University of Nairobi

College of Architecture & Engineering

Department of

Mechanical & Manufacturing Engineering

Designing and Building Integrated Photovoltaic Solar Roofing Tiles

Anthony Maina Nyaga

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Master of Science in Energy Management

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Declaration

I **Anthony Maina Nyaga** declare that this report is my original work, and except where acknowledgements and references are made to previous work, the work has not been submitted for examination in any other University.

Signature.........................Date..................

Approval by supervisors

I confirm that the study was carried out under my supervision and has been submitted for examination with my approval as University supervisor.

Prof. J. Mwangi Mbuthia Signature..............Date................

Dr. N. Odero Abungu Signature..............Date................

Dedication

I hereby dedicate this work to:-

A. My Parents: Mr & Mrs J. Nyaga

B. My Employer: The World Bank Group

C. The People of Kenya and Africa at Large

Acknowledgement

I hereby acknowledge the ideas and immense support accorded to me by:-

My Supervisors

1. Prof. Mwangi Mbuthia M.Sc.(IC), Ph.D.(UMIST), R.Eng., C.Eng.,MIEEE, MIEK

   Consultant & Lecturer - University of Nairobi
   P. O. Box 51785 00200, Nairobi, Kenya

2. Prof Nicodemus Abungu Odero,
   University of Nairobi,
   Department of Electrical and Information Engineering,
   P.O. Box 30197,
   Nairobi 00100.

My classmate(s)

1. D. Muthamia, PMP.

   P.O. Box 69882 – 00400

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List of Nomenclature

PV - PhotoVoltaic

BIPV - Building Integrated PhotoVoltaics

I - Current

V -Voltage

P – Power

PV - Photovoltaic

W - watts

MW – Megawatt

Mt – Million tonnes of Green House Gases.

MEA - Middle East and Africa

KEBS - Kenya Bureau of Standards

KPLC – Kenya Power & Lighting Company

ERC – Energy Regulatory Commission

Voc – Open circuit Voltage

Vmp – Maximum Power Voltage

Isc – Short Circuit Current

Imp – Maximum Power Current

Pmax – Maximum Power

MIT – Massachusetts Institute of Technology

Abstract

This project sought to design and build a low cost solar photovoltaic roofing tile prototype by incorporating photovoltaic cells into roof tiles. Such tiles have the potential to provide robust and distributed electricity contained within the construction industry.

70% of the African Population lacks access to clean affordable and sustainable electricity. This is more than 620Million. Kenya is no exception and requires 15,000MW of power to power our Kenyan 2030 Vision. So far and for the last 50+ years we have only managed to generate 2,295MW which is just slightly above a tenth of the required power. The Kenyan government is also pushing for an immediate milestone of 5,000MW by 2017 in a bid to keep up with anticipated development goals.

This power is mostly generated from hydro, geothermal, wind, diesel, and now coal and nuclear is envisaged as well in another 10 years among others. We also have instances of solar energy but only insignificant generation bearing in mind the fact that we benefit from solar emission in perpetuity (i.e. more than 11 months a year in our Middle East and Africa, MEA region).

Solar energy is a naturally occurring and God given clean energy resource available all year round and which we need to exploit in a big way. A Massachusetts Institute of technology Research depicts that that the amount of energy emanating from the sun at any one time can power 5,000+ similar earths like ours. This paper seeks to open a way to close this dichotomy of too much solar energy availability yet the region is the most energy poor, we expand the shareholder base of power generation even to the common homeowner.

The unique value proposition is to ensure that every household produces more than twice (2x) its usage capacity consequently the already existing power generation is deployed to other industrial and commercial usage to avoid power rationing and to lower the tariff by increasing supply, thereby releasing our Kenyan and East African industries to grow in leaps and bounds, seeing power shortage is one of the largest de-motivator.

Successful rollout of such solar tiles will result in the homeowner, having more than enough energy for their needs and instead of paying their power bills they get compensated for all the extra power that the sun has generated for them. A significant social economic benefit and thrust will be ensuring that specifically the lower middle income and poor part of the population also harbour a base income to cover their basic needs from income generated by selling surplus power.

The longer term objective and at a macro level is to expand our economy broadly by ending energy poverty, improving on both our environment and the populace's health by discouraging other non-renewable energy sources and providing extra purchasing power from extra electricity sales through net-metering, thereby presenting another opportunity for individuals unique contribution to build both their livelihoods as well as the national and regional economies without the pressure of meagre hand to mouth earnings in tandem with the Sustainable Development Goals (SDGs) ratified in Paris in 2015.

1. Introduction

1.1 Background

This project seeks to design and build photovoltaic infused roof tiles. The goal is to replace conventional roofing tiles with tiles that integrate photovoltaic (PV) cells and be connected together. This will allow a roof that is structurally modified to produce electricity for the occupants of the building.

The major challenge is how to incorporate the PV cells into the roof tile securely and cost effectively. After incorporation both the PV cell and the tile need to withstand the weather elements at the same time ensure the cells continue to work electrically for a long period, seeing homeowners need not retrofit their roofs regularly. The design of the tile needs to allow light through to the PV cells while still protecting them from mechanical, optical and chemical damage, yet give it an aesthetically appealing look.

Currently, photovoltaic roof tiles and roofing shingles are in production and limited use in other countries, such as Switzerland, Germany, the United States of America and Japan [4]. These tiles are used in conjunction with an inverter to produce power for the local electrical appliances. At some times of the day the power produced is greater than the power used by the household, this excess power is fed back into the regional electricity grid, resulting in a deduction from the bill of the household or business.

Photovoltaic power has the potential to benefit the Kenyan electricity provision greatly. KPLC, the electricity provider, is operating at less than a 10% power capacity margin at peak times of the day, and is below its planned margin. As a result KPLC is making regular use of planned power outages, referred to as load shedding, which are retrogressive to industry and commerce.

Kenya's grid capacity of about 2,295MW (as of December 2015) during normal hydrology and a peak demand of 1,347MW and therefore the grid would benefit greatly from a PV-peak reduction in load. Thus distributed solar power has the potential to alleviate KPLC's problem of the peak electricity demand on the regional grid.

Another benefit of solar power in general is its renewable nature. The 46.3 % dominant source of electricity in Kenya is hydro power stations. When there is low hydrology the country is forced to rely on expensive thermal and rental diesel power from Independent Power Producers (IPPs). Diesel-fired power generates approximately 0.68 kg of carbon dioxide per kWh of electricity [1].

This means a gigawatt of solar power, over a year's worth of 4 strong daylight hours per day, could save 1.4 Mt of carbon dioxide from entering the atmosphere. This is in line with the Sustainable Development Goals of the United Nations: Goal 7, Target 1 is to "Integrate the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources." One of the main components of this target is to contain rising greenhouse gas emissions (United Nations, 2000).

It can be seen that photovoltaic tiles could have benefits to Kenya, the economy and the environment. These benefits suggest subsidies to those consumers and businesses wishing to try the tiles once they are in production. This would hasten the adoption, and the costs of the subsidies should soon be recovered from the power saved due to the photovoltaic installations.

A form of subsidy that has found success in other countries is the net-metering, and now being considered in Kenya in addition to zero rating for PV roof tile products and installations.

1.2 Problem statement

70% of the African Population lacks access to clean affordable and sustainable electricity. This is more than 620Million. Kenya is no exception and requires 15,000MW of power to power our Kenyan 2030 Vision. So far and for the last 50+ years we have only managed to generate 2,295MW which is just slightly above a tenth of the required power. The Kenyan government is also pushing for an immediate milestone of 5,000MW by 2017 in a bid to keep up with anticipated development goals.

1.3 Objectives

The main objective of this project is to design and build a solar PV integrated roofing tile and come up with the cost per WHr generated from it. The following are the design objectives considered in making the solar integrated roofing tile considering the Kenyan market and the purpose of making a substantial electricity contribution:

- The tiles should be able to be installed easily in the same way as standard tiles, although the electrical connections may need to be done and by a certified ERC electrician.
- A collection of tiles to be installed on a domestic roof should be able to provide enough electricity so that it is useful for household usage and where applicable more to send back to the grid for extra credit to the homeowner.
- The power generated by the tiles will be harnessed and pass through a storage system, either batteries, the national grid or other air compression storage systems.
- The system should be robust and provide for redundancies so that, if a tile fails, it will still work at a proportionate level of effectiveness.
- The tiles should meet the relevant building regulator (KEBS).
- The tiles should have a lower cost than current domestic PV plus roof solutions in Kenya.

Current PV roof installations are complicated to install and alter the normal roof of the building both structurally and aesthetically. This is aesthetically unpleasing and makes them expensive. Thus it is important that the roof tile is able to fit into a standard roof tiling setup.

2. Literature Review

2.1 Working Principle

Solar energy can be harnessed using solar cells which are PV devices that convert the incident solar radiation into electricity with no noise, pollution or moving parts, making then robust, reliable and long lasting. Solar cells are made from semiconducting material. Light shining on a solar cell raises the electrons into higher energy states and this energy can be dissipated in an external circuit as electric energy.

2.1.1 PV Cell Characteristics

The PV cell can be modelled as a current source in parallel with a diode. When there is no light present to generate any current, the PV cell behaves like a diode. As the intensity of incident light increases, the current generated increases [4].

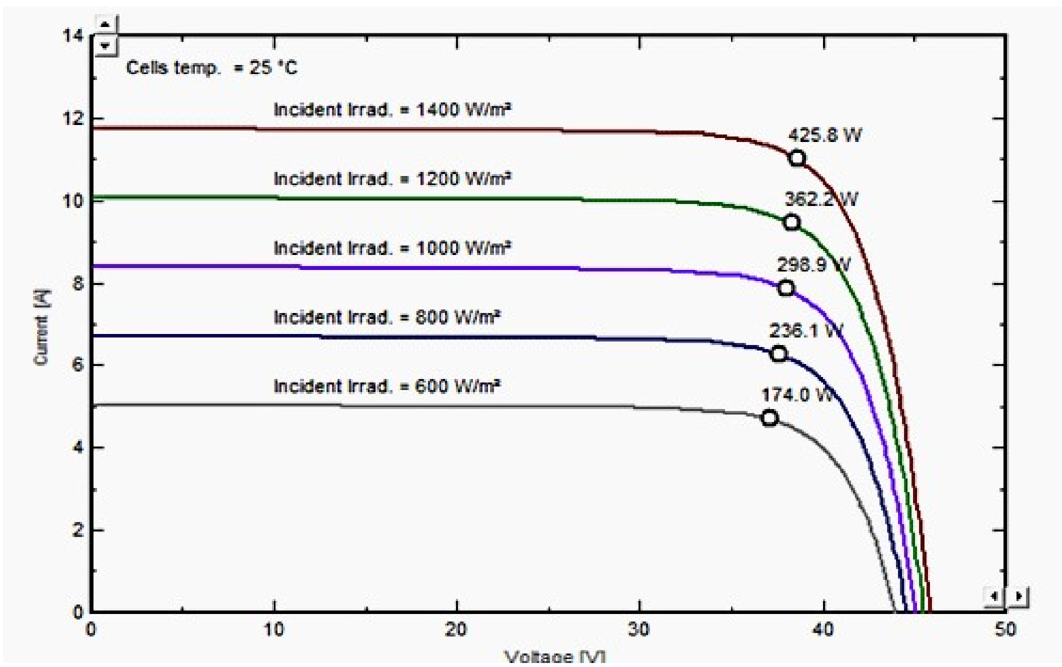

Fig. 2.1: **I-V Sweep Curve**

The graph shows that as the light intensity increases shown as the incident irradiance, increases the current generated hence the power output increases.

The I-V curve of an illuminated PV cell is the shape shown in Fig. 2.2 as the voltage across the measuring load is varied from zero to V_{OC}.

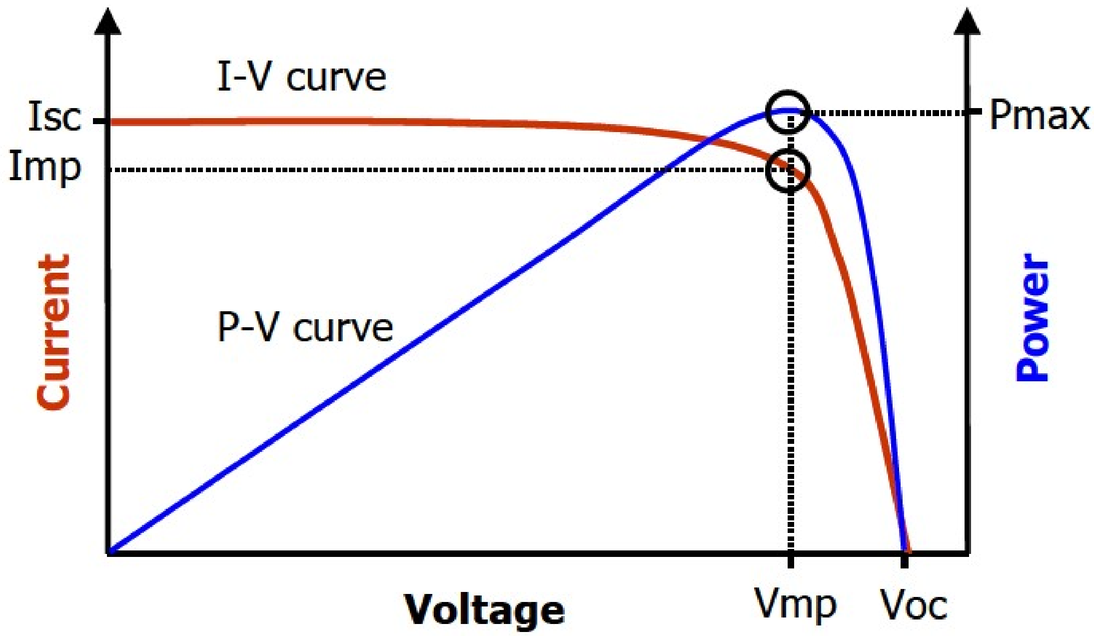

Fig. 2.2 The I-V and P-V curves of a photovoltaic device.

Where,

Voc – Open circuit Voltage

Vmp – Maximum Power Voltage

Isc – Short Circuit Current

Imp – Maximum Power Current

Pmax – Maximum Power

2.1.2 PV Performance Parameters

The P-V curve is calculated from the measured I-V curve. From the graphs above, there are many performance parameters for the cell that can be determined. These include:

2.1.2.1 Short Circuit Current (I_{SC})

The short circuit current I_{SC} corresponds to the short circuit condition when the impedance is low and is calculated when the voltage is equal to zero. I (at V=0) = I_{SC}

2.1.2.2 Open Circuit Voltage (V_{OC})

The open circuit voltage V_{OC} occurs when there is no current passing through the cell.

V (at I=0) = V_{OC}

2.1.2.3 Maximum Power P_{MAX}, Current at P_{MAX} (I_{MP}), Voltage at P_{MAX} (V_{PM})

The power produced by the cell can easily be calculated along the I-V sweep by the equation P =IV. At the I_{SC} and V_{OC} points, the power will be zero and the maximum value of power will occur between the two. The voltage and current at this maximum power point are denoted as V_{MP} and I_{MP} respectively [5]. See Fig 2.3 below.

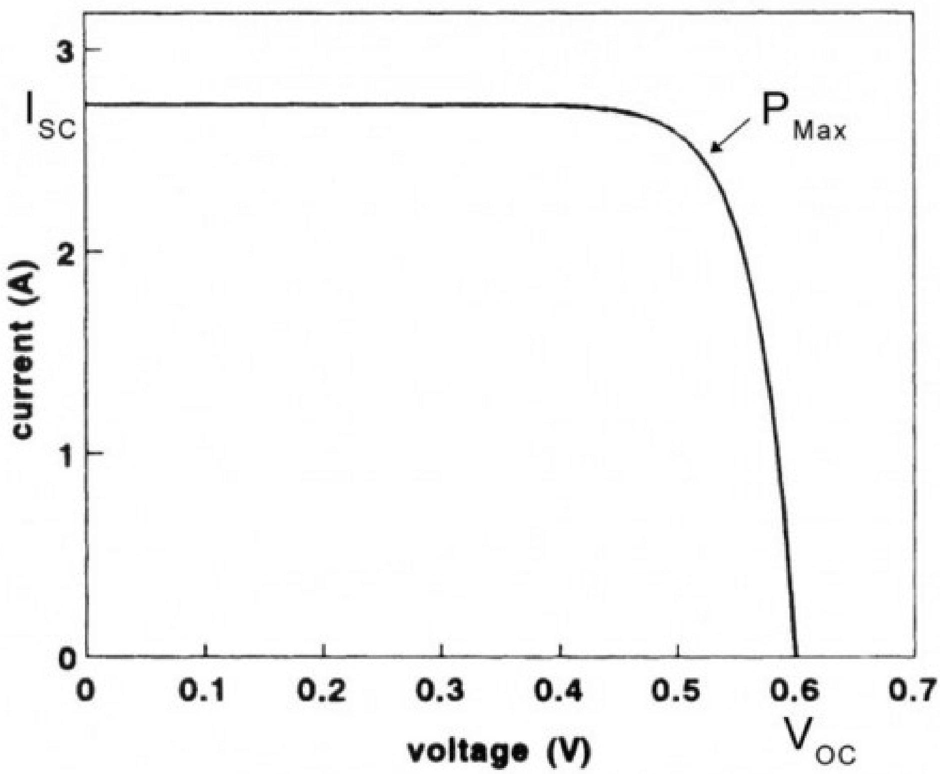

Fig 2.3: Maximum Power for an I-V Sweep

2.1.2.4 Fill Factor (FF)

This is the measure of the quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_t) that would be output at both the open circuit voltage and short circuit current together. Fill Factor (FF) can also be interpreted graphically as the ratio of the rectangular areas depicted in the Fig 2.4:

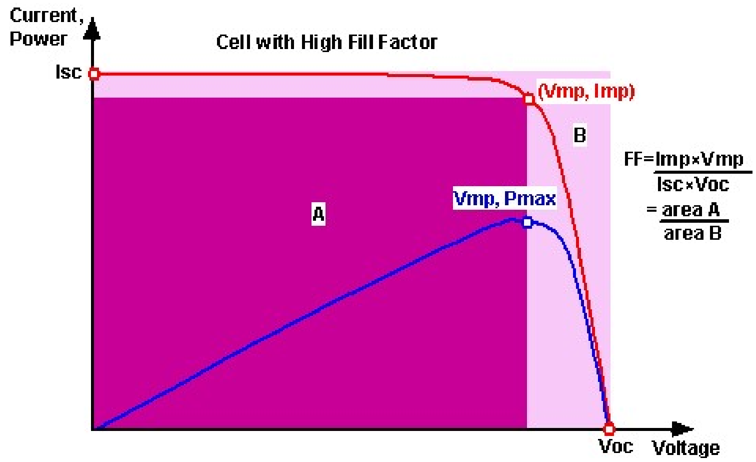

Fig 2.4: Getting the Fill Factor (FF) from the I-V sweep

A larger fill factor is desirable, and corresponds to an I-V sweep that is more square like. Typical fill factors range from 0.4 to 0.7. Fill factors are often represented as a percentage.

2.1.2.5 Efficiency (η)

Efficiency is the ratio of the electrical power output P_{out}, compared to the solar power input, P_{in}, into the PV cell. P_{out} can be taken to be P_{MAX} since the solar cell can be operated up to its maximum power output to get the maximum efficiency.

$$\eta = P_{out}/ P_{in} \text{ therefore } \eta_{max} = P_{max}/ P_{in}$$

P_{in} is taken as the product of the irradiance of the incident light, measured in W/m^2 or in suns (1000 W/m^2), with the surface area of the solar cell [m^2]. The maximum efficiency (η_{MAX}) found from a light test is not only an indication of the performance of the device under test, but, like all of the I-V parameters, can also be affected by ambient conditions such as temperature and the intensity and spectrum of the incident light. For this reason, it is recommended to test and compare PV cells using similar lighting and temperature conditions.

2.1.3 Temperature Measurement Considerations

The crystals used to make PV cells, like all semiconductors, are sensitive to temperature. Figure 2.5 depicts the effect of temperature on an I-V curve. When a PV cell is exposed to higher temperatures, I_{SC} increases slightly, while V_{OC} decreases more significantly.

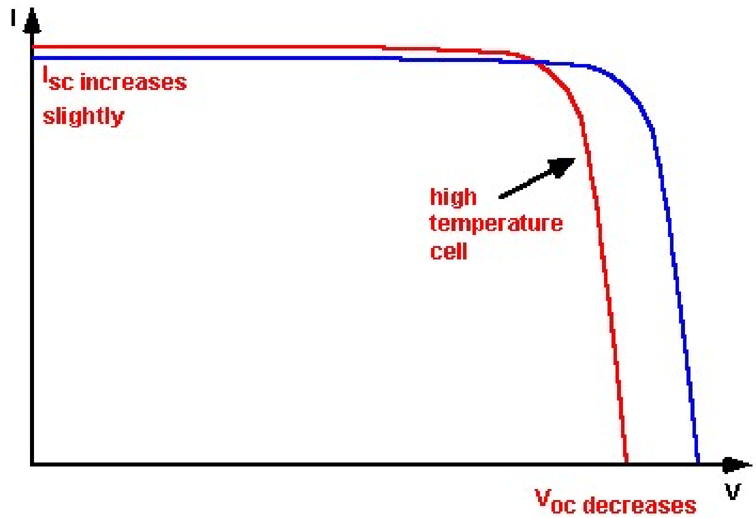

Fig. 2.5: Temperature effect on I-V curve

For a specified set of ambient conditions, higher temperatures result in a decrease in the maximum power output P_{MAX}. The I-V curve will vary according to temperature [6].

2.1.3.1 I-V Curves for Modules

For a module or array of PV cells, the shape of the I-V curve does not change. However, it is scaled based on the number of cells connected in series and in parallel. When 'n' is the number of cells connected in series and 'm' is the number of cells connected in parallel and I_{SC} and V_{OC} are values for individual cells, the I-V curve shown in fig. 2.6.

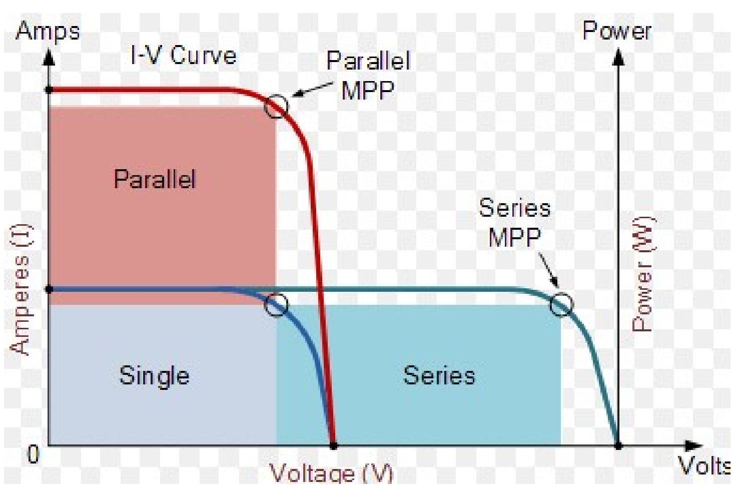

Fig 2.6 I-V Curve for Modules and Arrays

Standard Test Conditions (STC): Conditions under which a module is typically tested in a laboratory: (1) irradiance intensity of 1000 W/ m2, (2) Air Mass of 1.5 standard reference spectrum, and (3) cell or module temperature of 25 ± 2 degrees C. This allows for comparison to be done for different manufacturers.

2.2 Building Integrated Photovoltaics (BIPV)

Building Integrated Photovoltaics are photovoltaic materials that are used to replace conventional building material such as roofs or walls. These are then used to generate electricity that can be used in the building.

2.2.1 Forms of BIPV

Around the world BIPV are available in various forms. These include solar PV car ports, greenhouses, building facades and roofs.

3. Methodology

Each of the monocrystalline Silicon Solar Cell is rated to provide an Average Power of 1.8 Watts, Average Current (Amps): 3.6 Amps and Average Voltage (Volts): 0.5 V. They are very brittle and required careful handling to avoid breakage.

Each cell has two sides, the front is the part that will face the sun and capture the light (facing upward). This is the Negative Side of the solar cell. To connect the cells together, Tabbing Wires and Flux Pen were required.

Each of the solar tile consists of twelve cells connected in series to produce 5.5 to 6 volts DC, 30 watts and 3.5 AMP.

The electrical connection of each solar cell is shown in fig. 3.1 below:

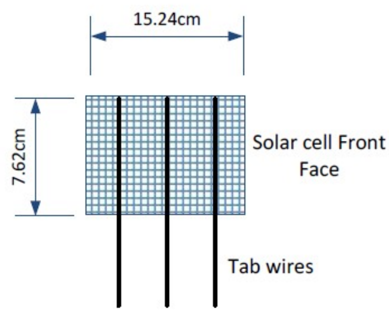

Fig. 3.1 Front view of a cell – Negatively Charged

On the back side, there are 6 white squares, 3 on both sides. A pair of tabbing wire will have to be connected to those squares, one on each set of 3 squares. The back side is normally light grey in colour and faces downward. This is the Positive Side of the solar cell.

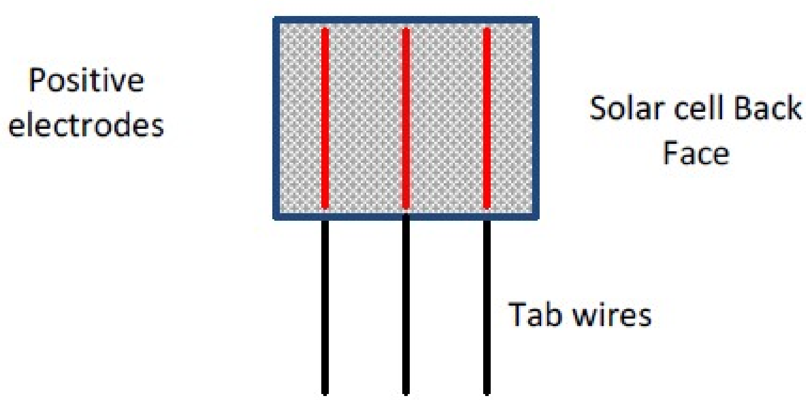

Fig. 3.2 Back view of a cell – Positively charged

Soldering the tabbing wires to the solar cell using Soldering Iron;

The electrodes run parallel from top to bottom on the front of each cell. The tabbing wires were welded onto these electrodes.

The solar cells were placed on a cardboard before soldering for support. The Flux Solution was applied on the two lines of the solar cell. The purpose of the flux pen is to help the tabbing wire to stay in place during the welding process. The tabbing wire was cut to about twice the height of the cell, (approximately 156mm long).

Each piece of tabbing wire was placed over the line and soldered together starting from the top moving slowly towards the bottom. The soldering was done on all the 12 cells gently since applying pressure on the cells may break them.

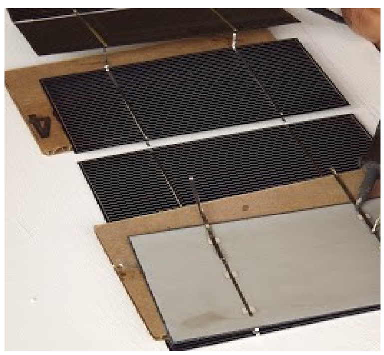

Fig 3.3: Picture of the solar cells with tabbing wires

Connecting the solar cells together in series:

Now the tabbing wires which had been connected to the solar cell were then connected to the positive poles of another solar cell. This was done as follows:

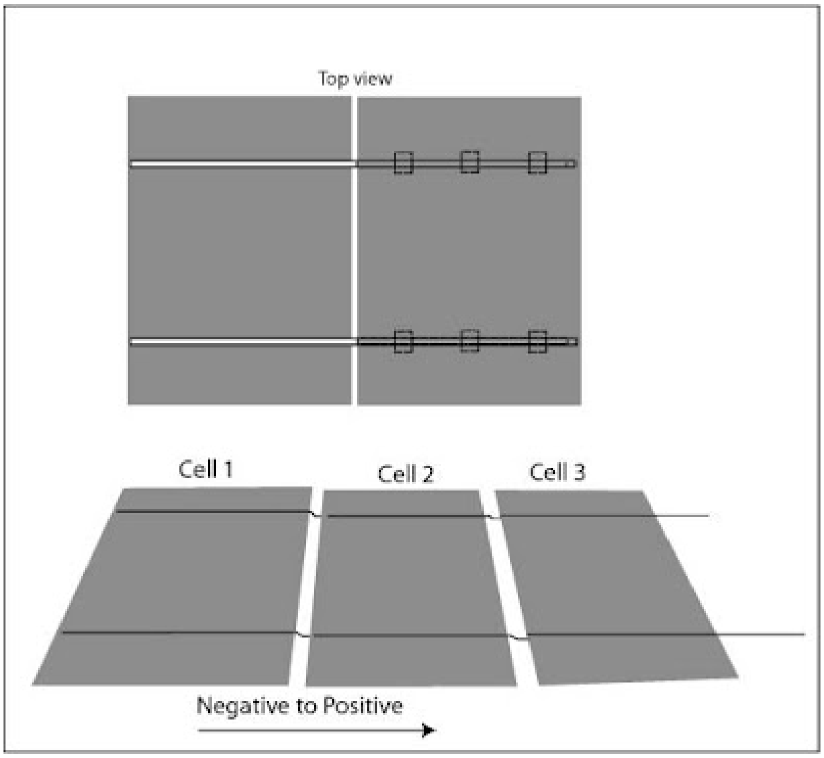

Fig. 3.4: Connecting the solar cells in series

Two tabbing wires were already connected to the negative poles on each cell. The same tabbing wires will now be connected to the positive poles of the next cell. Cell 1 was joined to cell 2 and cell 2 was joined to cell 3 and so on as shown on fig. 3.5 below:

Fig 3.5: the cells connected in series

To join the tabbing wires to the positive poles (3 squares on the grey back side), the flux was applied over each square and the tabbing wire was welded using the soldering iron.

Fig. 3.5 shows how the connections were made.

Mounting the solar tile:
The tile will consist of 4 cells by 3 cells which will be 45.72 cm by 30.48 cm in size. The tools materials required to assemble the tile include:

- Plastic substrate of size 45.72 cm by 30.48 cm ,
- 45.72 cm by 30.48 cm clear glass
- Silicone (both transparent and white).
- 20 screws (12mm),
- Electrical wires and
- Tabbing and BUS wires.

The tools required included a power drill and electric screw driver, metal saw to cut the aluminum bar.

The three sets of four cells were placed on the marine board as shown in the fig. 3.6 below:

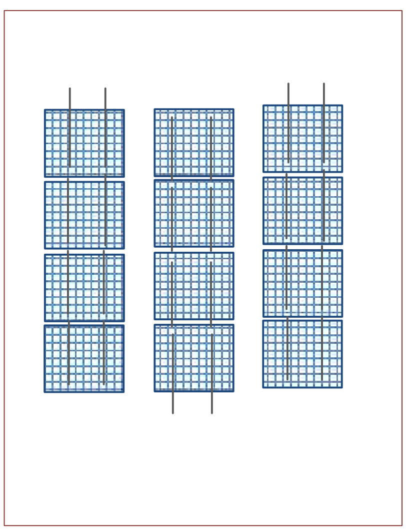

Fig. 3.6 Tabbed cells placed on the board

One set of 4 cells was connected to the 2nd, and 3rd set. This was done as follows:

Bus wires were used to join each series of 4 cells to each other. Bus wire is larger in width (0.6 mm) as compared to tabbing wire which is only 0.2 mm

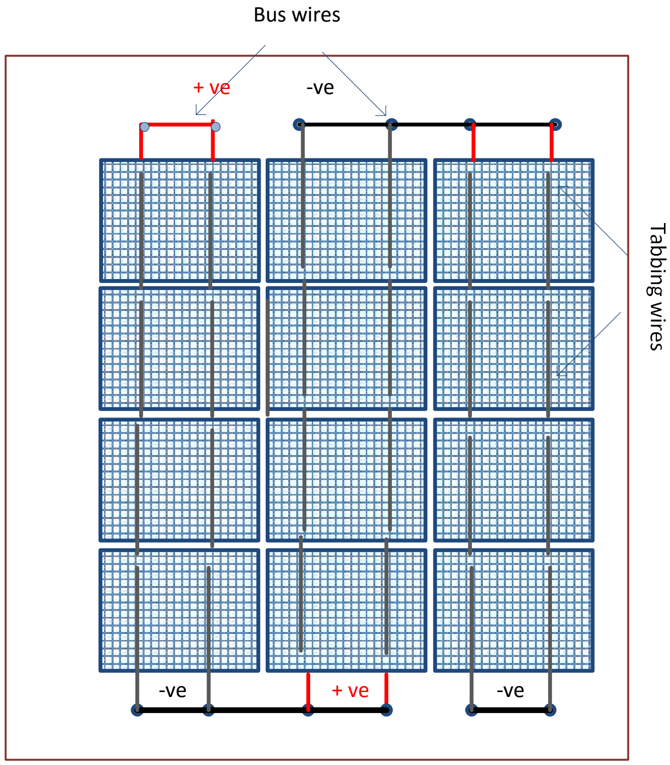

Fig: 3.7 Cells in series connected to bus wires

Fig: 3.8 Picture of Cells connected to bus wires

Next an electrical wires were used to connect to the positive bus wire and a second one was connected to the negative bus wire as shown in the figure 3.9 below.

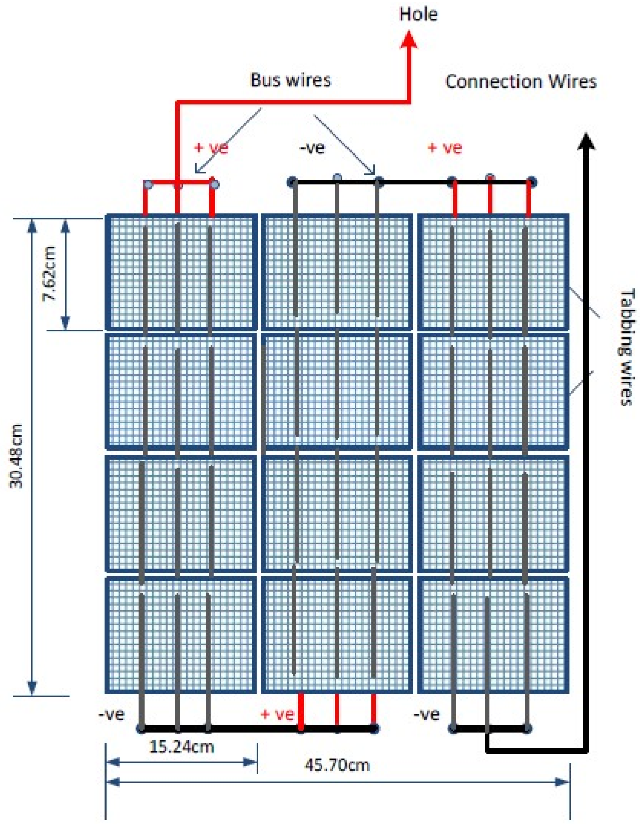

Fig. 3.9 Cells Electrical connection Front view

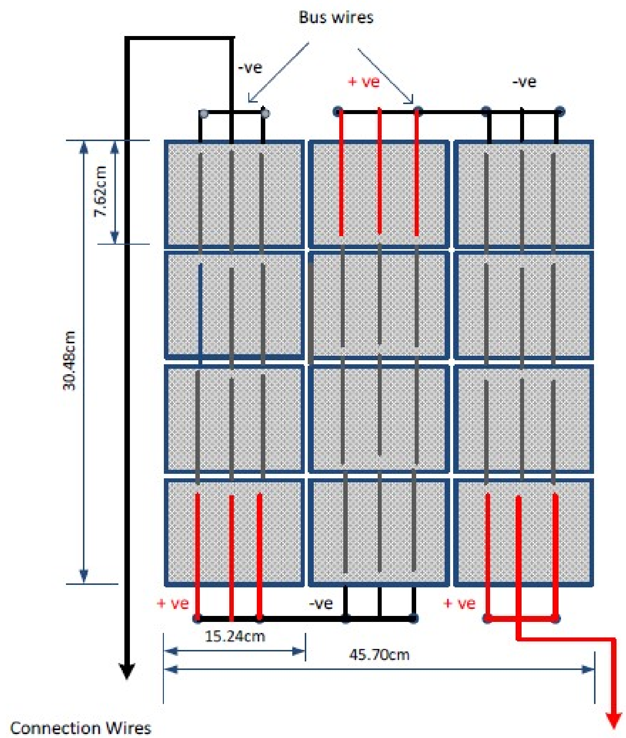

Fig. 3.10 Cells Electrical connection Back view

Mechanical support

The red cable is the positive while the black one is the negative lead. All connections which were in contact with the bus wires were further consolidated by using lead solder. After inserting the positive and negative wires into the hole, silicone was applied to fill in the hole. All openings, holes, gaps were filled in with white multi-purpose silicone.

These two wires were then inserted through a small hole that was drilled in the base of the tile support and connected in the junction box.

Once all the cells were stuck on the substrate and all connections were checked and consolidated, the next step was to place the glass over the cells.

The transparent silicone was applied in thick chunks on the 4 corners of the Plastic base and glass was then carefully laid over the cells. The glass will get stuck to the silicone. Furthermore, the thick chunks of silicone will prevent the glass from touching the solar cells, leaving a gap of 2 to 3 mm in between.

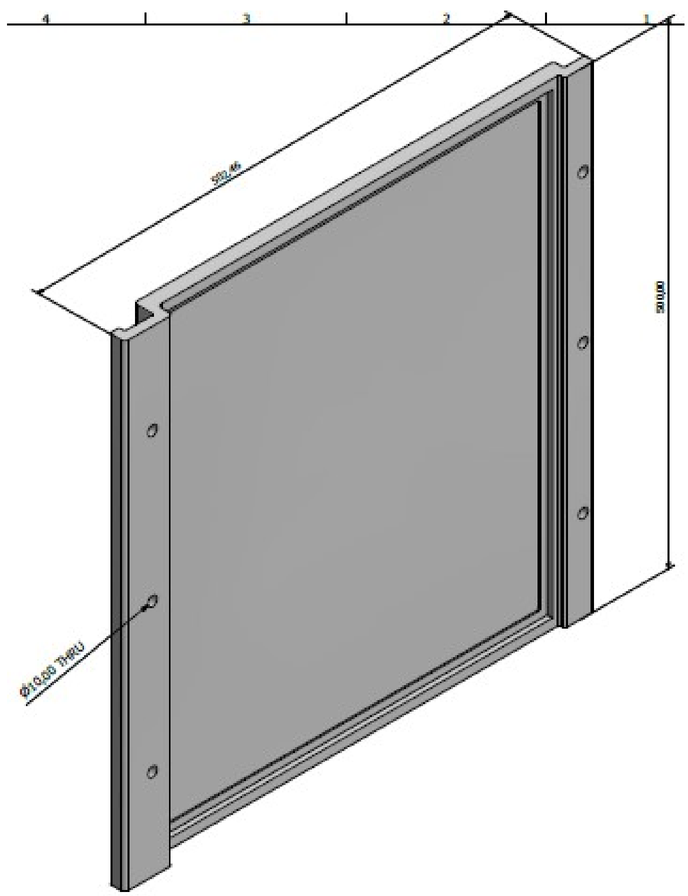

Fig 3.11: Plastic Substrate Mechanical Drawing

The substrate was made from recycled plastic as shown in the figure below:

Fig 3.12: Recycled Plastic used to make substrate

This was melted and compressed using a steel mould to form the substrate. The mould was assembled by a team of technicians as shown in the fig. 3.13 to fig 3.19 below:

Fig: 3.13: Lower face of the mould

Fig3.14: Upper face of the mould

Fig 3.15: Connecting steel Rods

Fig 3.16: Reinforced upper mould

Fig 3.17: Detailed connection of upper and lower mould

Fig 3.18: Complete mould

Fig 3.19: Output – Compressed plastic

Fig. 3.20 below shows the final assembly of the roofing tile

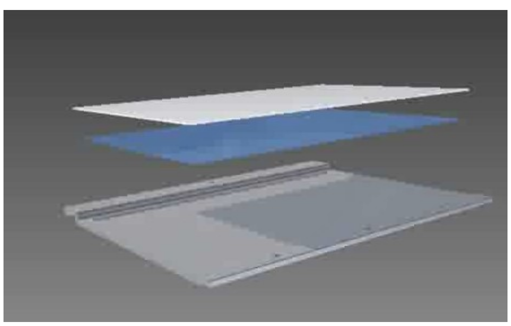

Fig 3.20: Final Assembly of Roofing tile

Once the solar roofing tile is ready, it will be installed over the roof. Three such tiles connected in series as shown in the electrical drawing in fig. 3.21 below have a rating of approximately 18V and can be used to charge a 12V battery system.

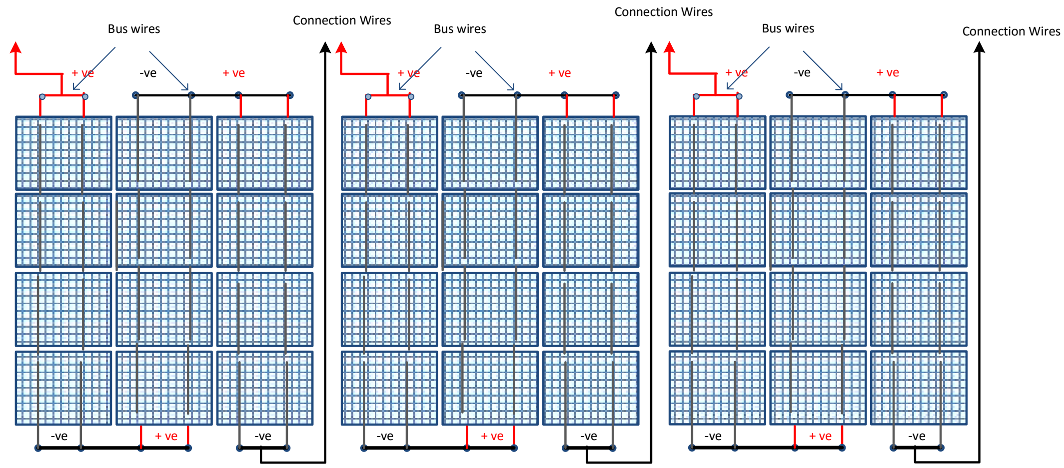

Fig. 3.21 Electrical connection of three tiles in series.

4. Results and Discussions

4.1 Description of the solar integrated roofing tile

The tile included 6 monocrystalline cells with the following properties:

Table 4.1: Properties of the Solar cells

Dimension	156mm by 78mm +/-5mm
Thickness	200µm+-20 µm
Front	Anisotropically texturized surface and dark silicon nitride anti-reflection coatings, 1.4mm silver bus bars
Back	Full size aluminum back surface field, 2.5mm discontinuous soldering pads
ELECTRICAL PERFORMANCE at light intensity of 1000W/m^2 and 25^{o}C	
Efficiency (%)	18.1
Power Pmp(W)	2.16
Max. Power Current Imp (A)	4.10
Short Circuit Current Isc (A)	4.38
Max. Power voltage Vmp (V)	0.527
Open circuit Voltage Voc (V)	0.626

For the assembled tile consisting of 10 cut solar cells, the nominal power measured was 15W. The test equipment used was a digital multimeter and a current measuring cramp meter.

Table 4.2: Properties of the Solar Integrated Roofing tiles

Nominal power (W)	15W
Module area (m^2)	0.15
Temperature ^{o}C	36.5
Irradiation W/m^2	1028
Inclination	2^o

Values at Standard Test Conditions	
Power Ppm(W)	12.94
Max. Power Current Ipm(A)	3.489
Short circuit Current Isc(A)	3.525
Max. Power voltage Vpm(V)	3.71
Open circuit Voltage Voc(V)	5.84
Calculated Values	
Filling Factor	0.63
Deviation from ideal curve	-13.7
Correction for voltage loss in cables	
Specific resistance	0.0178 $\Omega mm^2/m$

4.2 Test results of the solar integrated roofing tile

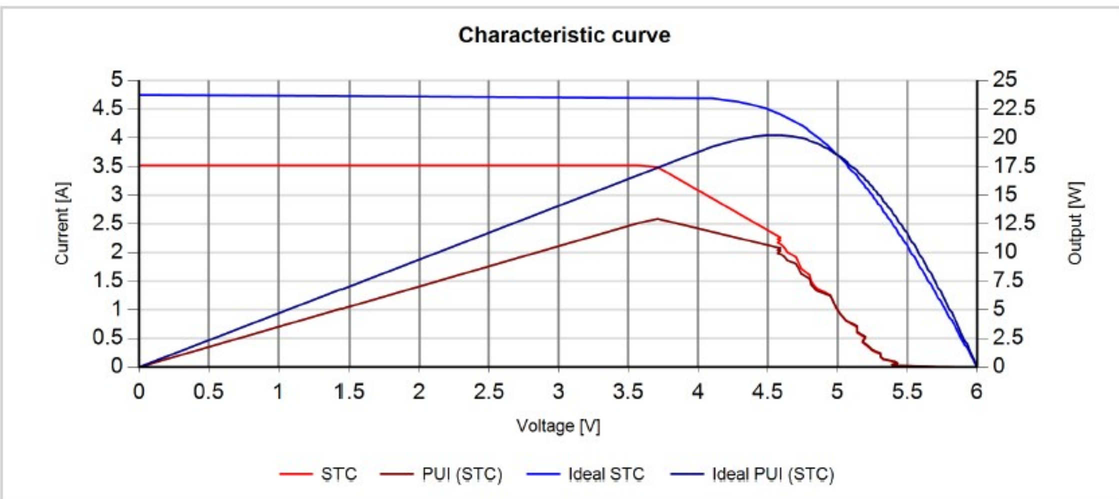

Fig. 4.1: Characteristic Curves for Power – voltage and Current Voltage

The tests were carried out at different temperature values, different irradiance and angle of inclination of the sample tile. The results are as shown in the graph below.

Table 4.3: Roofing tile Characteristic Curves case 1

Temperature °C	36.4
Irradiation W/m^2	899
Inclination	8°

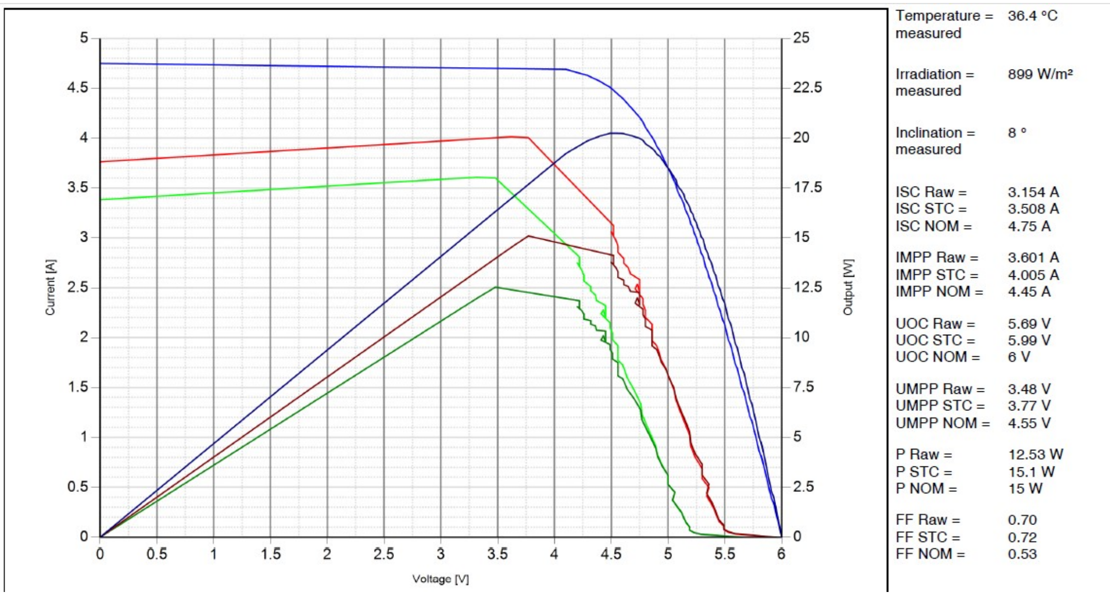

Fig. 4.2 Roofing tile Characteristic Curves case 1

Table 4.4: Roofing tile Characteristic Curves case 2

Temperature °C	37.0
Irradiation W/m²	992
Inclination	2°

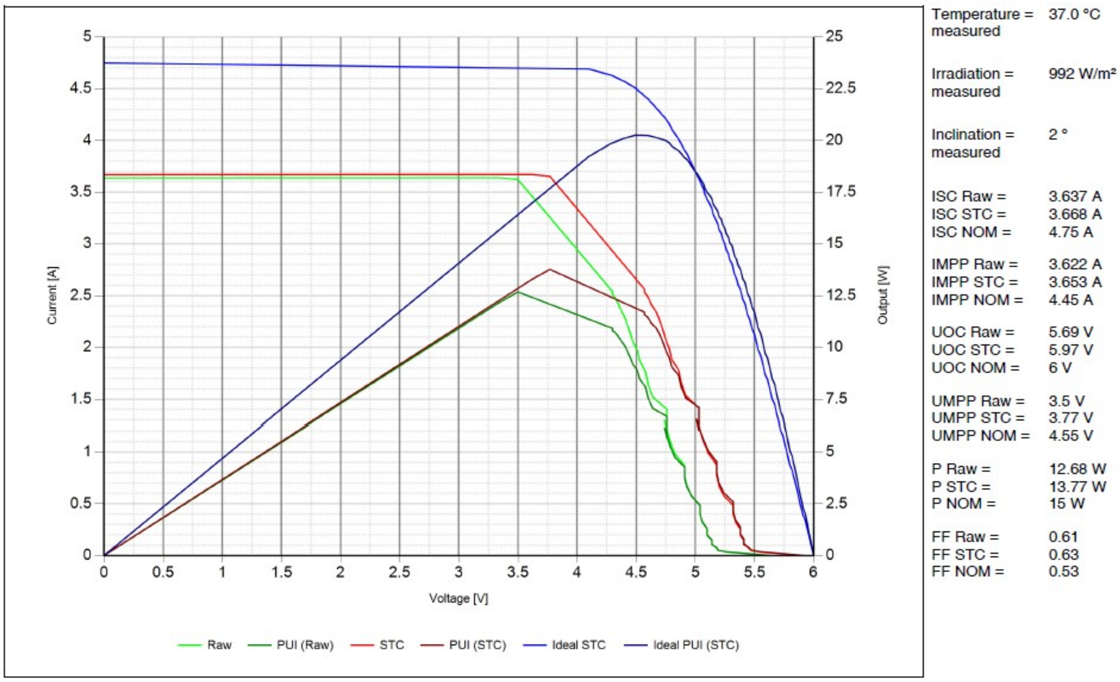

Fig. 4.3 Roofing tile Characteristic Curves case 2

Table 4.5: Roofing tile Characteristic Curves case 3

Temperature °C	37
Irradiation W/m^2	950
Inclination	4°

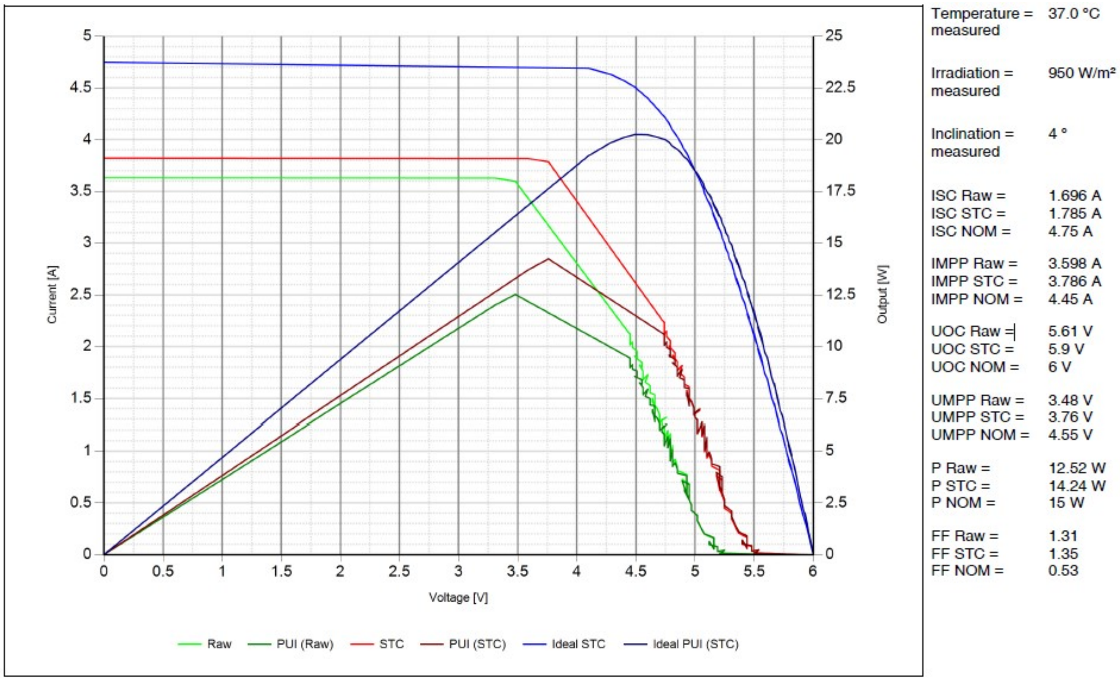

Fig. 4.4 Roofing tile Characteristic Curves case 3

Table 4.6: Roofing tile Characteristic Curves case 4

Temperature °C	36.5
Irradiation W/m^2	1023
Inclination	2°

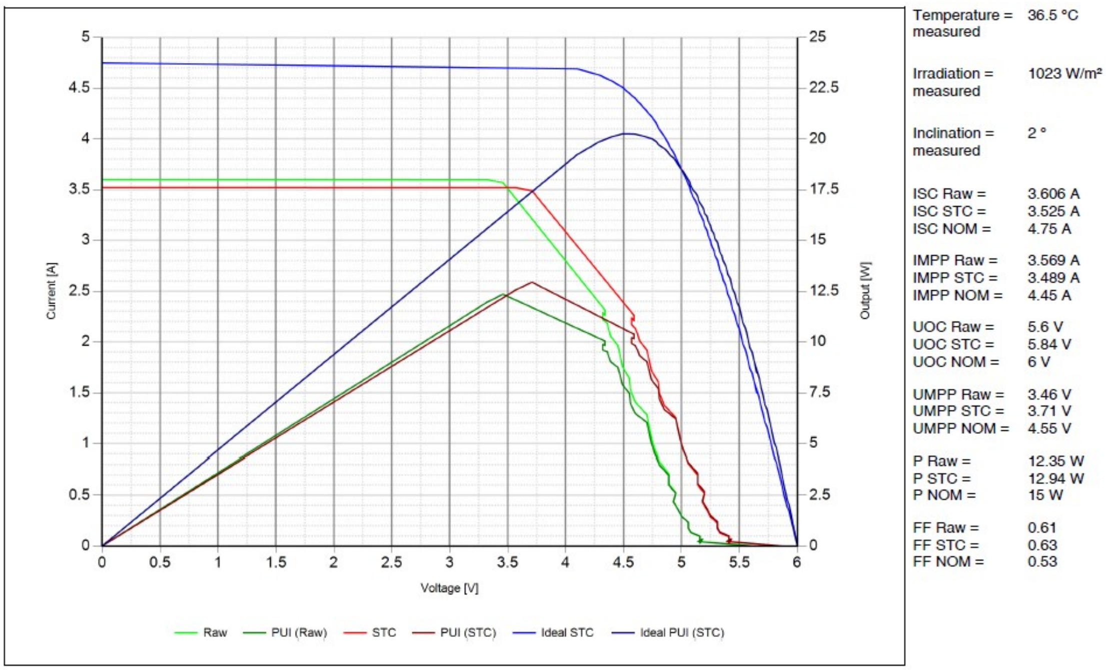

Fig. 4.5 Roofing tile Characteristic Curves case 4

4.3 Discussion

The module produced was tested to check if it can deliver the guaranteed rated power reliably, while withstanding an extremely wide range of environmental conditions. The module must also be safe and durable, ensuring the system's high yield over the long term. And, it should also be able to generate the total amount of energy that was used to manufacture it in the shortest possible time.

Since the I-V curve will vary according to temperature, the conditions under which the I-V sweep were conducted were all recorded. Temperature was measured using sensors such as RTDs, thermistors or thermocouples.

4.3.1 Cost Comparison with Ordinary roofing tiles

A cost comparison of the solar PV integrated roofing tiles versus ordinary roofing tiles with was done for a given roof size.

Size of roof

A typical roofing surface area of $100m^2$ was used for comparison purposes.

Number of solar PV integrated roofing tiles required

The average size of the solar PV integrated roofing tile is 0.5m X 0.5m = $0.25\ m^2$

The number of solar PV integrated roofing tiles required for $100m^2$ surface are $100\ m^2/0.25\ m^2 = 400$ solar PV integrated roofing

Cost of ordinary tile

The cost of the ordinary roofing tiles is KES 511per m^2 [The Joint Building Council, www.jbc.co.ke] thus whole roof = KES 51,197

Summary Comparison Table (overleaf)

Note: This costs however does not include the cost of other equipment required such as the solar charge controller, the deep cycle battery and the inverter. It is assumed that similar equipment will be required for both systems hence for comparison reasons there's no need to include them.

Sample roof area 100m²	Ordinary Tiles + Solar panels	Sample roof area of 100m²
No. of tiles required		35W tile area = 0.3m² 100m²/ 0.3m² = Approx.. 334tiles
Cost of tiles	Market rate = KES 2,500 per m² So, 100m² x2,500 = KES 250,000	(*USD 72*) @$72 per 35W solar tile @KES100/USD = KES (72x100x334) = KES 2,404,800
Roof cover + Solar panels installation costs	Normal Roof Daily Rate = KES 500/day/laborer. Assume 2 Laborers for 3days = KES (500x2x3) = KES 3,000 Solar Panel Installation Daily Rate = KES 3,500/day/technician. Assume 2 technicians for 3days = KES (3,500x2x3) = KES 21,000.	Solar roofing tile Installation Daily Rate = KES 3,500/day/technician. Assume 2 technicians for 5 days = KES (3,500x2x5) = KES 35,000
Electricity Capacity produced	Monocrystalline Solar Panel generating 100Watts = KES 23,000. No. of Solar Panels required to generate 11,690 Watts = 120 Panels 120 Panels to match 334 solar roofing tiles (9,352W) = KES (120 x23,000) = KES 2,760,000	1No. solar roofing tile = 35 Watts, 334 tiles = 334x35 = 11,690Watts @80% Efficiency = 0.8x12,250 = 9,352 Watts.
Total Roofing costs for representative area	KES (250,000+3,000+21,000+2,760,000) = KES 3,034,000	KES (2,404,800+35,000) = KES 2,439,800

CONCLUSION: Cost Comparison: Up to 19.5% cost efficiency from the Solar Roofing tile for a representative roof of 100m²
Solar Roofing Tile Cost per sq.m – KES 24,398/-

5. Conclusions and Recommendation for Future Work

5.1 Conclusion

The main objective of this project was to design and build a solar PV integrated roofing tile and come up with the cost per KWHr generated from it. From the results obtained in the comparison of the cost per KWHr generated from the Solar PV integrated roofing tile and the ordinary roof with ordinary solar panels it is clear that the cost of power from the designed and build tile is cheaper.

This cost is however high in both cases and measures need to be taken to bring the cost of solar equipment down.

The design objectives considered in making the solar integrated roofing tile were met. This included designing a tile that was easy to install to replace an ordinary roofing tile. The solar roofing tile could be installed by an ordinary roofing technician, although the electrical connections may need to be certified by an ERC accredited electrician.

With more controlled manufacturing and with a good load calculation, a collection of tiles would be able to provide enough electricity so that it is useful for household appliances and with extra to sell back to the national grid.

The tiles designed were similar in operation to the ordinary roofing tiles and are able to be integrated into a battery system with the necessary charge controllers in place.

5.2 Recommendations for future work

Future work will further seek to examine the economic feasibility by calculating the cost of electricity provided by the tiles considering the avoided costs due to replaced roofing, avoided costs due to electricity distribution infrastructure and exploitation of clean Development Mechanism credits.

From the results obtained, the following improvements should be made in any future designs:

- The termination of the solar cells strings was not done in a controlled factory hence the soldering was not even and this would pose a challenge in case of mass production.

- The glass used was a 6mm thick glass to protect the solar cells from damage. However this was too thick and resulted in reduction of the efficiency of the solar integrated roofing tiles. It was recommended to use a 3.2mm thick pattern, toughened glass instead. This would reduce the effective weight of the roofing tile and also eliminate the possibility of sunlight reflection on the roof which would act as a hazard to people in the nearby buildings and motorists.

- The colour of the roofing tile was black. This being too dark would absorb too much heat which would result in a reduction in the efficiency of the tile. It would be recommended to use a brighter colour that would easily blend in with other roofing tiles.

- As the temperature increases, the efficiency of the roofing tile decreases. In order to increase the rate of heat dissipation, it would be recommended to use a tile with fins or constructed to allow for air flow to reduce accumulation of heat.

- The tile should use standard multi-contacts and standard solar cables to avoid excess losses and to allow for voltage drop correction.

- In the design, there should be a bypass diode to ensure that the system is robust so that, if a few tiles fail, it will still work at a proportionate level of effectiveness.

- The tiles also would be required to meet the relevant building regulations of the Kenyan Bureau of Standards (KBS).

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