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Performance Evaluation of Multi-Layer Semi-Transparent Photovoltaic System

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Abstract. Solar Photovoltaic is one of the most promising technologies used to harness electrical energy from solar energy. The major challenge of photovoltaic application, in addition to the limited efficiency, is the land required for installation. Around 28 m² area of land is required for a solar plant to generate a KWh of energy. The semi-transparent photovoltaics is an innovative technology that generates electricity and at the same time transmits light. Another possible solution towards conserving land space is the concept of multi-layering of the semi-transparent photovoltaic modules. The electrical performance is measured analytically with the help of MATLAB simulation software. The current-voltage and power-voltage characteristics for one layer and for the multi-layered system is studied for real-time values of irradiance and ambient temperature. The results reveal that transparency is one of the key parameters dictating the number of layers for optimum efficiency. The results indicate that an increase in the generation of electricity with the multi-layered photovoltaic system by 415 Wh when compared to conventional PV system, increase in the yield by 30% minimizes the land area for energy generation.

1. Introduction

Solar photovoltaic cells are semiconductor diodes used to generate electricity directly from the sun. Photovoltaic means the process of converting light energy (photons) to electricity, this is called the Photoelectric Effect. This effect was discovered in 1954 when scientists in Bell Telephone Company discovered that Silicon, when exposed to sunlight, created a charge. This technology was initially used to power Space Satellites and small-scale electronic items such as calculators and watches because of their very low efficiency [1]. As the technology advanced, the efficiency of the PV modules improved. The present generation of the PV cells has conversion efficiency up to 40% [2].

Second-generation solar cells make use of amorphous or thin film silicon material. These have relatively lower efficiency compared to p-Si and m-Si solar cell, however, they have a lot of potential for increasing efficiency together with cheaper manufacturing cost compared to polycrystalline silicon solar cells. The second-generation solar cells are more popular in large-scale solar applications [3].

The third-Generation solar cells are made of different materials; including organic-inorganic compounds like perovskite, Metal-oxide-metal composition etc. These materials have a promising future in the field of Solar PV Technology. Recent development in Perovskite material for solar cells



have achieved an efficiency of 22.1%, this material is much cheaper and is quickly reaching the efficiency level of multi-junction Silicon PV. However, Perovskite material has the disadvantage of deteriorating very quickly [4].

Semi-transparent (SPTV) find their way in building integrated applications (BIPV). In Yunnan Normal University, a 120 kWp are installed on the south facing wall of the “Solar Energy Research Institute” building. The BIPV panels covered the wall having an area of 1560 m². 720 mono-crystalline Si semi-transparent PV modules with double glazing were used. The system generates 64 MWh energy in a year [5].

Another example of an installed BIPV system is the parking space at the Patras Scientific Park. Eighty-eight semi-transparent PV modules were installed as a rooftop for the car-park and a building in the Patras Scientific Park, Greece. Onyx Solar was the company that manufactured and supplied the solar panels. The material used was c-Si, with the power capacity of 233 Wp per module. The cell density of the panel was customized in accordance with the client’s specifications to enable daylight passage. Total installed capacity is 20 kWp, with a payback period of 2 years [6].

Light is one of the most important and a primary source of nourishment for agricultural plants. Despite the necessity of solar irradiation for an effective agricultural produce, high level of solar irradiation has a negative effect on the crop yield, and hence, crops grown in greenhouses are provided with a partial shade to ensure optimal yield [7]. Semi-transparent PV modules can be used instead of the shade to provide the necessary shading effect to the crops, the excess sunlight can be converted to electricity. This is very popular in areas where availability of land for a solar PV system is difficult [8].

One of the greatest disadvantages of solar photovoltaics is its efficiency, hence, to meet the demand, the number of panels need to be increased thereby increasing the area of the solar power plant. On an average it takes 7 acres of land covered with solar PV modules to generate 1 MW of electricity [9]. Thus, it is very difficult for populated countries like Bangladesh and Philippines to plan large scale Solar PV systems. Several methods are being deployed to counter this problem, as discussed above, BIPV is one such method. Multi-layering of semi-transparent PV modules is a novel technique to generate more energy per unit area of land. To check the feasibility of this concept it is essential to analyse the I-V and P-V characteristics of the multi-layered STPV system.

2. Methodology

The idea is to investigate the possibility of stacking one layer of semi-transparent photovoltaic (STPV) module on another module to generate more electricity, using real-time values of temperature and irradiance at Nilai-Seremban. External parameters affecting the performance of the STPV are irradiance levels during the day, the ambient temperature and the temperature of the cell. Those values are recorded on an hourly basis. Variation of cell temperature with respect to ambient temperature and irradiance was also analysed to understand the effect of temperature on the cell. The performance also varies with transparency and the conversion efficiency of the PV module.

2.1. Semi-transparent PV and Conventional PV

In this study, the module parameters that play an essential role in determining the current-voltage (I-V) and power-voltage (P-V) characteristics of a solar PV module are considered, including the conversion efficiency, irradiance level, transmissivity, and the temperature of the back layer [10]. Amongst the different varieties of semi-transparent PV modules available in the market, Mono-Crystalline STPV is one with the highest conversion efficiency and moderate transparency compared to other semi-transparent PV modules.

It is important here to note that the placement of cells on the module plays a pivotal role while using mono-crystalline or poly-crystalline semi-transparent PV module and it is possible to customise the solar panel with different transparency levels by varying the space between the solar cells.

Table 1: Module Specifications for STPV and Conventional PV

Parameters	m-Crystalline PV (Conventional)	m-Crystalline (STPV)
Module No.	S72MC-RE (Solartec)	Solar TYP 1 (Ertex)
Number of Cells per module	72	72
Power Peak P_{mp} (Wp)	330	318
Short-circuit current I_{sc} (A)	9.28	8.62
Current at max power I_{mp} (A)	8.77	8.13
Open circuit voltage V_{oc} (V)	46.20	46.22
Voltage at max power V_{mp} (V)	37.7	38.95
Transparency (%)	0	~40

2.2 Arrangement of STPV Modules in multilayer

The concept of multi-layering of the STPV modules is such that the semi-transparent PV module is stacked on top of another PV module figure 1. While a front view of a single layer STPV is shown in figure 2. Such arrangement will permit the light incident to transmit through the first layer to the second layer. The second layer of the PV module will generate a certain amount of electricity based on the amount of incident radiation received. It might be possible that, a third PV module is introduced if the irradiance passing through the second layer is high enough to excite the electrons in the solar cell of the third module.



Figure 1 Multi-Layering Concept with two layers of mono-crystalline Si, STPV modules, (SketchUp, 2017)



Figure 2 Front view of Single Layer Semi-Transparent PV module; Courtesy of solar-constructions.com [11]

2.3 Weather data

The date and the location were selected arbitrarily, the output also depends on the place and time. The total energy generated will vary when the location changes. Data for irradiance and temperature for

Nilai, Malaysia, for the 17th of July 2017 is considered.

The cell temperature (T_{cell}) depends on the ambient temperature (T_{amb}) and the level of irradiance n at that time and also the Nominal Operating Cell Temperature (NOCT) of the module. Instantaneous cell temperature is calculated using the equation 1 [12].

$$T_{cell} = T_{amb} + (NOCT - 20) \times \frac{Irradiance}{800 \text{ W/m}^2} \quad (1)$$

To obtain the cell temperature of the second PV layer of the multilayer PV, the rear side temperature of the first PV layer is assumed as the ambient temperature for the second layer. Rear side temperature of a PV module is calculated:

$$T_{rearside} = \frac{T_{cell} - 1.956 - (0.0175 \times \varphi)}{1.14} \quad (2)$$

The temperature obtained from equation. 2 is substituted in equation. 1 to find the cell temperature of the second PV layer [13].

It is important to note here that the multilayer performance analysis is made by assuming the intensity of the irradiation is high enough to excite the electrons in the second layer of the PV module. The confirmation of the above statement can only be done with actual components under real-time data.

2.4 Performance Parameters of multi-layer Semi-transparent solar PV

The MATLAB code for a conventional monocrystalline-Si PV [14], is rewritten for the semi-transparent PV under varying irradiance and temperature. The performance of multi-layer STPV is measured by varying the three parameters, cell temperature, Irradiance level and the number of layers. In this investigation, the performance is measured by relating the amount of energy generated from a single conventional PV module and a multi-layer STPV module, under two different operating conditions on days with different irradiance levels. The entire process is re-iterated for different values of irradiance, temperature and both layers of the STPV module.

2.5 Performance Analysis under different operating conditions

For comparison of STPV and conventional PV, it is logical to assume similar power rating for both PV panels. The open circuit voltage (V_{oc}) and short circuit (I_{sc}) may be different for the two modules.

It is necessary for the analysis of the performance of the multilayer STPV system to analyse the current-voltage (I-V) and power-voltage (P-V) characteristics of both layers combined for real-time irradiance and ambient temperature values.

It has to be noted that the analysis was conducted for different cases of arrangements of the STPV layers and the type of PV used in the lower layer, to evaluate the output energy produced with respect to the area. Therefore, the current-voltage (I-V) and power-voltage (P-V) characteristics are plotted for a single layer of the conventional PV, a single layer STPV and multi-layer PV with the first layer as STPV and the second layer as a conventional PV module.

Comparison of Multi-layer PV with Conventional PV module for three different geographical locations is carried out by changing the irradiance and ambient temperature of the location. The data for irradiance and the ambient temperature are acquired from the NREL website for India, USA and the Kingdom of Saudi Arabia [13]. The objective is to predict the performance of multi-layer PV in different climatic conditions.

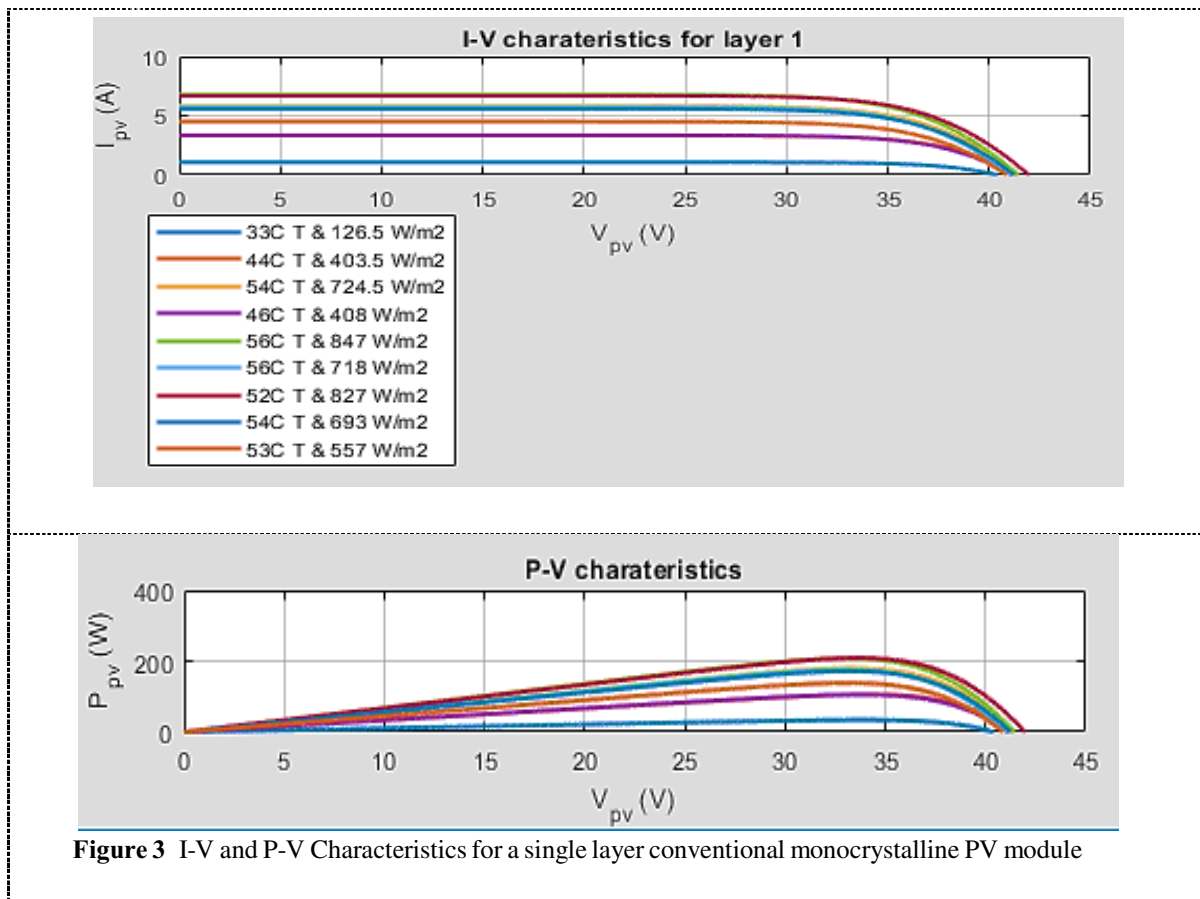
3. Results and Analysis

3.1 The I-V and P-V Characteristics for Single layer conventional PV module:

The current versus voltage and power versus voltage characteristics for a single layer conventional PV with varying irradiance and temperature is as shown in fig.3, It is obvious from the graphs that as the irradiance level and the ambient temperature varies during the day, the output power generated varies accordingly, and hence the total energy generated is a direct function of irradiance and temperature.

The variation of the power generated is compared to the total output power generated from a semi-transparent PV module with a similar power rating. The monocrystalline PV module has a power rating of 330 W under STP conditions, the maximum current under real-time conditions is around 7 A.

With the variation in irradiance level, the current varies, but as the temperature increases, the open circuit voltage reduces, thereby reducing the output power.



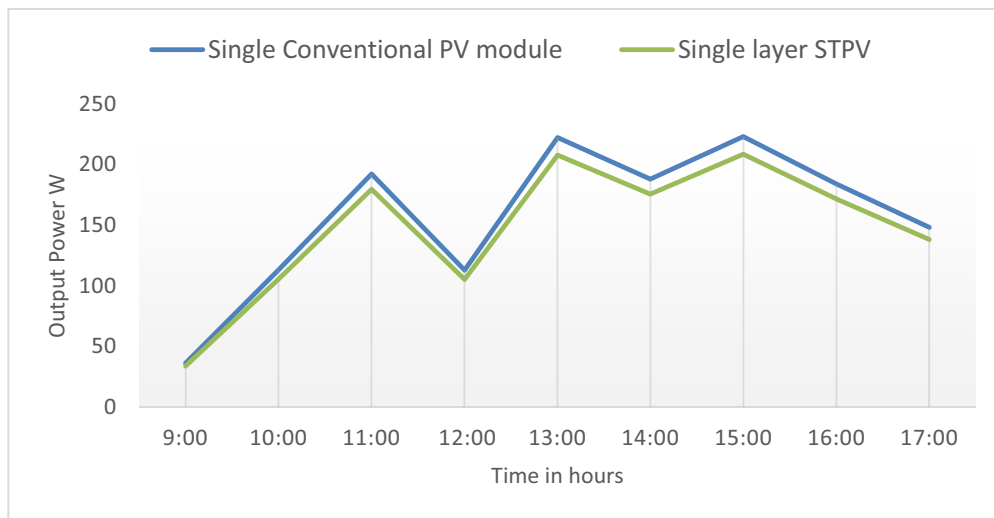


Figure 4 Output power generated from a conventional layer and a single layer semi-transparent PV module on an hourly basis with varying irradiance and temperature.

Figure 4 illustrates the energy generated by the conventional m-crystalline PV during the day, which is considered slightly higher than an m-crystalline STPV module (single layer). This could be mainly due to the higher conversion efficiency of the conventional PV.

3.2 The I-V and P-V Characteristics of Double Layer PV

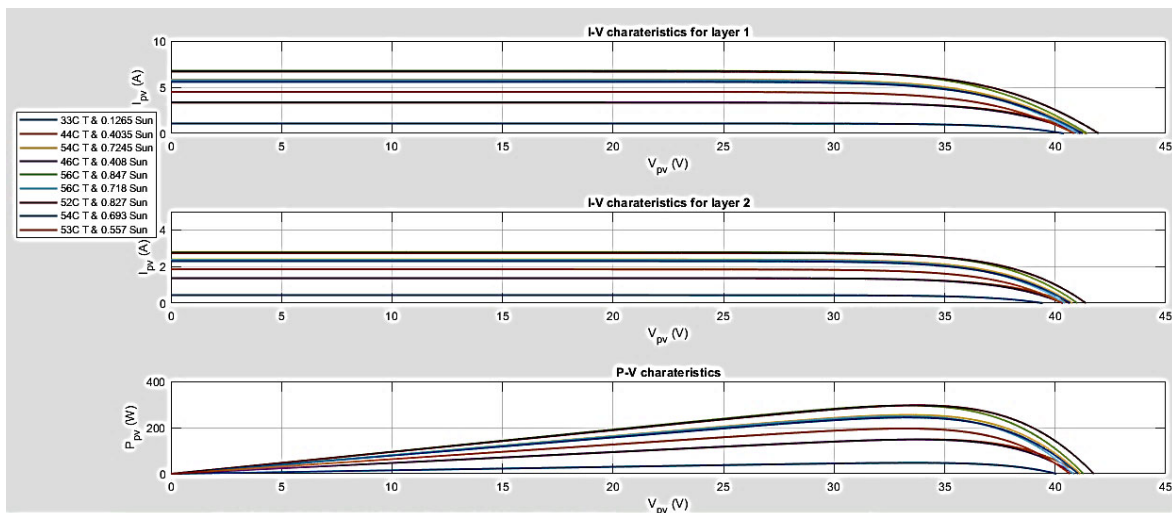


Figure 5 I-V characteristics of two layer PV with a STPV as the first layer and the conventional PV as the second layer and, P-V characteristics for combined layers.

Figure 5, shows the I-V characteristics for the multilayer PV system, at 9:00 am, the first layer generates a maximum current of around 1A at an irradiance level of 126.5 W/m², and temperature of 28 °C, the irradiance level at noon, increases to a maximum of 847 W/m² with a moderate ambient temperature of 32 °C and then decreases slightly at around 05:00 PM, when the level of irradiance is low and the temperature rose to 33 °C. The I-V characteristics also illustrate the

variation of voltage V_{pv} (V) due to the variation of temperature. Voltage V_{oc} varies as the temperature varies and hence the output power. It is also worth noting, the fact that the variation of temperature has a very little impact on the short-circuit current.

This can be analysed by observing the I-V curve for the first layer for 2:00 PM and 3:00 PM, the irradiance is almost same, but the cell temperature is differing by 2 °C, I_{sc} does not show considerable variation, but the V_{oc} for the two curves are seen to diverge distinctly.

The I-V characteristics of the second layer show around 65% -70% less energy production than the first layer, this is mainly because of the level of transparency of the first layer.

From the analysis, the energy generated in a day from the multi-layer PV system is compared to the energy produced by a single conventional PV module, it was found that the multi-layer PV generates 415 Wh more than a conventional solar PV module. This is around 30% increase in energy production.

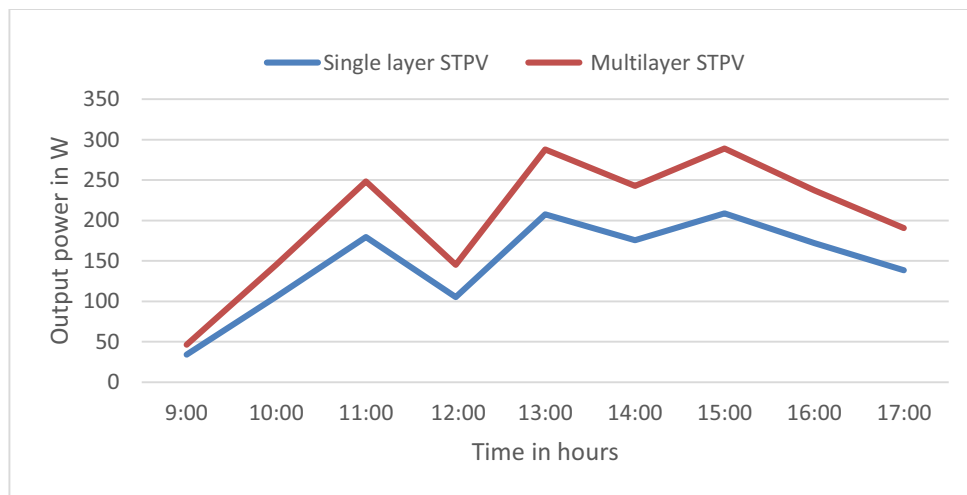


Figure 6 Comparison of the output power between conventional single layer PV and multilayer (Conventional and STPV).

3.3 Comparison of Electrical Performance of Multi-Layer PV with Single layer PV

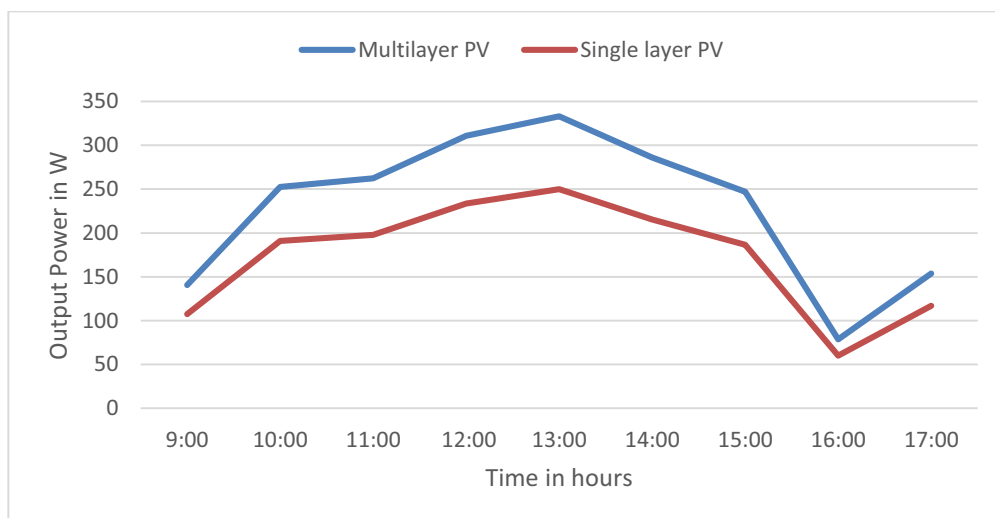


Figure 7 Output power for multilayer PV and single layer PV on the day with the highest irradiance.

The above analysis of multi-layer PV was done for 17th July 2017. It is important to know the performance of multi-layer PV on days with maximum and minimum values of irradiance and temperature. This analysis will contribute to the evaluation of the feasibility of the multi-layer PV.

Figure 7 shows the comparison of power for the multi-layer PV and single layer PV for the temperature and irradiance recorded on the day with highest irradiance, the multi-layer PV generates 506 Wh of energy more than the single layer PV panel.

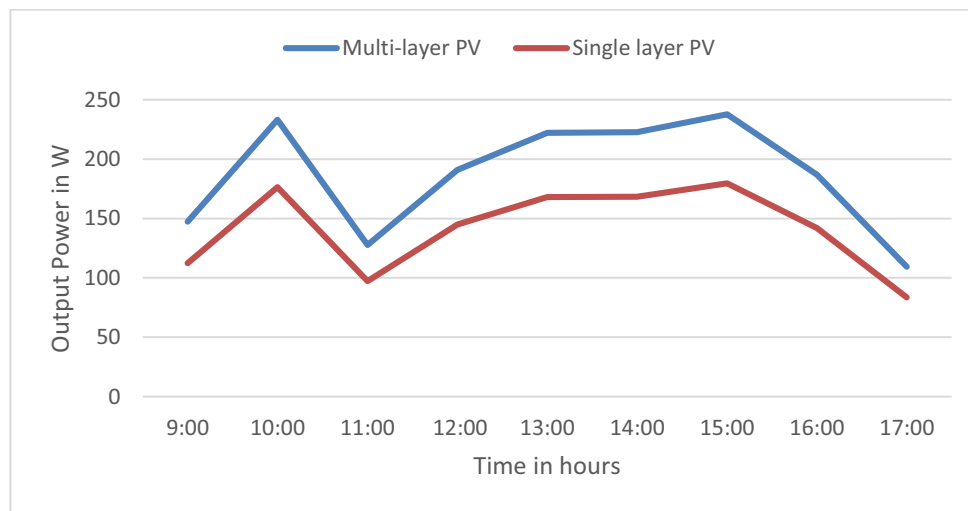


Figure 8 Comparison of output power (Watt) for multi-layer PV with single layer PV (13th day of July 2017).

For a day with irradiance level very low, the output power generated is found to be more in the case of multi-layer PV by 405 Wh, i.e., about 28% more than a conventional PV.

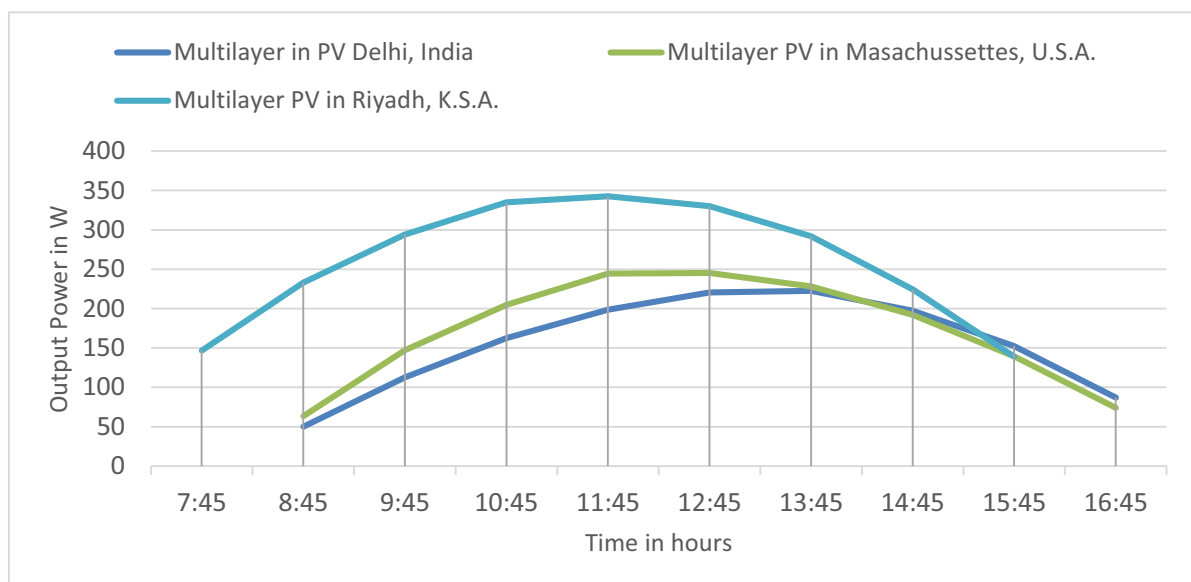


Figure 9 Comparison of output power (Watt) for multi-layer PV for 3 different Locations (Delhi, India; Massachusetts, U.S.A.; Riyadh, K.S.A.)

Figure 9 illustrates the performance of multilayer STPV for a location in Delhi (India), Massachusetts (U.S.A) and Riyadh (K.S.A) for their respective irradiance and temperature [15].

4. Conclusions

This paper introduced the concept of semi-transparent photovoltaic (STPV) and the multilayer application. The understanding of the optical characteristics of the STPV is an important parameter which may dictate the relevant application of the STPV.

A study about the characteristics and performance of a double layer PV system had been carried out; the investigation covers the electrical parameters such as the I-V and P-V characteristic of the double layer PV and the single layer PV modules. The results obtained from the analysis portrays that the multi-layer concept is effective in producing 415 Wh more energy than a single layer, which is roughly 30%. This was illustrated with the help of the output power Vs Time graphs, which showed power generation for real-time hourly values of irradiance and temperature in Malaysia. A study on the effect of variable temperature on the single and multi-layer PV system is also done with the result that the energy generated is inversely proportional to the cell temperature.

This investigation focused on two of the main parameters that affect the PV performance, namely, cell temperature and irradiance level and depending upon these parameters, an attempt was made to prove the feasibility of multi-layering concept in different parts of the world. Irradiance levels and temperatures of randomly selected sites from India, Kingdom of Saudi Arabia and the United States of America. From the simulations, all the sites show positive results of using multi-layer PV.

From the analysis, it was evident that the second layer of the multi-layer PV is exposed to diffuse irradiation, and therefore, not much energy is generated from the second PV. Hence to increase the intensity of the solar irradiation on the second layer, concentrator prisms and Fresnel lenses may be used to enhance the exposure of sunlight to the second layer [16]. The lenses may be placed between the spaces between the cells of the first PV layer.

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