics of the module were conducted on a shed (to simulate conditions in a house) mounted at the test site of the Metrological department (University of Reading).

<u>AIM</u>

The aim of this research is to assess the potential for using building-integrated photovoltaic roof shingles made from triple-junction amorphous silicon (3a-si) as a roofing material and for electrification in tropical countries, such as Accra, Ghana.

<u>OBJECTIVES</u>

The objectives to achieve this aim are:

- ❖ Optimization of angle of tilt
- ❖ To determine the different effects of temperature on roofing tiles and triple junction amorphous-silicon (3a-Si).
- ❖ To measure the current-voltage characteristics of the shingles.
- ❖ To measure the performance of the shingles at high and low irradiance

BACKGROUND OF EXISTING THEORY AND TECHNOLOGY

Triple-junction amorphous technology was introduced at the end of 1997 by Uni-solar to overcome some of the shortfalls of amorphous-silicon technology (Figure 1). Solar cells using amorphous silicon have different form of junction between the positive (p-) and the negative (n-) material. The junction normally formed is known as the ***p-i-n*** junction, where ***"i"*** is an intrinsic material (Boyle, 2000). The Uni-solar product is based on a sophisticated multi-layer of amorphous silicon thin film solar cell developed originally by energy conversion devices.

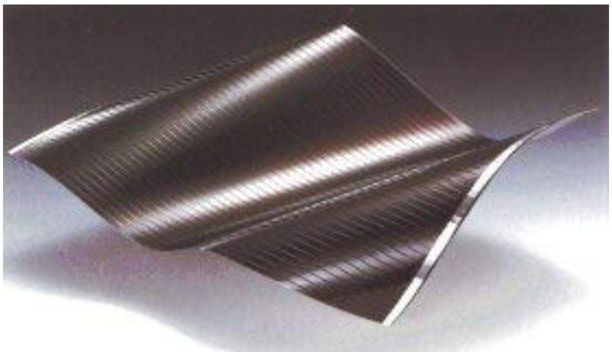

Figure 1 Cell of triple junction amorphous silicon *(Source: Essah, 2002).*

The construction of the spectrum-splitting cell shown in Figure 1 is illustrated schematically in Figures 2. The construction is based on three separate **p-i-n** sub-cells, on a roll-to-roll vacuum deposition process which uses a continuous roll of stainless steel sheet as the substrate upon which the cells are mounted. The three amorphous semiconductor sub-cells are designed and built such that each has different spectral response characteristics (no numerical data was given for the different responses). This enables the cell to convert the various wavelengths of sunlight with maximum efficiency. The spectrum splitting capacity of the cell is such that, the bottom sub-cell (red-cell) absorbs red light, the middle sub-cell (green-cell; ***p-type***) absorbs green light and that on top (blue-cell; ***n-type***) absorbs blue light. The fact that it is capably of absorbing the various aspects of light is the key to its high efficiency and higher energy output, especially at lower irradiation levels and diffuse light conditions.

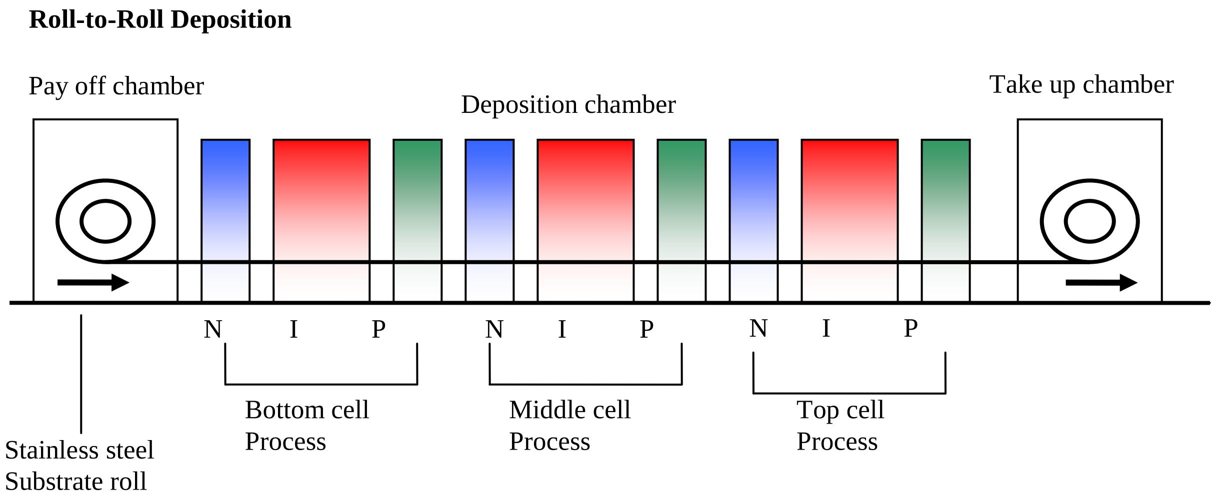

Figure 2 Schematic layout of the roll-to-roll deposition *(Source: Essah, 2002)*

The cells are then inter-connected and assembled into modules which are encapsulated in ultra-violet stabilised and weather resistant polymers and framed with anodized aluminium at the front, which further enhance the durability of the module as well as reducing cost. A coated galvalume steel backing plate provides stiffness (Essah, 2002).

The operation of the PV effect in amorphous silicon is generally similar to that of crystalline silicon, except that in 3a-Si, the band gap is less clearly defined although it is wider. This improves its efficiency over that of single-junction amorphous silicon because the cell absorbs well over a wide wavelength range. It is also known to have an improved performance under diffused radiation. Also, by-pass diodes are integrated to each cell, allowing the modules to produce power even when partially shaded (Essah, 2002). Manufacturers recommend that, it is weather resistant (www.uni-solar.com) and able to withstand high temperatures (values not specified).

In addition, several factors influence the performance of all photovoltaic modules. These include the solar irradiance level, operating temperature, solar spectrum and the angle of incidence at which sunlight strikes the module. Based on these, the modules must be compared under Standard Test Conditions, which are:

- Solar irradiance 1000Wm^{-2}

- Air mass 1.5 spectrum
- Cell temperature 25°C

METHODOLOGY

DESIGN AND CONSTRUCTION OF SHED

To simulate the effects of the shingles an already built shed was used. The dimensions of the shed was; 1.83 m by length, 1.22 m by width and 1.80 m by height. The area occupied by the roof of the shed was practically too small (1.3 m^2) to be used for the 2.25 m shingles, hence a new one (2.0 m^2) was built to serve the purpose. The specifications of the Uni-Solar SHR-17 shingles are two fold;

a) ***Electrical:*** - rated at 17Wp (watt peak), with a Voc of 13 V and Isc of 2.35 A. It has a maximum voltage point of 9 V and that of current is 1.9 A.
b) ***Dimensions:*** - a single 3a-Si measures 0.13 m in width and 2.25 m in length, with an extending polymer lamination of width approximately 0.25 m for the same length.

Building the Roof

One side of the new roof was designed and built taking into consideration the number (six in all), and the length of the shingles (about 2.25 m). The other side was designed as a conventional tiled roof to simulate a normal roof. The dimensions of the new roof sections were approximately 2 m^2 (2.25 m by 0.8 m) each. It was impossible to mount the roof sections side by side because of the size of the shed, which would have been the most appropriate situation. The type of tiles used is known as the Light Mixed Brindle, noted to withstand stormy weather conditions and efficient for roofing structures of inclined angles greater than 20°. After construction, the weight of the separate sections was as follows: weight of total roof with shingles on was 32.7 kg and that of the roof with battens and tiles was 96 kg

The Shed

The shingles were oriented south facing at a slope angle of 45° corresponding to that of the shed roof (Figure 3). However, as would be determined in Section below the most appropriate angle depends on location and latitude).The other section of the shed, which is north facing (Figure 4) had the tiles on, oriented at the same angle as that of the shingles.

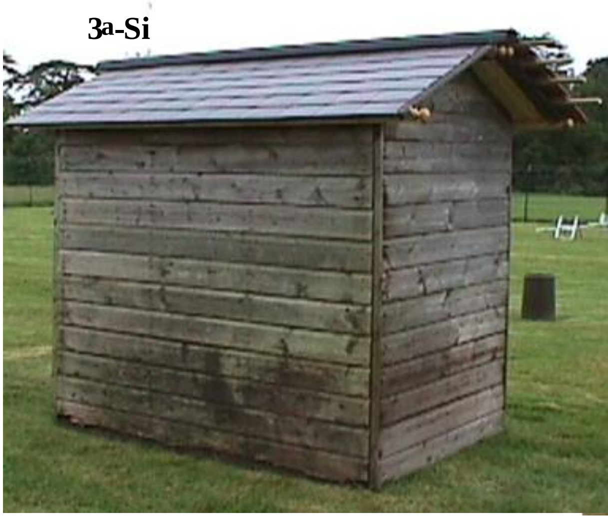

Figure 3 Section of the shed with shingles south facing

Figure 4 Section of the shed with tiles, north facing

<u>EXPERIMENT: SYSTEM SET-UP</u>

Thermocouples of type *K* were used in obtaining temperature readings from six different parts of the shed. It measures between the range of -200°C to +1200°C and has a sensitivity of approximately 41µV/°C (www.picotech.com). All thermocouples were then connected to a Model 3081 Hybrid recorder, logging every second and averaging over a minute. A Kipp SP-lite semiconductor solarimeter was also connected to the section of the roof which was south facing at the same roof angle, through to a channel on the recorder. The sensitivity of the solarimeter was $10\mu V/Wm^{-2}$.The shingles were connected as pairs in series with the three pairs connected in parallel because that is the normal way they are connected. Figure 5 illustrates a block diagram of the system set-up.

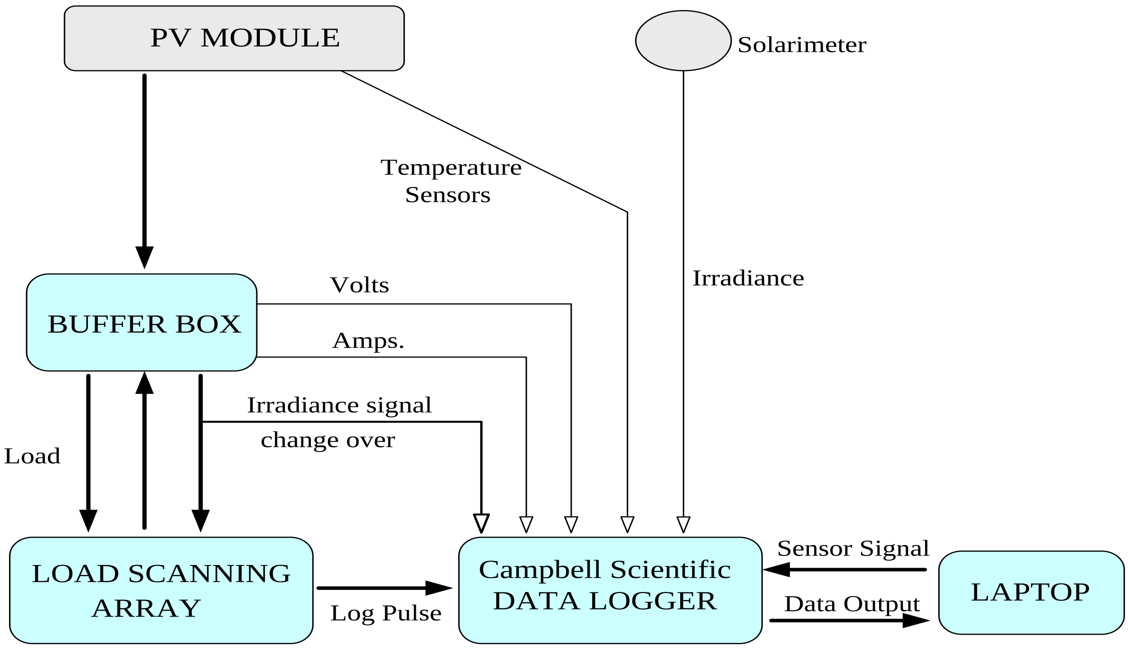

Figure 5 Block diagram of the set-up used for module characteristics

To simulate normal operation, the energy produced by the shingles was used to charge a 56Ah battery. The shingles were connected to the battery through a Solstice MX120 charge controller and a load of about 22 ohms set by a variable resistor was also connected.

RESULTS AND DISCUSSION

<u>OPTIMUM ANGLE OF TILT</u>

The optimum pitched angle for most buildings (domestic and offices) in Ghana are between the ranges of 30° to 45°, as a result most BIPV (if any) will be considered at this angle. However, because Ghana is close to the Equator the angle of inclination of the panel is affected by this latitude. Considering this condition and the most appropriate azimuth, PVSyst; a computer based software package for the study, sizing and data analysis of complete PV systems (www.pvsyst.com), was used for sensitivity analysis. It is evident that the most appropriate tilt angle for effective output is at 5° and South facing because Ghana is close to the Equator. Considering current pitched angles in Ghana (30°- 45°), about 20% of the output is lost even before energy is generated. Where is it oriented in any direction but for South facing, then a further loss is incurred (Figure 6).

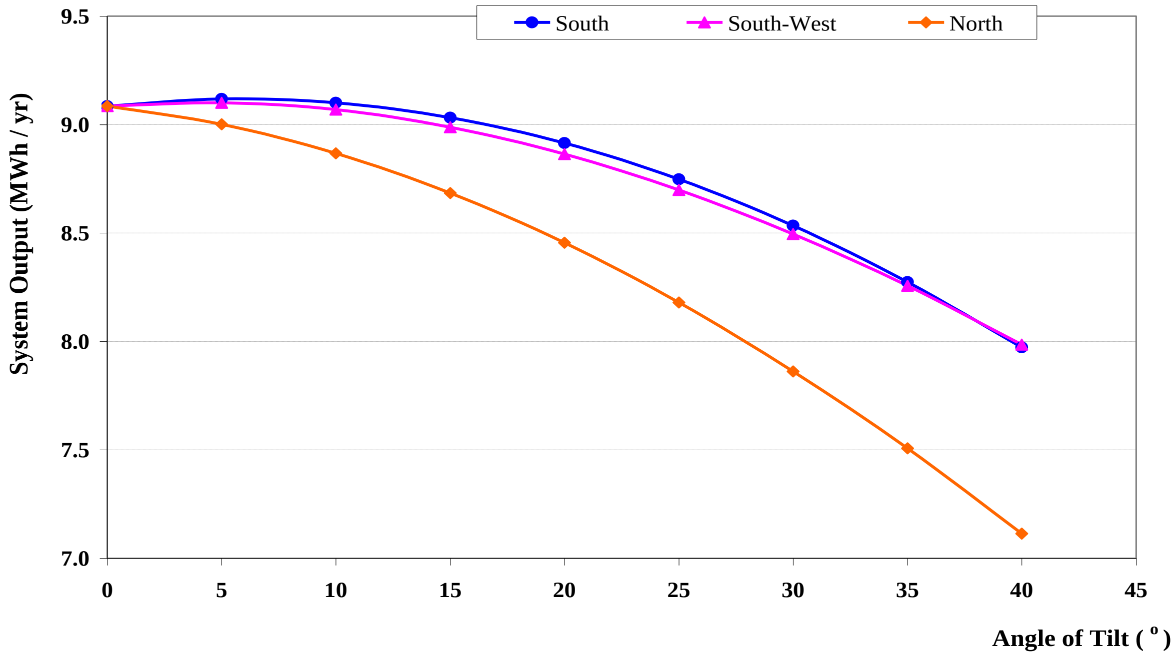

Figure 6: Effect of tilt angle and azimuth

<u>DIFFERENCE IN TEMPERATURE VERSES IRRADIATION</u>

In this section the effects of 3a-Si/ tiles with temperature differences is assessed. A graph of difference in temperature (ΔT) against irradiation (H) is a first simple approach to verify this. The graph below shows results of data collected over a period of fourteen days for each roofing section south facing.

ΔTmax is the difference between the maximum daily internal temperature and the maximum daily external temperature. In Figure 7, the difference in temperature tends to increases with solar irradiation in both instances. The range of scatter indicates that there is a very weak correlation between points. The shingles appears to give a higher internal temperature because of the following factors;

- The surface of the shingles is much darker than that of the tiles hence absorbs and transmits much heat.
- Another fact can be attributed to their masses. The shingles cannot store much heat because of their small mass whiles the tiles stores much more heat.

Though there is a weak correlation in the points plotted above, the range given indicates that the shingles when used as BIPV would increase the internal temperature by about 1 - 2 °C when used in Ghana.

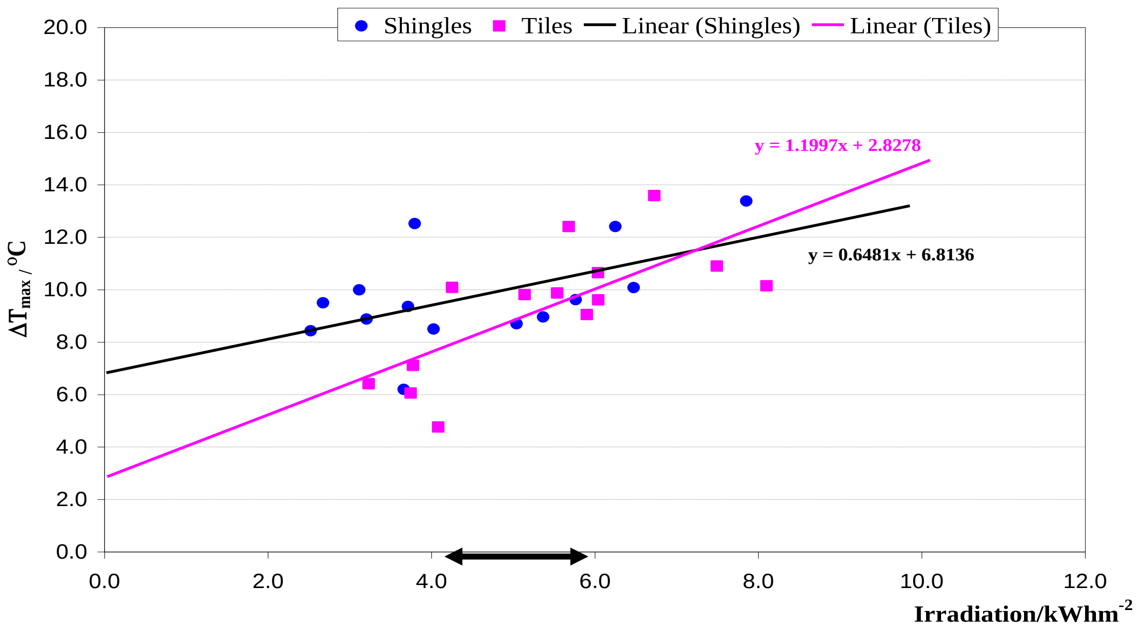

Figure 7: A graph of temperature difference with irradiation for both roofing sections

MODULE CHARACTERISTICS

Effect of Irradiance

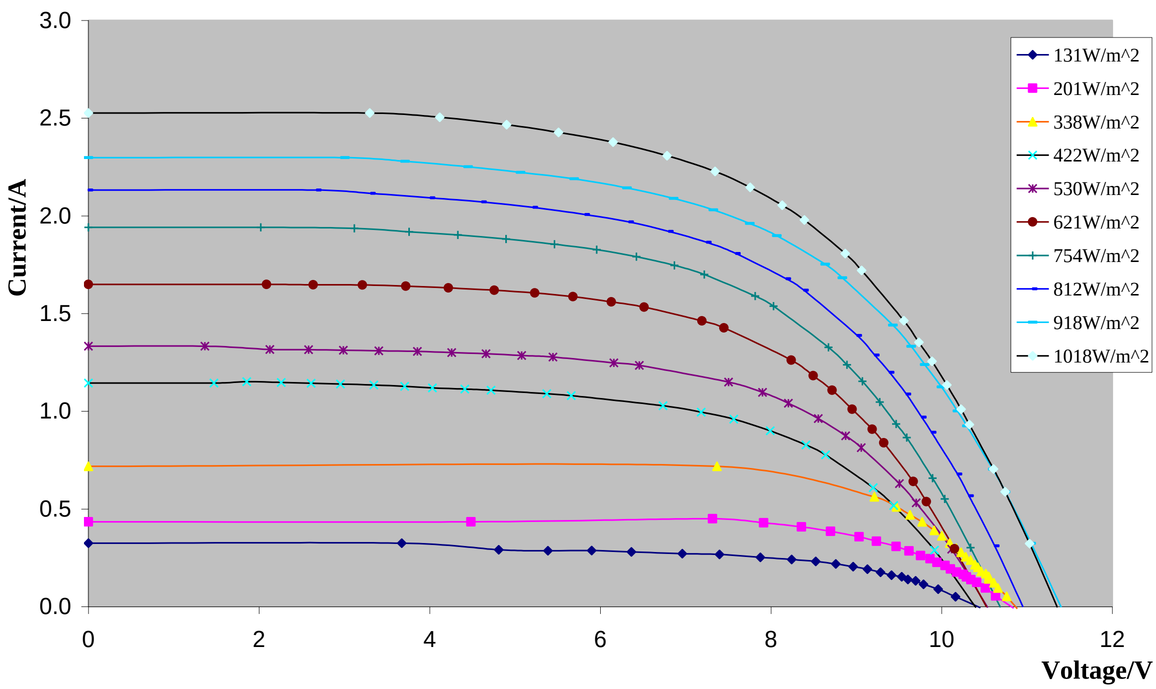

Figure 8: A graph of the I-V characteristics of the shingles

The I-V characteristics for most measured irradiance were plotted (Figure 8). The values obtained for these graphs were collected on separate days since irradiance varied considerable on daily basis. The open circuit voltage (Voc) was 13V, the device used was set to 12V because of limitations set on the buffer box. It was interesting to observe that for all levels the curves were quite smooth indicating rapid switching through the resistors so that irradiance would remain almost constant throughout measurements.

Temperature Effects

The operating temperature of solar cells in practice can vary over wide ranges for different kinds of photovoltaic modules. Different module design will cause cell encapsulation within them to reach different temperatures under identical operating conditions (Essah, 2002).

A study by Cereghetti et al, (2000) revealed that, considering the behaviour of triple-junction amorphous, increase in temperature causes an increase in efficiency. It was further observed that, during summer months, the efficiency increases as compared to other months buttressing the point above. Also, during the summer months (increase in temperature), efficiency results differ between series of 6 to 9% whereas during the winter months the series maintains a fairly constant ratio. However, these findings are different from that of crystalline PV modules.

To verify these deductions by Cereghetti et al, (2000), the power output obtained from measurements were plotted against the voltage at a particular irradiance but different temperatures. At 915Wm^{-2}, it is observed that due to temperature effects, there is reduction in power output by a coefficient of 0.09 %/°C (Figure 9). At 248Wm^{-2} the reduction in power output gave a coefficient of 0.3 %/°C (Figure 11). These reductions are made distinct when the I-V characteristics are considered (Figures 10 and 12). At the high and low irradiance levels, their Voc's reduce with increase in temperature by 4.3% and 5% respectively. However, their Isc increases slightly by about the same percentages as the Voc.

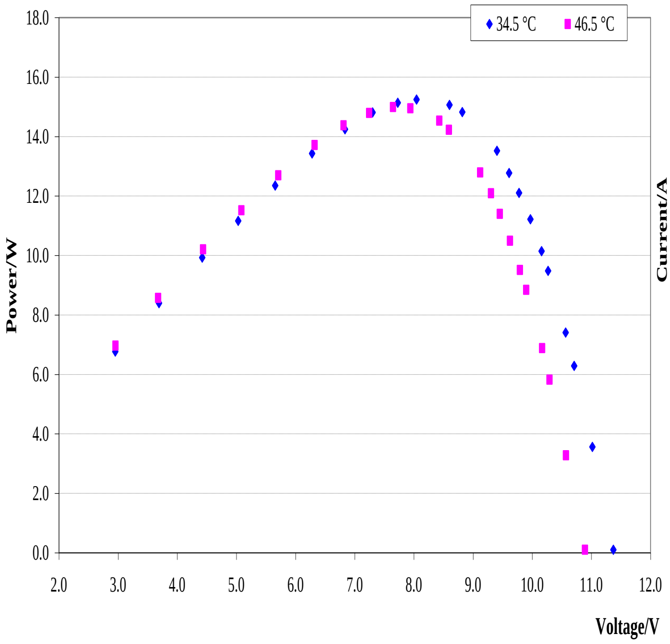

Figure 9 Effect of temperature on power output of the shingles at high irradiance (915 Wm^{-2})

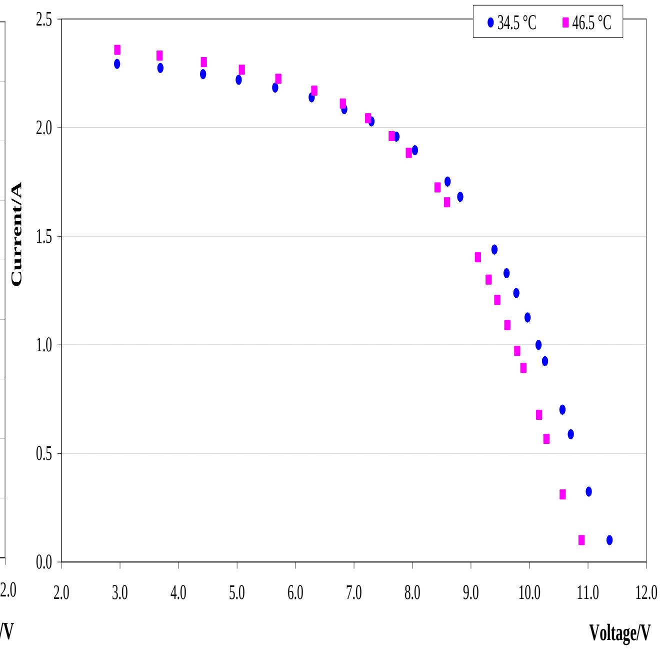

Figure 10 Effect of temperature on I-V characteristics at high irradiance (915 Wm^{-2})

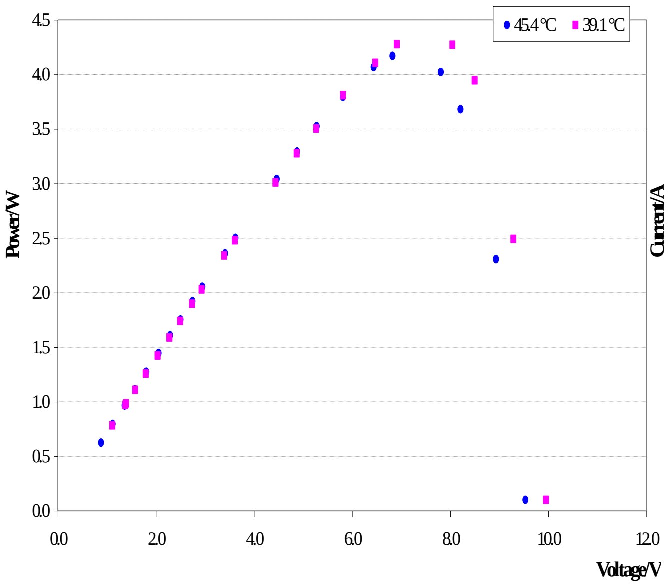

Figure 11 Effect of temperature on power output of the shingles at low irradiance (248 Wm^{-2})

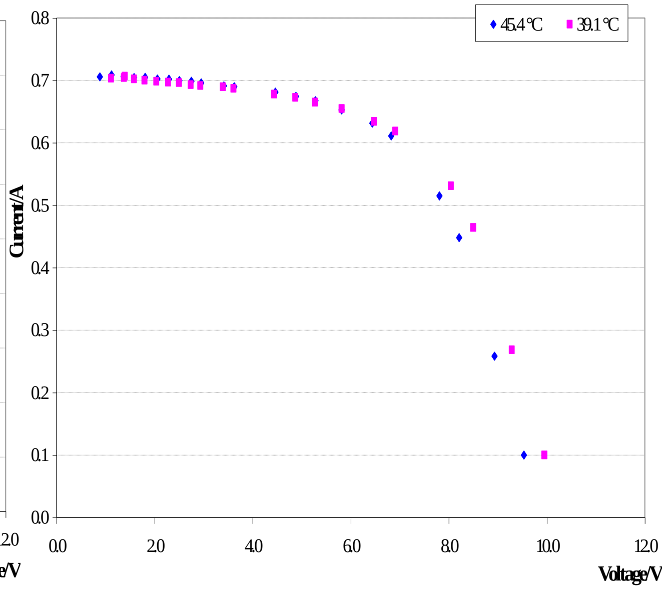

Figure 12 Effect of temperature on I-V characteristics at low irradiance (248 Wm^{-2})

<u>Shading Effect</u>

a) Triple- Junction Amorphous Silicon (3a-Si) PV

Figure 13 Shading 3a-Si with battens

Figure 14 Shading 3a-Si with mesh

The total area of the shingle shaded with battens was about 30% resulting in a power output decline of 35% for both high and low irradiance (Figure 13). Mesh of coarse wires was also used as shading objects (Figure 14). This resulted in 13% of output power loss. This decline is attributed not only to shading from the objects but also to the geometrical position of the sun. The position of the sun is relevant, i.e. if over head or at an angle, a shadow of the shading object is also cast on the PV, which also accounts for some percentage loss. Also the effect of temperature contributes significantly to the total power loss (Table 1).

Table 1 Comparison of shading and temperature effects at low and high irradiance

Level of Shading	Irradiance (Wm^{-2})	Temperature (°C)	Percentage of panel receiving light (%)	Maximum Power (W)
Not shaded	275	34	100	4.6
Top third	275	31	65	3
Bottom third	275	32	65	3
Mesh	275	39	87	4
Not shaded	894	42	100	14.8
Top third	894	49	63	9.3
Bottom third	894	44	69	10.2
Not shaded	965	44	100	14.5
Mesh	965	49	84	12.2

b) Crystalline silicon(c-Si) PV module

For a similar test a polycrystalline silicon PV module was considered. At high irradiance, a comparison of shading effects as in Figures 13 and 14 was configured. For the same percentage of shading used during tests of the 3a-Si, the effect on the c-Si was greatly pronounced (Table 2). Compared with the 3a-Si where at high irradiance there is a power loss of average 34% when shaded one-third, that of the c-Si is averaged at 55%. This effect is 21% more than the former which reduces the efficiency of the panel significantly. The loss in power output when shaded totally by mesh was equally high (11%) as compared to that of the 3a-Si, which was 4%. Despite the fact that the geometrical position of the sun is a factor in the power reduction, the reason is attributed to the lack of in built by-pass diodes in the c-Si. As a result, shading one cell affects other cells, reducing the power output drastically and hence the efficiency.

Table 2 Comparison of shading and temperature effects

Level of Shading	Irradiance (Wm^{-2})	Temperature (°C)	Percentage of panel receiving light (%)	Maximum Power (W)
Not shaded	750	47	100	42.1
Top third	750	41	46	19.2
Bottom third	750	44	44	18.4
Mesh	750	46	89	37.6

CONCLUSIONS

The collection and monitoring of data has brought to light the fact that, integrating 3a-Si into the building façade in Ghana, would provide the building a secure roofing material and the supply of electricity. It also avoids high construction cost that may be incurred from some stand alone PV systems. Eventually it helps reduce the environmental impact that would occur from the use of conventional energy.

Triple junction amorphous silicon PV is less affected at high operating temperatures as compared to crystalline silicon(c-Si) PV. However, internal temperatures of the building would increase by some amount of degrees, depending on the surface area of the roof that is covered with the shingles. It tends to cool faster than the conventional roofing tiles therefore reducing the internal temperature during some hours of the day. It is also less sensitive to shading. Further studies by Essah (2002) confirm that, it works effectively with individual module inverters at all weather conditions as compared to c-Si which comparatively does not work well at lower irradiance. These qualities of the 3a-Si are preferred for the BIPV industry, especially in conditions such as that of Accra, Ghana.

Considering the high levels of annual sunshine duration (1800 - 3000 hours) in the Sub-Sahara region, the results from this study applies to, and it is of equal importance to countries (such as: Nigeria, Togo, Ivory Coast, etc) in that region. Equally, because all these countries are along the same latitude (above the Equator), the effective angle of the roof (Figure 6) is applicable.

The results demonstrated in this paper confirm the dual significance of the BIPV system to the building in Ghana and more importantly it is adaptive to other neighbouring countries

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