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Construction of a Solar Panel Using Solar Oven for the Panel Lamination

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Abstract

A 160W solar panel of dimension 1480 x 680mm was constructed using 36 grade 'A' monocrystalline silicon cells with properties: P_{max} = 4.5W, I_{pm} = 8.12A, I_{sc} = 8.72A, V_{oc} = 0.63, V_{pm} = 0.54, and dimension = 156 x 156mm. Solar oven was used for the panel lamination. The lamination was done by placing the interconnected cells in-between two layers of Ethylene Vinyl Acetate (EVA) film with glass in front of the *eva* and cells, and TPT solar back sheet at the back, after which the arranged setup was placed in a solar oven using lamination platen. Performance test was carried out on the constructed solar panel by comparing it with a standard 160W solar panel. The performance of the constructed solar panel was observed to match that of the standard panel at high solar irradiance but at low irradiance, the power output was lower. The highest output power realized from the constructed panel was 100.85W at an irradiance of 1053W/m^2.

Keywords: solar panel, silicon cells, lamination, ethylene vinyl acetate, irradiance

1.0 Introduction

Photovoltaic systems convert light to electricity through the principle of photo generation of charge carriers. A solar cell is basically a p-n junction diode that converts sunlight directly to electricity with large conversion efficiency. When a p-n junction diode is exposed to light, photons are absorbed and electron-hole pairs are generated in both the p-side and n-side of the junction. The electrons and hole that are produced over a small distance from the junction, reach the space-charge region by diffusion. The electron-hole pairs are then separated by strong barrier field that exist across the region. The electrons in the p-side slide down the barrier potential to move towards the n-side while holes in the n-side move towards the p-side (Jha, 2010).

Solar cells are connected in series and parallel to form solar panels which have higher voltage and power capacity. Solar panels can be used with batteries as stand-alone power source or as grid connected power supply. To understand the electronic behavior of a solar cell, it is useful to create a model which is electrically equivalent to a solar cell and is based on discrete electrical components whose behaviors are well known (Ohajianya, 2010). An ideal solar cell may be modeled by a current source in parallel with a diode. In practice, no solar cell is ideal, so a shunt resistance and a series resistance are added to the model. The resulting equivalent circuit of a solar cell is as shown in Figure 1(a) while the schematic circuit symbol of a solar cell is indicated in Figure 1(b).

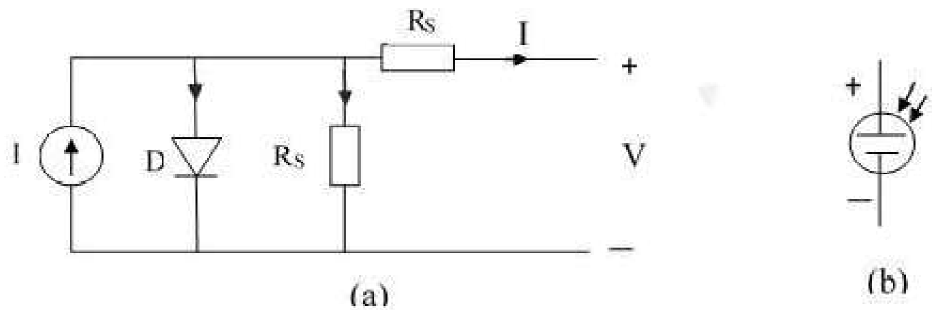

Figure 1: (a) The equivalent circuit of a solar cell (b) The schematic symbol of a solar cell

From the equivalent circuit, it is evident that the current produced by the solar cell is given by:

$$I = I_L - I_D - I_{SH} \qquad ...1$$

where I = output current, I_L = photo generated current, I_D = diode current, and I_{SH} = shunt current. The current flowing through the diode and the shunt resistance is governed by the voltage across them given by:

$$V_j = V + IR_s \qquad ...2$$

where V = voltage across the output terminals, I = output current, and R_s = series resistance.
In accordance with Shockley diode equation, the current diverted through the diode is given by (Chi-Tang, 1991):

$$I_D = I_O\left[\exp\left(\frac{qV_j}{nkT}\right) - 1\right] \qquad ...3$$

where I_0 = reverse saturation current, n = diode ideality factor (1 for an ideal diode), q = elementary charge, k = Boltzmann's constant, and T = absolute temperature.
By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}} \qquad ...4$$

Substituting equation 2, 3 and 4 in equation 1, one obtains the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$I = I_L - I_O\left\{\exp\left[\frac{q(V + IR_S)}{nkT}\right] - 1\right\} - \frac{V + IR_S}{R_{SH}} \qquad ...5$$

If one assumes infinite shunt resistance, the characteristic equation can be solved for V_{oc}:

$$V_{OC} = \frac{kT}{q}\exp\left(\frac{I_{SC}}{I_O} + 1\right) \qquad ...6$$

Thus, an increase in I_0 produces a reduction in V_{oc} proportional to the inverse of the logarithm of the increase.

A solar cell's energy conversion efficiency (η), is the percentage of power converted from absorbed light to electrical energy and collected when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of the maximum power point, P_m, divided by the product of the input light irradiance (E_I, in W/m^2) under standard test conditions (STC) and the surface area of the solar cell (A_c in m^2), that is:

$$\frac{\qquad}{*} \qquad ...7$$

STC specifies a temperature of 25°C and an irradiance of 1000W/m^2 with an air mass 1.5 (AM1.5) spectrum. This condition approximately represents solar noon near the spring and autumn equinoxes in the continental United States with surface of the cell aimed directly at the sun. Thus, under these conditions, a solar cell of 12% efficiency with a 100cm^2 (0.01m^2) surface area, can be expected to produce approximately 1.2watts of power. The losses of a solar cell may be broken down into reflectance losses, thermodynamic efficiency, recombination losses and resistive electrical losses.

Energy payback is the recovery period of the energy spent for manufacturing of the respective technical energy systems, also called harvesting ratio. In the 1990's, when silicon cells were twice as thick, efficiencies were 30% lower than today and lifetimes were shorter. It may well have cost more energy to make a cell than it could generate in lifetime. In the mean time, the technology has progressed significantly, and the energy payback time of a modern photovoltaic module is typically from 1-4 years depending on the type and where it is used. Generally, thin film technologies despite having comparatively low conversion efficiencies, achieve significantly shorter energy payback times than conventional systems (often < 1 year) (Chipra *et al.*, 2004) with typical lifetime of 20-30 years. This means that modern solar cells are net energy producers, i.e. they generate significantly more energy over their lifetime than the energy expended in producing them.

The oven used for solar panel lamination is the double vacuum oven. This oven is very expensive and high power consuming. For instance, the semi-automatic Solar Panel Laminating Machine marketed by Changzhou Steer Trade Co., Ltd, China, costs about $200,000 (about N33million) and consumes electrical power of 45KW (Ohajianya *et al.*, 2014). This contributes to the high cost of solar panel and consequently increases its energy payback period. Solar oven can attain temperatures over 120^{0}C in Nigeria, which is the temperature at which the solar panel laminating film, EVA (Ethylene Vinyl Acetate) fuses completely with glass. This means that solar oven, which operates with free energy, can serve the purpose of this high energy consuming solar panel laminating oven (Ohajianya *et al.*, 2014).

Silicon solar cells can either be monocrystalline cells or polycrystalline cells. Monocrystalline cells of up to 4.5W normally have three bus bars while lower powers can have either one or two bus bars depending on their size and power. Examples of solar cells with one to three bus bars are shown in Figures 2 (a), (b) and (c).

(a) (b) (c)

Figure 2: Solar cell with (a) one bus bar, (b) two bus bars and (c) three bus bars

A standard solar panel has four layers fused together to form the panel. The different layers and their position are as shown in Figure 3. The laminating material is eva (ethylene vinyl acetate) film and the back sheet material is tedler (polyvinyl fluoride)/ *pet* (polyester)/ tedler (polyvinyl fluoride). The properties of these materials are as given in Tables 1, 2 and 3.

Table 1: Properties of Solar Panel Back Sheet Material, TPT.

ITEM		UNIT	TPT-30
Tensile strength		N/cm	= 120
Elongation ratio		%	130
Tearing strength		N/mm	140
Interlaminar strength		N/5cm	=25
Peeling strength	TPT/EVA	N/cm	=20
	TPE/EVA		=50
Weightlessness (24h/150degree)		%	<2.0
Shrinkage ratio(0.5h/150degree)		%	<0.6
Water vapor transmission		$g/m^2 24h$	<2.0
Breakdown voltage		KV	=45
Partial discharge		VDC	>1000
UV aging resistance(100h)		—	No discoloration, non-foaming, non-color change
Life		—	More than 25 years

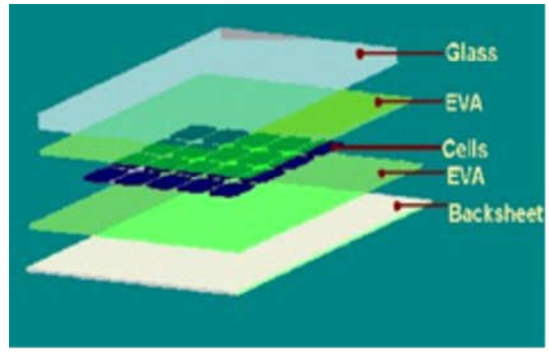

Figure 3: Standard solar panel layers

Table 2: Properties of Solar Panel Laminating Film, EVA

ITEM		UNIT	FAST CURING
VA content		%	33
Melting point (Before cross-linking)		degree	65
Density		g/cm^3	0.96
Transmittance		%	=91
Refractive index		—	1.48
Tensile strength		Mpa	16
Elongation ratio		%	420
Shrinkage ratio (120degree,3min)		%	3
Completely Gel content (150degree,15min)		%	=75
Peeling strength	Glass/EVA	N/cm	=60
	TPT/EVA	N/cm	=50
UV aging resistance		—	No cracks, no discoloration
Temperature resistance (85degree/-40degree)		—	No thermal expansion and contraction

Table 3: EVA film lamination and curing.

CONDITIONS		FAST CURING		
Lamination	Laminating machine heat board(degree)	100-120	135-140	145
	Vacuumzing time(min)	5-8	5	3
	Pressure time(min)	2-3	15-20	12-15
Curing	Curing oven temperature degree	135-140	—	—
	Curing time(min)	15-20		
Remark	—	Two steps	One step	One step

2.0 Materials and Methods

The following steps were followed to construct and test a 160W solar panel with the panel lamination done by using one reflector solar oven. For information on construction and characterization of the one-reflector solar oven used for the solar panel lamination here (see Ohajianya *et al.*, 2014).

2.1 Solar Cells and Materials Sourcing

Three bus bar solar cells were purchased from Mars Rock Science Technology Co., Ltd., China. The cells were 156 x 156mm GRADE A MONOCRYSTALLINE SILICON CELLS with the following characteristics: P_{max} = 4.5W, I_{pm} = 8.21A, I_{sc} = 8.72A, V_{oc} = 0.63V, V_{pm} = 0.54V. Other materials bought from the company include: 680mm TPT PV back sheet, 680mm Solar EVA film, tabbing wires, busbar wires, flux pens, 160-240W solar junction box. Materials sourced locally for the construction include: 4mm clear glass, angle aluminum frame, solder, and silicone gum. The materials prepared for the construction of the panel are as given in Table 4.

Table 4: Materials for the solar panel construction

Materials	Picture	Description	Dimension	Quantities
Solar Cell		Three Bus Bar Grade A Monocrystalline Silicon Cells with properties: P_{max} = 4.5W, I_{pm} = 8.21A, I_{sc} = 8.72A, V_{oc} = 0.63V, V_{pm} = 0.54V	156 x 156mm	36 pieces
Solar EVA Film		Ethylene Vinyl Acetate film with properties as given in Table 2.x and 2.x	1480 x 680mm	2 pieces
TPT Solar Back Sheet		Tedler (Polyvinyl Fluoride)/ Pet (Polyester)/ Tedler (Polyvinyl Fluoride) with properties as given in Table 2.x	1480 x 680mm	1 piece
Tabbing Wire		Copper Ribbon Coated with Tin	2000 x 5mm	1 piece
Bus bar Wire		Copper Ribbon Coated with Tin	30 x 2mm	120 pieces
Flux Pen		Pen with Liquid Flux Inside	150 x 14mm	2 pieces
Solar Junction Box		Junction Box with 4 Diodes, V_{max}: 1000V, Imax: 12A, Work temp: 40°C~85°C, Contact R: =5mn , power for panel: 160-240W	130×124×29mm	1 piece
Glass Window		Clear Glass	1480 x 680 x 4mm	2 pieces

2.2 Cells Connection Preparation and Soldering

The temperature of the soldering station to be used was set to 320^{0}C. With face up, a solar cell was placed on a table with glass top. The three bus bars of the cell were cleaned with flux pen after which the bus bar wire was soldered to each of them with the help of the soldering station. This was done for all the 36 cells. The cells were then arranged face-down on one of the two 1480 x 680 x 4mm glass. Four rows of nine cells each were soldered in series connection. The rows were also connected and soldered in series with tabbing wires and with tabbing wires also, connection to the positive and negative ends of the cell series lines were made and brought out. After the connections, one of the 1480 x 680 EVA film was placed on the cells and the TPT solar back sheet was then placed on the film. This was followed by the placement of the second glass on the TPT solar back sheet. The whole set up was turned and the first glass was removed and put back after placing the second EVA film on the face of the cells. With this done, the panel was ready for lamination.

2.3 Solar Panel Lamination

The panel was placed face down on the base part of the laminating platen and the top part of the platen was placed on it. Four G-clamps were used to fasten the top and base parts of the laminating platen with the panel inside them. The platen was then placed inside the solar oven and the glass window of the oven was used to cover the oven. This was at 9.00am. The oven temperature, ambient temperature and solar irradiance were measured. The measurements were repeated every 30 minutes and the last reading was made by 2.30pm. After the last reading, the glass window of the oven was removed and the oven left open till 5.00pm for the platen and panel to cool down. The panel was brought out from the platen and oven around 5.00pm. The following day, aluminum frame was constructed for the panel and using silicone gum, the panel was fixed to the frame. The solar junction box was also connected and fixed to the back of the panel with the help of the silicone gum. The constructed panel is as shown in Figure 4.

2.4 The Constructed Solar Panel Test

A 160W solar panel was purchased from Roy Solar Co. Ltd, China. Operation test was run on the constructed panel using the purchased panel as control. To do this, the two panels were placed on a horizontal platform. Four d.c. wattmeters were mounted on a board such that their faces can be got in a snap shot. Two solar charge controllers were also mounted on the board. Two 100Ah batteries were placed at the back of the board (under the panels). Connections were made between the panels, charge controllers, wattmeter and battery as follows: wattmeter 1(the topmost one) was connected to read the Output Voltage (V_P) and Output Current (I_P) of the constructed panel, wattmeter 2 to read the voltage (V_B) and Current (I_B) supplied to batteries 1 by the constructed panel, wattmeter 3 to read the Output Voltage (V_{CP}) and Output Current (I_{CP}) of the control panel, and wattmeter 4 to read the Voltage (V_{CB}) and Current (I_{CB}) supplied to battery 2 by the control panel. The experimental setup is as shown in Figure 5.

Figure 4: The constructed solar panel front and back view.

Before the connections to the panels were switched 'ON', the voltage reading of the batteries were recorded. And immediately the connections to the panels were switched 'ON', at 9.30 hours Nigerian time, readings of the wattmeters were taken through snap shop to ensure simultaneous measurement. The irradiance was also measured by pacing the solar irradiance meter on a horizontal platform with the solar sensor facing vertically upwards. Ambient temperature was also measured. The reading was repeated at 30 minutes intervals and a total of fourteen readings were taken. The last reading was

Figure 5: The experimental setup

(a) (b)

Figure 6: (a) The first reading snap shot, (b) The last reading snap shot.

taken at 16.00 hours Nigerian time. The results were tabulated. The first and last snap shop readings are shown in Figure 6 (a) and (b).

3.0 Results and Discussion

3.1 Results

Result of the solar panel comparison test between the locally constructed solar panel and the purchased control panel is presented in Table 4 while plots of constructed panel power output against time, control panel power output against time, solar irradiance against time, and ambient temperature against time are presented in Figure 7.

3.2 Discussion

The constructed solar panel was compared with a standard 160W panel by using them to charge battery through charge controller and using watt meters to measure their output voltage and current. The result of the comparison test, whose graph is shown in Figure 8, shows that the constructed panel works better at high solar irradiance as its power output matched that of the control panel at high irradiance but at low solar irradiance, the power output of the constructed panel was lower. This is believed to be caused by the fact that the solar oven used for the panel lamination did not achieve temperature up to 120^{o}C during the lamination, and because of this, the EVA laminating film did not fuse completely with the glass and therefore contributed to lowering the light transmission efficiency of the glass. But at high irradiance, enough light gets to the cells and the effect of the limited light transmission efficiency of the glass

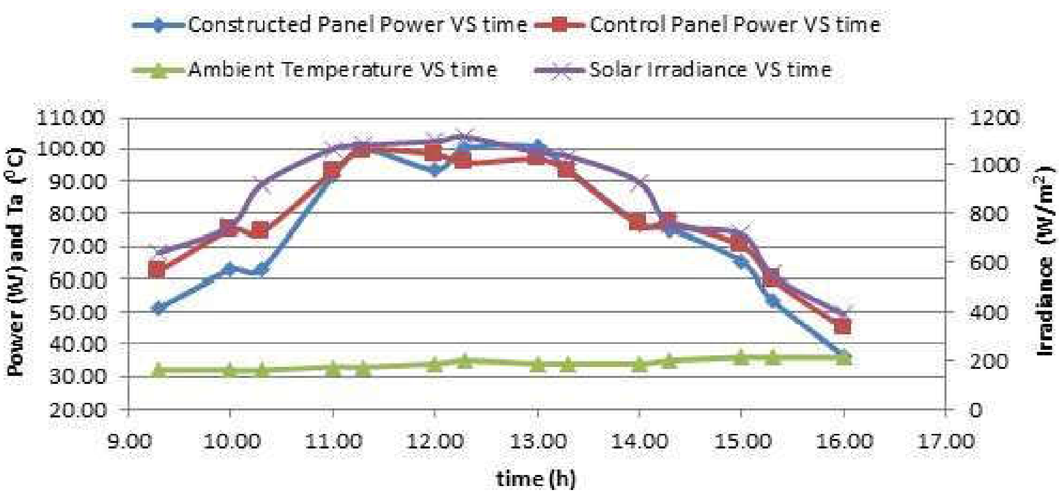

Figure 7: Graphs of constructed panel power, control panel power, solar irradiance, and ambient temperature against time.

Table 4: Result of the Solar Panel Comparison Test

	Constructed Panel					Control Panel						
t (h)	V_P (V)	I_P (A)	P_p (W)	V_B (V)	I_B (A)	V_{CP} (V)	I_{CP} (A)	P_{cp} (W)	I_{CB} (V)	V_{CB} (V)	I (Wm^2)	Ta (^0C
9.30	12.09	4.25	51.38	11.92	4.38	11.61	5.37	62.35	11.05	5.02	640	32
10.00	12.18	5.15	62.73	11.97	4.30	12.40	6.05	75.02	11.84	6.07	750	32
10.30	12.25	5.13	62.84	12.01	4.90	12.49	5.94	74.19	11.95	5.57	919	32
11.00	13.36	6.85	91.52	12.17	6.23	12.71	7.31	92.91	12.14	7.26	1068	33
11.30	13.45	7.42	99.80	12.30	7.74	12.81	7.77	99.53	12.25	7.48	1085	33
12.00	12.61	7.42	93.57	12.28	6.26	12.88	7.63	98.27	12.30	7.40	1101	34
12.30	13.51	7.42	100.24	12.42	7.74	12.92	7.40	95.61	12.36	7.25	1119	35
13.00	13.61	7.41	100.85	12.40	7.19	12.99	7.45	96.78	12.42	7.36	1053	34
13.30	12.76	7.33	93.53	12.50	6.82	13.02	7.14	92.96	12.45	6.83	1037	34
14.00	13.56	5.67	76.89	12.46	5.85	12.89	5.93	76.44	12.41	5.60	928	34
14.30	12.69	5.93	75.25	12.47	4.98	13.02	5.92	77.08	12.45	5.60	757	35
15.00	12.72	5.13	65.25	12.52	5.30	13.02	5.39	70.18	12.46	5.24	716	36
15.30	12.61	4.26	53.72	12.47	4.08	12.81	4.70	60.21	12.44	4.36	552	36
16.00	12.55	2.89	36.27	12.41	2.73	12.77	3.51	44.82	12.38	3.15	390	36

with EVA film is eliminated. During the comparison test, it was required that six different readings be taken at the same time, especially the four wattmeter readings which must be taken simultaneously to ensure that solar irradiance variations do not render the tests useless. After trying different methods to achieve this, including involving four different persons to take the readings, it was discovered that it is practically impossible to achieve the aim with human reading. After serous thought work and practice, it was discovered that mounting the four wattmeters on a board and using snap shots to take the reading, was a perfect way of achieving the purpose of the test. This method was adopted for the test. The first and last snap shot test pictures are as shown in Figure 6.

4.0 Conclusion

A 160W solar panel was constructed using one-reflector solar oven for the solar panel lamination. A performance test was carried out on the constructed panel by comparing it with a standard 160W solar panel. The performance of the constructed solar panel matched that of the standard panel at high solar irradiance but at low irradiance, the power output was lower. The highest output power realized from the constructed panel was 100.85W at an irradiance of 1053W/m^2.

The difference between the maximum realized power and the quoted power of 160W was as a result of light transmission losses and the efficiency of the solar charge controller used.

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