Research Article

Performance of Photovoltaic Modules of Different Solar Cells

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In this paper, an attempt of performance evaluation of semitransparent and opaque photovoltaic (PV) modules of different generation solar cells, having the maximum efficiencies reported in the literature at standard test conditions (STC), has been carried out particularly for the months of January and June. The outdoor performance is also evaluated for the commercially available semitransparent and opaque PV modules. Annual electrical energy, capitalized cost, annualized uniform cost (unacost), and cost per unit electrical energy for both types of solar modules, namely, semitransparent and opaque have also been computed along with their characteristics curves. Semitransparent PV modules have shown higher efficiencies compared to the opaque ones. Calculations show that for the PV modules made in laboratory, CdTe exhibits the maximum annual electrical energy generation resulting into minimum cost per unit electrical energy, whereas a-Si/nc-Si possesses the maximum annual electrical energy generation giving minimum cost per unit electrical energy when commercially available solar modules are concerned. CIGS has shown the lowest capitalized cost over all other PV technologies.

1. Introduction

According to the Annual Energy Review of US Energy Information Administration (EIA) in 2011, industrial, residential and commercial, transportation, and electric power generation are the primary sectors of energy consumption that account for, respectively, ~21%, 11%, 28%, and 40% of the total consumption. Petroleum (37%), natural gas (26%), coal (20%), renewable energy (9%), and nuclear electric power (8%) are the main sources being utilized to run the energy consumption sectors. The large percentage of energy is driven from the fossil fuels. In 2011, the US energy consumption accounted for $\sim 2.84 \times 10^{13}$ kWh, whereas the production was just only $\sim 2.28 \times 10^{13}$ kWh. And as per the Annual report of European Commission on Energy 2011, transport, industry, household, services, and agriculture account for, respectively, 32%, 25%, 27%, 14%, and 2% of total energy consumption. Petroleum accounts 35.1%, solid fuels account for, and 15.9%, renewable account for, 9.8%, nuclear power and natural gases account for, respectively, the 13.5% and 25.1% for fulfillment of the total energy requirement. Compared to 2009, the gross consumption increased by 3.3% in 2010. In the context of present energy crisis in terms of demand and supply and the

bad consequences of fossil fuels on our delicate environment, the development and use of renewable sources of energy has become very important.

Solar photovoltaic (PV) technology is one of the most important renewable sources of energy generation. Since the early realization of PV effect in 1839, there have been steady improvements in the performance of solar cells and the application of advanced materials has given birth to new generations of solar cells. Crystalline silicon (c-Si) was the first material giving practical solar cell [1]; therefore, the solar cells, based on c-Si are known as first generation solar cells. From the cost, performance, and processibility points of view, the application of new advanced materials gave birth to new generations of solar cells. The second and third generation PV cells were based on the thin film materials such as amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), organic semiconductors and organic dyes. Thin film materials are deposited either in single-junction or multijunction configurations referred to as stacked junction or tandem cells. A brief overview of different solar cells with their latest laboratory efficiencies is given in Table 1. The values have been taken from the website of National Renewable Energy Laboratory (NREL), USA [2].

TABLE 1: Latest efficiencies of different solar cells [2, 3].

Solar cell materials	Efficiency η_0 (%) (Source: NREL, USA)
Mono c-Si	25.0
Poly c-Si	20.4
a-Si	10.1
a-Si/nc-Si	12.3
CdTe	18.3
CIGS	20.3
Organic semiconductors	10.7
Organic dyes	11.0

PV modules have got various applications for electricity generation in remote, rural, and even in urban areas. They have got applications in different sectors ranging from agriculture, household to industry. PV modules can be used in most of the sectors where energy is required. The PV modules can be integrated in buildings to fulfill dual purposes, namely, generation of electricity and harvesting of thermal energy too. Such systems are known as building-integrated photovoltaic thermal (BIPVT) systems. BIPVT systems have got tremendous household and industry applications [4, 5]. The demand of solar PV devices is increasing very fast, and as per the US-EIA report, the US photovoltaic industry hit a record in 2009 by shipping ~ 1.3 GWp solar cells and solar modules, that is, $\sim 30\%$ more than that in 2008. Out of that ~ 0.58 GWp was accounted by mono c-Si, ~ 0.4 GWp by poly c-Si, and ~ 0.27 was accounted by thin films (a-Si, nc-Si, CdTe, and CIGS) solar cells. From the beginning, the PV modules based on c-Si have continued to dominate the PV market. Application of PV modules can fulfill our long-term energy demand, but they have got some implications too. High cost, cumbersome processing and difficulty in handling are some of the main implications in the present commercial PV technologies. Research is being done to make them more viable and more cost effective. In view of the increasing demand, the understanding of their performance in different environmental conditions becomes of high importance. An analysis of the outdoor performance of PV modules made of different generation solar cells is presented. The PV modules have been considered in the two well-known configurations, for example, semitransparent and opaque as shown in Figure 1, where the PV modules are prepared, respectively, on the glass and tedlar plates. For the PV modules made of c-Si and poly c-Si solar cells, the top encapsulating covered plate is considered to be made of highly transparent glass, whereas the thin films PV modules are considered to be encapsulated by an EVA encapsulant only.

For incidence of the maximum solar radiation, the PV modules in northern hemisphere are placed south oriented, having inclination for horizontal surface equal to the latitude of the system's station [6–8]. The performance analysis of PV modules for the cold (January) and hot (June) climatic conditions of 2012 of New Delhi has been presented. New Delhi is located at 28.38°N , 77.12°E in India; therefore, all the modules are considered to be south oriented and inclined at an angle of

30° to the horizontal (see Figure 1). The analytical expressions for the electrical efficiency and temperatures of thin film PV modules have been derived. The performance of PV modules made of the solar cells with maximum laboratory efficiency is compared with that of those available in the market. The annual electrical energy and unit electrical generation of different PV modules have been computed by considering the following weather conditions for New Delhi [9].

- (a) Clear days (blue sky),
- (b) Hazy days (fully),
- (c) Hazy and cloudy days (partially),
- (d) Cloudy Days (fully).

2. Modeling

The efficiencies and temperature of PV module are calculated using energy balance equations. To write the energy balance equations for PV modules, the following assumptions have been considered:

- (i) One-dimensional heat conduction,
- (ii) the encapsulant ethylene vinyl acetate (EVA) is purely transparent,
- (iii) the ohmic losses in solar cells and PV modules are negligible.

2.1. Energy Balance Equations

2.1.1. For Semitransparent Mono c-Si and Poly c-Si PV Modules. The energy balance equation for the semitransparent mono c-Si or poly c-Si PV modules can be written as [10, 11]

$$\begin{aligned} \alpha_c \tau_g \beta_c I(t) &= U_T (T_c - T_a) + U_b (T_c - T_a) + \eta_c \tau_g \beta_c I(t) \\ \text{[Rate of absorbed solar radiation received by solar cells]} \\ &= \text{[Rate of thermal energy loss from solar cells to} \\ &\quad \text{ambient through top glass surface]} \\ &+ \text{[Rate of thermal energy loss from solar cells to} \\ &\quad \text{ambient through back glass surface]} \\ &+ \text{[Rate of electrical energy generated from solar} \\ &\quad \text{cells of PV module]}. \end{aligned} \quad (1)$$

Here U_T and U_b can be defined as

$$\begin{aligned} U_T &= \left[\frac{L_g}{K_g} + \frac{1}{h_0} \right]^{-1}, \\ U_b &= \left[\frac{L_g}{K_g} + \frac{1}{h_i} \right]^{-1}. \end{aligned} \quad (2)$$

From (1), the cell temperature can be expressed as

$$T_c = \frac{T_a U_L + (\alpha_c \tau_g \beta_c - \eta_c \beta_c \tau_g) I(t)}{U_L}, \quad (3)$$

FIGURE 1: Schematic representation of (a) semitransparent c-Si, poly c-Si, (b) semitransparent thin films, (c) opaque c-Si, poly-Si, and (d) opaque thin films PV modules, inclined at an angle of 30° from horizontal.

or

$$T_c - T_0 = T_a - T_0 + \frac{(\alpha_c \tau_g \beta_c - \eta_c \beta_c \tau_g) I(t)}{U_L}, \quad (4)$$

where $U_L = U_T + U_b$. According to Evan [12, 13], the temperature dependence of the cell efficiency can be written as

$$\eta_c = \eta_0 [1 - \beta_0 (T_c - T_0)]. \quad (5)$$

With the help of (4) and (5), one can get the electrical efficiency of the cell as

$$\eta_c = \frac{\eta_0 [1 - \beta_0 \{(T_a - T_0) + (\tau_g \alpha_c \beta_c / U_L) I(t)\}]}{[1 - (\eta_0 \beta_0 \tau_g \beta_c / U_L) I(t)]}, \quad (6)$$

and the module efficiency as

$$\eta_m = \frac{P_o}{P_{in}} = \frac{\eta_c \beta_c \tau_g I(t)}{I(t)} \quad (7)$$

or

$$\eta_m = \eta_c \beta_c \tau_g. \quad (8)$$

2.1.2. For Opaque Mono c-Si and Poly c-Si PV Modules. The energy balance equation for the opaque mono c-Si or poly c-Si PV modules can be written as [10, 11]

$$\begin{aligned} & \tau_g [\alpha_c \beta_c I(t) + (1 - \beta_c) \alpha_T I(t)] \\ &= U_T (T_c - T_a) + U_b (T_c - T_a) + \tau_g \eta_c \beta_c I(t) \end{aligned}$$

$$\begin{aligned} & [\text{Rate of absorbed solar radiation received by solar cells}] \\ &= [\text{Rate of thermal energy loss from solar cells} \\ & \quad \text{to ambient through top glass surface}] \\ &+ [\text{Rate of thermal energy loss from solar cells} \\ & \quad \text{to ambient through back glass surface}] \\ &+ [\text{Rate of electrical energy generated from the solar} \\ & \quad \text{cells of PV module}]. \end{aligned} \quad (9)$$

From (9), the cell temperature can be written as

$$T_c = \frac{[\tau_g \{\alpha_c \beta_c + (1 - \beta_c) \alpha_T - \eta_c \beta_c\}] I(t) + U_L T_a}{U_L}, \quad (10)$$

or

$$T_c - T_0 = T_a - T_0 + \frac{[\tau_g \{\alpha_c \beta_c + (1 - \beta_c) \alpha_T - \eta_c \beta_c\}] I(t)}{U_L}, \quad (11)$$

where $U_L = U_T + U_b$. Therefore, now from (5) and (11) one gets

$$\eta_c = \frac{\eta_0 [1 - \beta_0 \{(T_a - T_0) + (\tau_g \alpha_c \beta_c + (1 - \beta_c) \alpha_T) / U_L\} I(t)]}{[1 - (\eta_0 \beta_0 \tau_g \beta_c / U_L) I(t)]} \quad (12)$$

and the module efficiency

$$\eta_m = \eta_c \beta_c \tau_g. \quad (13)$$

2.1.3. For Thin Film PV Modules. For a thin film PV module, the energy balance equation can be written as

$$\begin{aligned} & \alpha_c (1 - R_E) I(t) \\ &= h_0 (T_c - T_a) + U_b (T_c - T_a) + \eta_c (1 - R_E) I(t) \\ & [\text{Rate of absorbed solar radiation received by solar cells}] \\ &= [\text{Rate of thermal energy loss from solar cells} \\ & \quad \text{to ambient through top surface}] \\ &+ [\text{Rate of thermal energy loss from solar cells} \\ & \quad \text{to ambient through back surface of glass/tedlar}] \\ &+ [\text{Rate of electrical energy generated by} \\ & \quad \text{the solar cells of PV module}]. \end{aligned} \quad (14)$$

For semitransparent PV module, U_b is written as $U_b = [L_g / K_g + 1 / h_i]^{-1}$ (effective $\tau > 0$) whereas for the opaque

PV modules, U_b is given by $U_b = [L_T/K_T + 1/h_i]^{-1}$ (effective $\tau = 0$). Now from (14), T_c can be written as

$$T_c = T_a + \frac{\alpha_c (1 - R_E) I(t) - \eta_c (1 - R_E) I(t)}{U_L} \quad (15)$$

or

$$T_c - T_0 = (T_a - T_0) + \frac{\alpha_c (1 - R_E) I(t) - \eta_c (1 - R_E) I(t)}{U_L}, \quad (16)$$

where $U_L = h_0 + U_b$. Now from (5) and (16) the cell efficiency can be given by

$$\eta_c = \frac{\eta_0 [1 - \beta_0 \{(T_a - T_0) + (\alpha_c (1 - R_E) / U_L) I(t)\}]}{[1 - (\eta_0 \beta_0 (1 - R_E) / U_L) I(t)]}, \quad (17)$$

and the module efficiency will now be given by

$$\eta_m = \eta_c (1 - R_E). \quad (18)$$

2.2. Annual Electrical Energy. The hourly electrical energy of a PV module can be given by $E_{el, hourly} = \eta_m \times A_m \times I(t)$ [12]. And the daily electrical energy in KWh is obtained by $E_{el, daily} = \sum_{i=1}^{N_1} (E_{el, hourly, i} / 1000)$, where N_1 is the number of sun shine hours per day. The monthly electrical energy for the clear days (condition (a)) in KWh is calculated by the following expression:

$$E_{el, monthly} = E_{el, daily} \times n_1, \quad (19)$$

where n_1 is the number of clear days in a month. Now the annual electrical energy is calculated by

$$E_{el, annual} = \sum_{i=1}^{12} E_{el, monthly, k}. \quad (20)$$

2.3. Cost Analysis. The capitalized cost (K) is defined on the equivalent present value (P_n) of the system lasting for n years. The present value of the system based on an infinite time period can be represented as shown in Figure 12.

For a system costing P_n and having service lifetime of n years, the present value replacing out to infinity is given by [7, 10]

$$K = P_n F_{PK, i, n}, \quad (21)$$

where K is the capitalized cost and $F_{PK, i, n} = (1 + i)^n / (1 + i)^n - 1$ is the capitalized cost factor. P_n can be calculated from

$$\begin{aligned} P_n = & \text{Total Initial Cost of module (P)} \\ & + \text{Operational and maintenance cost (OM)} \\ & \times \text{Unacost present value factor (F}_{rp, i, n}) \\ & - \text{Salvage value} \times \text{Present value factor (F}_{sp, i, n}), \end{aligned} \quad (22)$$

where,

$$\begin{aligned} F_{RP, i, n} &= \left[\frac{(1 + i)^n - 1}{i(1 + i)^n} \right], \\ F_{SP, i, n} &= (1 + i)^{-n}. \end{aligned} \quad (23)$$

The annualized uniform cost (Unacost, R) and capitalized cost (K) are related as [7, 10];

$$R = i \cdot K,$$

$$\text{Annualized uniform cost} \quad (24)$$

$$= \text{Worth of money} \times \text{Capitalised cost}.$$

The cost for per unit electric energy production by a PV module is evaluated by

$$\text{Unit electrical energy generation cost}$$

$$= \frac{\text{Unacost}}{\text{Annual Electrical Energy}}. \quad (25)$$

3. Methodology

The climatic data for the solar radiation $I(t)$ on horizontal surface, ambient temperature (T_a), and the number of days for the weather conditions (a), (b), (c), and (d) for Delhi was obtained from the Indian Metrological Department (IMD), Delhi. The following methodology has been used to evaluate the electrical efficiencies, annual electrical energy, and cost per unit electrical energy for the PV modules.

Step 1. The hourly solar radiation on the PV modules, at the 30° inclination from the horizontal, was calculated using the Liu and Jordan method [14].

Step 2. The designed parameters, for both laboratory made and commercially available PV modules, used for calculations have been tabulated in Table 2. The corresponding references for the values of different parameters have been given in the table, and the values of rest of the parameters have been taken from [11].

Step 3. For the known climatic conditions and designed parameters, the cell temperatures and electrical efficiencies of the PV modules have been evaluated using the modeling given above. *Note.* The expressions of cell and module efficiencies are valid only for the condition $T_c - T_0 > 298$ K.

Step 4. The temperature of PV modules has been considered to be equal to that of the solar cells and calculated by the modeling above.

Step 5. The monthly electrical energy for clear days (condition (a)) has been evaluated using (19), and the same process was adopted to calculate the monthly electrical energy for other climatic conditions (b), (c), and (d). The total electrical energy for each month was obtained by adding the energy generations in the climatic conditions (a), (b), (c), and (d) in that month.

TABLE 2: Design parameters of opaque and semitransparent PV modules.

Parameters	c-Si	Poly-Si	a-Si	CdTe	CIGS	a-Si/nc-Si	OPV
A_m (m ²)							
Com.	0.646	0.598	1.17	0.72	0.72	1.054	—
Lab.	0.25	0.3006	0.29	0.325	0.507	0.401	0.487
α_c	0.9	0.9	0.85	0.8	0.8	0.8	0.6
β_c	0.89	0.89	1	1	1	1	1
β_0	0.0062	0.0049	0.001	0.002	0.0031	0.0023	0.002
	[15]	[16]	[15]	[16]	[15]	[17]	[calculated]
η_{m0} (%) Com.	14.2	12.53	6.4	10.4	10.42	8.5	—
	[18]	[18]	[19]	[20]	[21]	[22]	
α_T	0.5						
τ_g	0.95						
h_0 (W/m ² K)	5.7 + 3.8v; $v = 0.5$ m/s						
h_i (W/m ² K)	2.8 + 3.0v; $v = 0.2$ m/s						
L_g (m)	0.003						
K_g (W/m K)	1.1						
L_T (m)	0.0005						
K_T (W/m K)	0.033						

Step 6. The Annual electrical energy was calculated using (20).

Step 7. P_n has been calculated by (22). Operational and maintenance costs have been considered to be 10% whereas salvage value has been taken 5% of the initial cost (P) of the modules.

Step 8. While calculating the electrical energy, the degradation rates per year of individual systems (Table 4) were also taken into account [23].

Step 9. The annualized capitalized cost (K) has been calculated using (21).

Step 10. The unacost (R) has been calculated using (24).

Step 11. Finally, the cost per unit electrical energy was calculated using (25). For the calculations of K and R , interest rate has been considered to be 8%.

Note. The values of different parameters given in Table 2 have been taken from the websites of different world known institutions/companies. First Solar is the world leading company of USA. in thin film PV module manufacturing. It is world's leading provider of solar energy solutions. First Solar holds the world record in CdTe module and cell efficiencies and owns mega solar projects in the world. Global Solar, USA, is a leading manufacturer of flexible solar technologies and produces CIGS solar cells at record efficiency. Global Solar is the only manufacturer for full-scale production of flexible CIGS solar cells. Sharp Solar is a world leading solar company of Japan and aims to provide reliable solar power from lighthouses to space satellites to mega solar

FIGURE 2: Hourly variations of solar intensity $I(t)$ and ambient temperature (T_a) for the months of January and June.

power plants. Sharp Solar has developed world's highest power conversion efficiency of 44.4% using a concentrator triple junction solar cell. Sharp has also established its own standards for accelerated tests and endurance tests, which are more demanding than the standards set by IEC and JIS international industrial standards.

4. Results and Discussion

To solve the mathematical equations, a computer program Mathcad 8 has been used. The calculated hourly variations of $I(t)$ at 30° inclination and T_a for typical clear days of January

FIGURE 3: Hourly variations of electrical efficiencies for different commercially available PV modules in the month of January.

and June are shown in Figure 2. As expected, the solar intensity is maximum at ~13:00 hrs where the intensity in January is greater than that in June. It is important to note that the solar intensity at any surface depends on its declination angle and the solar altitude. The smaller the angle of inclination of the radiation with horizontal surface, the greater will be the path to travel and the lower radiation reaching the surface. The altitude is more in summer compared to that in winter. The altitude is more in summer compared to that in winter for a given inclination of PV module ($\beta = 30^\circ$). It is also observed that the angle of incidence in January is less than that in June, leading to higher intensity in January. The higher intensity in January due to small angle of incidence (θ_i) compared to that in June due to large value of angle of incidence (θ_i) can be understood from the fact that a south facing surface receives higher amount of radiation during winter than during the summer (~1.5 times) for a given inclination β . As expected, the ambient temperature in January is smaller than that in the June. Figure 3 shows the variation in module efficiency of commercially available different PV modules with time. The calculations have also been done for PV modules which have been considered to be prepared in the laboratory, with STC cell efficiencies (figure not shown). Among the different PV technologies, c-Si PV technology has shown the maximum efficiency for both the modules, commercially available and prepared in laboratory. However, a-Si PV modules have shown the minimum efficiency in both cases. For all the PV technologies, the module efficiencies first decrease and then increase with time. The minimum efficiency for all the PV modules is observed at ~13:00 hrs. The variation in module efficiencies can be correlated with the module temperatures shown in Figure 4. Because of different temperature coefficients of different materials, the module temperatures are different. The temperature coefficient of OPV modules has

FIGURE 4: Hourly variations of module temperatures for different commercially available PV modules in the month of January.

been calculated using (5), where the desired parameters were obtained from [24]. a-Si has shown the maximum module temperature whereas c-Si exhibited the minimum module temperature. The module temperatures first increase and then decrease with time and are maximum at ~13:00 hrs which correspond to maximum solar intensity (see Figure 2). Therefore, it can be inferred that the module efficiencies are minimum for maximum module temperatures, and it is because of the maximum electrical losses due to enhanced collisions of electrons at high temperatures. It is worth mentioning that the electrical resistance in a system is controlled by the electron collisions. For high temperatures the collision will be more that it would result into high resistance, and high resistance would lead to more recombination losses.

Performance evaluation has been carried out for the semi-transparent and opaque PV modules, which are commercially available and those prepared in laboratory for the months of January and June. Though all the performance evaluations have been carried out on different PV module technologies, further the results of those prepared with c-Si only are presented, as it is most studied and efficient material. Figure 5 compares the performance of commercially available c-Si semitransparent and opaque PV modules in the months of January and June. In all the cases, the module efficiencies first decrease and then increase with time and are minimum at ~13:00 hrs. The reason behind minimum module efficiencies at ~13:00 hrs has already been discussed above. It is observed that in both months and semitransparent PV modules have shown the higher efficiencies compared to the opaque ones. The same effect has been observed for all the PV module technologies. Dubey et al. studied the module efficiencies of only c-Si-based semitransparent and opaque modules [11] and observed the similar results. It is important to note that in the case of c-Si and poly c-Si PV modules, the packing factor is considered to be 0.89. In that case, the solar radiation falling

FIGURE 5: Hourly variations of electrical efficiencies of commercially available c-Si semitransparent and opaque PV modules in the months of January and June.

on the nonpacking area is transmitted through the semitransparent module whereas in case of opaque modules it is absorbed by the tedlar sheet. The absorption of solar radiation by tedlar sheet results into the increment in cell temperature, due to which the module efficiency decreases. But in case of thin film PV modules, the packing factor is considered to be 1 and there will be no nonpacking area. However, the higher efficiencies in semitransparent thin film PV modules compared to the opaque ones can be understood from their thin film property. Due to very low thicknesses, some of the heat of the incident radiation is transmitted through the back glass sheet, but in case of opaque modules, it, absorbed by the tedlar sheet. The absorption of solar heat by the tedlar sheet results into increment in the module temperature, due to which the module efficiency decreases. The average module efficiency is observed higher in the month of January than in the month of June. It is because of the reason that in January the ambient temperature is lower compared to that in June. The performance of semitransparent and opaque c-Si PV modules, those are commercially available, is compared in Figure 6 with those considered prepared in the laboratory for the month of January. In both cases, the modules prepared in the laboratory have shown higher efficiencies compared to those available in the market. Similar studies have been carried out for different PV module technologies, which have shown the similar behavior. The reason behind this fact is that the cell efficiencies of the modules prepared in the laboratory are higher compared to those prepared on the commercial scale. It is the well-known fact that the efficiencies of the solar cells prepared on the commercial level are always lower than those prepared in the laboratory.

Figure 7 shows the variation of module efficiency as a function of $T_m - T_a/I(t)$ for commercially available c-Si semitransparent and opaque PV modules in the months of January and June. These characteristics curves are similar to

FIGURE 6: Hourly variation of electrical efficiencies of commercially available and laboratory prepared c-Si semitransparent and opaque PV modules in the month of January.

FIGURE 7: Variations of electrical efficiencies of commercially available c-Si semitransparent and opaque PV modules with $T_m - T_a/I(t)$ in the months of January and June.

the Hottel-Whiller-Bliss equations of a flat plat collector [25]. Both semitransparent and opaque PV modules have shown similar variation in efficiency in the months of January and June; however, their gain factor (c) and loss coefficient (m) are different. All other PV module technologies have also shown the similar behavior but with different loss coefficients and gain factors. The semitransparent PV modules have shown lower modules temperatures compared to the opaque ones irrespective of the testing months of January and June. Similarly, the variation in module efficiencies for opaque and semitransparent c-Si PV modules, those are commercially available and prepared in the laboratory, is shown in Figure 8 as a function of $T_m - T_a/I(t)$ for the month of January. Though the variation is similar in all cases, their gain factors

TABLE 3: Loss coefficients (m) and gain factors (c) for different PV modules.

PV Technology			c-Si	Poly-Si	a-Si	CdTe	CIGS	a-Si/nc-Si	OPV		
January	Lab.	Semitransparent	<i>m</i>	1082.8	1072.3	1084.6	1084.9	1079.3	1081	1075	
			<i>c</i>	76.248	75.653	85.827	76.272	75.964	85.611	56.782	
		Opaque	<i>m</i>	1067.2	1079	1057.6	1070.9	1069.5	1070.5	1064.4	
			<i>c</i>	81.333	81.258	84.827	76.22	76.139	85.74	56.886	
	Com.	Semi-transparent	<i>m</i>	1079.1	1079.2	1092.7	1083.3	1072.9	1076.6	—	
			<i>c</i>	76.041	76.044	86.431	76.201	75.562	85.257	—	
		Opaque	<i>m</i>	1067.7	1078.5	1063.4	1064	1065.6	1064.5	—	
			<i>c</i>	81.64	81.494	84.282	75.813	75.913	85.316	—	
	June	Lab.	Semi-transparent	<i>m</i>	1080.4	1080.2	1086.7	1084	1080.8	1079.8	1084.7
				<i>c</i>	76.117	76.107	85.975	76.223	76.041	85.486	57.207
			Opaque	<i>m</i>	1067.9	1065.3	1089.3	1068	1065.3	1073.8	1062.6
				<i>c</i>	81.373	81.212	86.157	76.056	75.91	85.968	56.807
Com.		Semi-transparent	<i>m</i>	1081.6	1079	1089.4	1079.5	1079.6	1077.4	—	
			<i>c</i>	76.192	76.036	86.187	75.971	75.974	85.314	—	
		Opaque	<i>m</i>	1065.9	1066.3	1073.2	1073.6	1065.5	1065.7	—	
			<i>c</i>	81.524	81.549	85.962	76.413	75.905	85.407	—

FIGURE 8: Variations of electrical efficiencies of commercially available and laboratory prepared c-Si semitransparent and opaque PV modules with $T_m - T_a/I(t)$ in the month of January.

and loss coefficients are different. The laboratory-prepared PV modules have shown lower module temperatures compared to those available commercially, irrespective of their transparency. A similar behavior has been observed for other PV module technologies. The gain factors and loss coefficients for electrical efficiencies of different commercial and laboratory prepared semitransparent and opaque PV modules for the months of January and June have been summarized in Table 3.

Now the cost analysis of different PV modules is presented. Though the different PV modules have different lifetime, the annual electrical energy and cost per unit electrical energy have been calculated for 30 years. The calculations were done for all the materials even considering their degradation. The degradation rates for different PV modules

FIGURE 9: Variations in annual electrical energy and cost per unit electrical energy of commercial and laboratory-prepared semitransparent and opaque PV modules of c-Si.

are given in Table 4. The obtained annual electrical energy and cost per unit electrical energy for different commercial semitransparent and opaque PVs are given in Tables 5 and 6, respectively. Similarly, the annual electrical energy and cost per unit electrical energy for different laboratory prepared PV modules are given in Tables 7 and 8, respectively. The calculations show that for all the PV modules irrespective of their transparency, the annual electrical energy would decrease with time which will result into increment in their corresponding cost per unit electrical energy. Figure 9 shows the variation in annual electrical energy and cost per unit electrical energy of commercial and laboratory prepared c-Si PV modules with time for both semitransparent and opaque structures. Figure 10 compares the initial (maximum) annual electrical energy for different commercial semitransparent and opaque PV modules. For all the PV technologies, semitransparent PV modules have shown higher annual electrical

TABLE 4: Equivalent present value (Pn), capitalized cost (K), and unacost (R) for different PV modules (75 W_p).

PV Technology	Module cost (P1) (\$)			Lifetime (n) (years)	Degradation rate (%/year)	Equivalent present value Pn (\$)	Capitalized cost (K) (\$)	Annualized uniform cost (unacost) (R) (\$)
	Panel cost* (a)	Stand cost (b)	Total (P1) (a + b)					
c-Si	105	2.96	107.96	30	0.36	241.30	21.43	1.714
Poly-Si	90	2.78	92.78	30	0.64	207.37	18.42	1.473
a-Si	60	3.70	63.70	20	0.87	141.27	14.39	1.151
CdTe	67.5	3.24	70.74	25	0.40	157.61	14.77	1.181
CIGS	60	3.24	63.24	20	0.96	140.25	14.29	1.142
a-Si/nc-Si	60	3.70	63.70	20	0.87	141.27	14.39	1.151

*The panel cost has been calculated from the \$/Wp values of different modules [26].

TABLE 5: Yearly annual electrical energy (kWh) of different commercial PV modules.

Year	c-Si		Poly-Si		a-Si		CdTe		CIGS		a-Si/nc-Si	
	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque
1	132.29	126.51	114.64	105.56	136.79	132.59	130.73	124.56	124.7	118.89	153.89	149
2	131.82	126.06	113.91	104.88	135.6	131.43	130.2	124.06	123.5	117.75	152.55	147.71
3	131.34	125.6	113.18	104.21	134.42	130.29	129.68	123.57	122.32	116.62	151.22	146.42
4	130.87	125.15	112.46	103.55	133.25	129.16	129.16	123.07	121.14	115.5	149.91	145.15
5	130.4	124.7	111.74	102.88	132.09	128.03	128.65	122.58	119.98	114.39	148.6	143.88
6	129.93	124.25	111.02	102.23	130.94	126.92	128.13	122.09	118.83	113.29	147.31	142.63
7	129.46	123.81	110.31	101.57	129.8	125.81	127.62	121.6	117.69	112.2	146.03	141.39
8	128.99	123.36	109.6	100.92	128.67	124.72	127.11	121.11	116.56	111.13	144.76	140.16
9	128.53	122.92	108.9	100.28	127.55	123.64	126.6	120.63	115.44	110.06	143.5	138.94
10	128.07	122.47	108.21	99.633	126.44	122.56	126.09	120.15	114.33	109	142.25	137.73
11	127.61	122.03	107.51	98.996	125.34	121.49	125.59	119.67	113.23	107.96	141.01	136.54
12	127.15	121.59	106.82	98.362	124.25	120.44	125.09	119.19	112.15	106.92	139.79	135.35
13	126.69	121.15	106.14	97.732	123.17	119.39	124.59	118.71	111.07	105.89	138.57	134.17
14	126.23	120.72	105.46	97.107	122.1	118.35	124.09	118.24	110	104.88	137.37	133
15	125.78	120.28	104.79	96.485	121.04	117.32	123.59	117.76	108.95	103.87	136.17	131.85
16	125.33	119.85	104.12	95.868	119.99	116.3	123.1	117.29	107.9	102.87	134.99	130.7
17	124.87	119.42	103.45	95.254	118.94	115.29	122.61	116.82	106.87	101.88	133.81	129.56
18	124.43	118.99	102.79	94.645	117.91	114.28	122.12	116.36	105.84	100.91	132.65	128.43
19	123.98	118.56	102.13	94.039	116.88	113.29	121.63	115.89	104.82	99.937	131.49	127.32
20	123.53	118.13	101.48	93.437	115.86	112.3	121.14	115.43	103.82	98.978	130.35	126.21
21	123.09	117.71	100.83	92.839	114.86	111.33	120.66	114.97	102.82	98.028	129.21	125.11
22	122.64	117.29	100.18	92.245	113.86	110.36	120.17	114.51	101.83	97.087	128.09	124.02
23	122.2	116.86	99.54	91.655	112.87	109.4	119.69	114.05	100.86	96.155	126.98	122.94
24	121.76	116.44	98.903	91.068	111.89	108.45	119.21	113.59	99.888	95.232	125.87	121.87
25	121.32	116.02	98.27	90.485	110.91	107.5	118.74	113.14	98.93	94.317	124.78	120.81
26	120.89	115.61	97.641	89.906	109.95	106.57	118.26	112.68	97.98	93.412	123.69	119.76
27	120.45	115.19	97.016	89.331	108.99	105.64	117.79	112.23	97.039	92.515	122.61	118.72
28	120.02	114.77	96.395	88.759	108.04	104.72	117.32	111.78	96.108	91.627	121.55	117.69
29	119.59	114.36	95.778	88.191	107.1	103.81	116.85	111.34	95.185	90.747	120.49	116.66
30	119.16	113.95	95.165	87.627	106.17	102.91	116.38	110.89	94.271	89.876	119.44	115.65

energy compared to the opaque ones. a-Si/nc-Si PV modules have shown the maximum annual electrical energy, whereas poly c-Si PV modules have shown the minimum annual electrical energy. It is found that in case of the PV modules prepared in the laboratory, the maximum annual electrical energy is observed for CdTe, whereas minimum annual electrical energy is observed for a-Si/nc-Si PV modules. After

calculation of annual electrical energy, the unit electrical energy was calculated for different PV module technologies. For calculation of unit electrical energy, the annualized uniform cost was calculated using the financial parameters given in Table 4 for interest rate of 8%. The capitalized cost (K) and unacost (R) have also been calculated, and the values are given in Table 4. The minimum capitalized cost is found

TABLE 6: Yearly variations of cost per unit electrical energy (\$/kWh) of different commercial PV modules.

Year	c-Si		Poly-Si		a-Si		CdTe		CIGS		a-Si/nc-Si	
	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque
1	0.013	0.0136	0.0129	0.014	0.0084	0.0087	0.009	0.0095	0.0092	0.0096	0.0075	0.00773
2	0.013	0.0136	0.0129	0.0141	0.0085	0.0088	0.0091	0.0095	0.0093	0.0097	0.0076	0.00779
3	0.0131	0.0137	0.013	0.0141	0.0086	0.0088	0.0091	0.0096	0.0093	0.0098	0.0076	0.00786
4	0.0131	0.0137	0.0131	0.0142	0.0086	0.0089	0.0092	0.0096	0.0094	0.0099	0.0077	0.00793
5	0.0132	0.0138	0.0132	0.0143	0.0087	0.009	0.0092	0.0096	0.0095	0.01	0.0078	0.008
6	0.0132	0.0138	0.0133	0.0144	0.0088	0.0091	0.0092	0.0097	0.0096	0.0101	0.0078	0.00807
7	0.0133	0.0139	0.0134	0.0145	0.0089	0.0092	0.0093	0.0097	0.0097	0.0102	0.0079	0.00814
8	0.0133	0.0139	0.0135	0.0146	0.009	0.0092	0.0093	0.0098	0.0098	0.0103	0.008	0.00821
9	0.0133	0.014	0.0135	0.0147	0.009	0.0093	0.0093	0.0098	0.0099	0.0104	0.008	0.00828
10	0.0134	0.014	0.0136	0.0148	0.0091	0.0094	0.0094	0.0098	0.01	0.0105	0.0081	0.00836
11	0.0134	0.0141	0.0137	0.0149	0.0092	0.0095	0.0094	0.0099	0.0101	0.0106	0.0082	0.00843
12	0.0135	0.0141	0.0138	0.015	0.0093	0.0096	0.0094	0.0099	0.0102	0.0107	0.0082	0.00851
13	0.0135	0.0142	0.0139	0.0151	0.0094	0.0096	0.0095	0.01	0.0103	0.0108	0.0083	0.00858
14	0.0136	0.0142	0.014	0.0152	0.0094	0.0097	0.0095	0.01	0.0104	0.0109	0.0084	0.00865
15	0.0136	0.0143	0.0141	0.0153	0.0095	0.0098	0.0096	0.01	0.0105	0.011	0.0085	0.00873
16	0.0137	0.0143	0.0142	0.0154	0.0096	0.0099	0.0096	0.0101	0.0106	0.0111	0.0085	0.00881
17	0.0137	0.0144	0.0142	0.0155	0.0097	0.01	0.0096	0.0101	0.0107	0.0112	0.0086	0.00888
18	0.0138	0.0144	0.0143	0.0156	0.0098	0.0101	0.0097	0.0102	0.0108	0.0113	0.0087	0.00896
19	0.0138	0.0145	0.0144	0.0157	0.0099	0.0102	0.0097	0.0102	0.0109	0.0114	0.0088	0.00904
20	0.0139	0.0145	0.0145	0.0158	0.0099	0.0103	0.0098	0.0102	0.011	0.0116	0.0088	0.00912
21	0.0139	0.0146	0.0146	0.0159	0.01	0.0103	0.0098	0.0103	0.0111	0.0117	0.0089	0.0092
22	0.014	0.0146	0.0147	0.016	0.0101	0.0104	0.0098	0.0103	0.0112	0.0118	0.009	0.00928
23	0.014	0.0147	0.0148	0.0161	0.0102	0.0105	0.0099	0.0104	0.0113	0.0119	0.0091	0.00936
24	0.0141	0.0147	0.0149	0.0162	0.0103	0.0106	0.0099	0.0104	0.0114	0.012	0.0092	0.00945
25	0.0141	0.0148	0.015	0.0163	0.0104	0.0107	0.01	0.0104	0.0116	0.0121	0.0092	0.00953
26	0.0142	0.0148	0.0151	0.0164	0.0105	0.0108	0.01	0.0105	0.0117	0.0122	0.0093	0.00961
27	0.0142	0.0149	0.0152	0.0165	0.0106	0.0109	0.01	0.0105	0.0118	0.0124	0.0094	0.0097
28	0.0143	0.0149	0.0153	0.0166	0.0107	0.011	0.0101	0.0106	0.0119	0.0125	0.0095	0.00978
29	0.0143	0.015	0.0154	0.0167	0.0108	0.0111	0.0101	0.0106	0.012	0.0126	0.0096	0.00987
30	0.0144	0.0151	0.0155	0.0168	0.0108	0.0112	0.0102	0.0107	0.0121	0.0127	0.0096	0.00995

FIGURE 10: Initial (maximum) annual electrical energy for different commercial semitransparent and opaque PV modules.

for the CdTe PV modules which means that these are the most economical ones. The initial (maximum) cost per unit electrical energy for different commercial semitransparent and opaque PV module technologies is shown in Figure 11. For all the PV module technologies, the semitransparent PV modules have shown lower unit electrical energy compared to the opaque ones; however, c-Si has shown the maximum cost per unit electrical energy whereas minimum cost per unit electrical energy is observed for a-Si/nc-Si PV modules. It is observed that in case of the PV modules prepared in the laboratory, the maximum cost per unit electrical energy is observed for c-Si PV modules whereas the minimum cost per unit electrical energy is observed for CdTe PV modules.

5. Conclusion

The outdoor performance of commercially available and laboratory-made different semitransparent and opaque PV modules has been evaluated. The analysis was carried out particularly for the climatic conditions in the months of

TABLE 7: Yearly annual electrical energy (kWh) of different laboratory- prepared PV modules.

Year	c-Si		Poly-Si		a-Si		CdTe		CIGS		a-Si/nc-Si	
	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque
1	91.34	89.537	93.816	92.246	90.853	90.754	102.42	102.32	96.93	96.782	90.06	89.921
2	91.011	89.214	93.215	91.655	90.062	89.964	102.01	101.91	96	95.853	89.276	89.139
3	90.684	88.893	92.619	91.069	89.279	89.181	101.6	101.5	95.078	94.933	88.499	88.363
4	90.357	88.573	92.026	90.486	88.502	88.405	101.2	101.1	94.166	94.021	87.729	87.594
5	90.032	88.254	91.437	89.907	87.732	87.636	100.79	100.69	93.262	93.119	86.966	86.832
6	89.708	87.936	90.852	89.332	86.969	86.874	100.39	100.29	92.366	92.225	86.21	86.077
7	89.385	87.62	90.27	88.76	86.212	86.118	99.985	99.888	91.48	91.339	85.46	85.328
8	89.063	87.304	89.693	88.192	85.462	85.369	99.585	99.488	90.601	90.462	84.716	84.586
9	88.742	86.99	89.119	87.627	84.719	84.626	99.187	99.09	89.732	89.594	83.979	83.85
10	88.423	86.677	88.548	87.066	83.981	83.89	98.79	98.694	88.87	88.734	83.248	83.12
11	88.105	86.365	87.982	86.509	83.251	83.16	98.395	98.299	88.017	87.882	82.524	82.397
12	87.787	86.054	87.418	85.956	82.527	82.437	98.001	97.906	87.172	87.038	81.806	81.68
13	87.471	85.744	86.859	85.405	81.809	81.719	97.609	97.514	86.335	86.203	81.094	80.97
14	87.156	85.436	86.303	84.859	81.097	81.008	97.219	97.124	85.506	85.375	80.389	80.265
15	86.843	85.128	85.751	84.316	80.391	80.304	96.83	96.736	84.686	84.556	79.69	79.567
16	86.53	84.821	85.202	83.776	79.692	79.605	96.443	96.349	83.873	83.744	78.996	78.875
17	86.218	84.516	84.657	83.24	78.999	78.912	96.057	95.963	83.067	82.94	78.309	78.188
18	85.908	84.212	84.115	82.707	78.311	78.226	95.673	95.58	82.27	82.144	77.628	77.508
19	85.599	83.909	83.576	82.178	77.63	77.545	95.29	95.197	81.48	81.355	76.952	76.834
20	85.291	83.607	83.042	81.652	76.955	76.871	94.909	94.817	80.698	80.574	76.283	76.165
21	84.984	83.306	82.51	81.129	76.285	76.202	94.529	94.437	79.923	79.801	75.619	75.503
22	84.678	83.006	81.982	80.61	75.621	75.539	94.151	94.06	79.156	79.035	74.961	74.846
23	84.373	82.707	81.457	80.094	74.964	74.882	93.774	93.683	78.396	78.276	74.309	74.195
24	84.069	82.409	80.936	79.582	74.311	74.23	93.399	93.309	77.643	77.524	73.663	73.549
25	83.766	82.113	80.418	79.072	73.665	73.584	93.026	92.935	76.898	76.78	73.022	72.909
26	83.465	81.817	79.903	78.566	73.024	72.944	92.654	92.564	76.16	76.043	72.387	72.275
27	83.164	81.522	79.392	78.063	72.389	72.31	92.283	92.193	75.429	75.313	71.757	71.646
28	82.865	81.229	78.884	77.564	71.759	71.681	91.914	91.825	74.705	74.59	71.132	71.023
29	82.567	80.936	78.379	77.067	71.135	71.057	91.546	91.457	73.987	73.874	70.514	70.405
30	82.269	80.645	77.877	76.574	70.516	70.439	91.18	91.091	73.277	73.165	69.9	69.792

FIGURE 11: Initial (maximum) cost per unit electrical energy for different commercial semitransparent and opaque PV modules.

FIGURE 12

January and June in New Delhi, India. On average, the commercial c-Si PV module has shown 1.8 time more efficiency compared to that of a-Si, whereas laboratory-made c-Si PV module has shown 1.9 times more efficiency compared to that of a-Si PV module. For all the PV module technologies, the efficiency first decreases and then increases with time from morning to evening in both months of January and June. This variation in efficiency has been correlated with the module temperature. At high module temperatures, the efficiency is observed to be low. The commercial a-Si PV module has shown 0.8% more temperature compared to that of c-Si. Nearly, all the PV technologies for both opaque and

TABLE 8: Yearly variations of cost per unit electrical energy (\$/kWh) of different laboratory prepared PV modules.

Year	c-Si		Poly-Si		a-Si		CdTe		CIGS		a-Si/nc-Si	
	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque	Semi	Opaque
1	0.0188	0.0192	0.0157	0.016	0.0127	0.0127	0.0115	0.0115	0.0118	0.0118	0.0128	0.0128
2	0.0188	0.0192	0.0158	0.0161	0.0128	0.0128	0.0116	0.0116	0.0119	0.0119	0.0129	0.0129
3	0.0189	0.0193	0.0159	0.0162	0.0129	0.0129	0.0116	0.0116	0.012	0.012	0.013	0.013
4	0.019	0.0194	0.016	0.0163	0.013	0.013	0.0117	0.0117	0.0121	0.0122	0.0131	0.0131
5	0.0191	0.0194	0.0161	0.0164	0.0131	0.0131	0.0117	0.0117	0.0123	0.0123	0.0132	0.0133
6	0.0191	0.0195	0.0162	0.0165	0.0132	0.0133	0.0118	0.0118	0.0124	0.0124	0.0134	0.0134
7	0.0192	0.0196	0.0163	0.0166	0.0134	0.0134	0.0118	0.0118	0.0125	0.0125	0.0135	0.0135
8	0.0193	0.0196	0.0164	0.0167	0.0135	0.0135	0.0119	0.0119	0.0126	0.0126	0.0136	0.0136
9	0.0193	0.0197	0.0165	0.0168	0.0136	0.0136	0.0119	0.0119	0.0127	0.0128	0.0137	0.0137
10	0.0194	0.0198	0.0166	0.0169	0.0137	0.0137	0.012	0.012	0.0129	0.0129	0.0138	0.0139
11	0.0195	0.0199	0.0168	0.017	0.0138	0.0138	0.012	0.012	0.013	0.013	0.014	0.014
12	0.0195	0.0199	0.0169	0.0171	0.014	0.014	0.0121	0.0121	0.0131	0.0131	0.0141	0.0141
13	0.0196	0.02	0.017	0.0173	0.0141	0.0141	0.0121	0.0121	0.0132	0.0133	0.0142	0.0142
14	0.0197	0.0201	0.0171	0.0174	0.0142	0.0142	0.0122	0.0122	0.0134	0.0134	0.0143	0.0143
15	0.0198	0.0201	0.0172	0.0175	0.0143	0.0143	0.0122	0.0122	0.0135	0.0135	0.0145	0.0145
16	0.0198	0.0202	0.0173	0.0176	0.0144	0.0145	0.0123	0.0123	0.0136	0.0137	0.0146	0.0146
17	0.0199	0.0203	0.0174	0.0177	0.0146	0.0146	0.0123	0.0123	0.0138	0.0138	0.0147	0.0147
18	0.02	0.0204	0.0175	0.0178	0.0147	0.0147	0.0124	0.0124	0.0139	0.0139	0.0148	0.0149
19	0.02	0.0204	0.0176	0.0179	0.0148	0.0148	0.0124	0.0124	0.014	0.0141	0.015	0.015
20	0.0201	0.0205	0.0178	0.0181	0.015	0.015	0.0125	0.0125	0.0142	0.0142	0.0151	0.0151
21	0.0202	0.0206	0.0179	0.0182	0.0151	0.0151	0.0125	0.0125	0.0143	0.0143	0.0152	0.0153
22	0.0203	0.0207	0.018	0.0183	0.0152	0.0152	0.0126	0.0126	0.0144	0.0145	0.0154	0.0154
23	0.0203	0.0207	0.0181	0.0184	0.0154	0.0154	0.0126	0.0126	0.0146	0.0146	0.0155	0.0155
24	0.0204	0.0208	0.0182	0.0185	0.0155	0.0155	0.0127	0.0127	0.0147	0.0147	0.0156	0.0157
25	0.0205	0.0209	0.0183	0.0186	0.0156	0.0156	0.0127	0.0127	0.0149	0.0149	0.0158	0.0158
26	0.0205	0.021	0.0184	0.0188	0.0158	0.0158	0.0128	0.0128	0.015	0.015	0.0159	0.0159
27	0.0206	0.021	0.0186	0.0189	0.0159	0.0159	0.0128	0.0128	0.0152	0.0152	0.016	0.0161
28	0.0207	0.0211	0.0187	0.019	0.016	0.0161	0.0129	0.0129	0.0153	0.0153	0.0162	0.0162
29	0.0208	0.0212	0.0188	0.0191	0.0162	0.0162	0.0129	0.0129	0.0155	0.0155	0.0163	0.0164
30	0.0208	0.0213	0.0189	0.0192	0.0163	0.0163	0.013	0.013	0.0156	0.0156	0.0165	0.0165

semitransparent modules have shown similar behavior, but semitransparent modules exhibited higher efficiencies (~ 1.04 times) compared to the opaque ones. However, the module efficiency in January is ~ 1.02 time more than that in June. Laboratory made PV modules have shown ~ 1.5 times higher efficiencies compared to those available in the market. For laboratory made PV modules, CdTe has shown the maximum annual electrical energy, whereas among the commercial PV modules, a-Si/nc-Si has shown maximum annual electrical energy generation. In case of laboratory PV modules, a-Si/nc-Si has the minimum annual electric energy generation, whereas in case of commercial PV modules, poly-Si has shown the minimum annual electric energy generation. For the PV modules made in the laboratory, c-Si has shown the maximum cost per unit electrical energy, whereas among the commercial PV modules, poly-Si has shown the maximum cost per unit electrical energy. For laboratory made PV modules, CdTe has shown the minimum cost per unit electrical energy, whereas among the commercial PV modules, the

a-Si/nc-Si has shown the minimum cost for unit electrical energy. The capitalized cost is found to be minimum for CIGS PV modules.

Nomenclature

- A_m : Area of module (m^2)
- h_0 : Heat loss coefficient from the top (W/m^2)
- h_i : Heat loss coefficient from the bottom (W/m^2)
- $I(t)$: Incident solar intensity (W/m^2)
- K : Thermal conductivity ($\text{W}/\text{m K}$)
- T : Temperature (K)
- U_T : Overall top loss heat transfer coefficient from solar cell to ambient ($\text{W}/\text{m}^2 \text{K}$)
- U_b : Overall bottom loss heat transfer coefficient from solar cell to ambient ($\text{W}/\text{m}^2 \text{K}$)
- L : Length (m)

R: Reflectivity
 v : Air velocity.

Subscripts

a : Ambient
 c : Solar cell
 g : Glass
 m : Module
 T : Tedlar
 E : EVA.

Greek letters

α : Absorption factor
 β_0 : Temperature coefficient of the material
 β : Packing factor
 η : Efficiency
 η_0 : Solar cell efficiency at standard test condition (STC)
 η_{m0} : PV module efficiency at standard test conditions (STC)
 τ : Transmissivity.

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