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Research Article

Exergoeconomic and Enviroeconomic Analysis of Photovoltaic Modules of Different Solar Cells

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The exergoeconomic and enviroeconomic analysis of semitransparent and opaque photovoltaic (PV) modules based on different kinds of solar cells are presented. Annual electricity and net present values have also been computed for the composite climatic conditions of New Delhi, India. Irrespective of the solar cell type, the semitransparent PV modules have shown higher net energy loss rate (L_{en}) and net exergy loss rate (L_{ex}) compared to the opaque ones. Among all types of solar modules, the one based on c-Si, exhibited the minimum L_{en} and L_{ex}. Compared to the opaque ones, the semitransparent PV modules have shown higher CO_2 reduction giving higher environmental cost reduction per annum and the highest environmental cost reduction per annum was found for a-Si PV module.

1. Introduction

In this era of advanced technologies the demand of energy is increasing day by day. The sources of energy are very limited and are running out very rapidly. Emission of greenhouse gases from the fossil fuels is another major concern as it is causing the global warming [1]. Therefore, the renewable sources of energy are developed which have no harmful effects on our delicate environment. To reduce the impacts related to processing of any energy source the efficiency of energy plants should be improved and such studies are done by exergoeconomic and enviroeconomic analysis. The exergoeconomic analysis is basically the exergy analysis along with the cost analysis in order to access the performance of the energy systems [2]. It reveals the relative cost importance of each component and provides the ways to improve overall cost effectiveness [3, 4]. On the other hand, enviroeconomic analysis (also known as environmental cost analysis) identifies the options for reducing the environmental impact associated with the overall system [5].

Photovoltaic (PV) energy conversion is considered as one of the most promising renewable energy technology which has the potential to contribute significantly to a sustainable energy supply and to mitigate greenhouse gas emissions. PV systems are free from greenhouse gases emission. Badescu analyzed a heating system of an ecology building and found that a PV array can provide all the energy required to derive the heat pump compressor, if an appropriate electricity storage system is provided [6]. Ozgener and Hepbasli investigated the capital costs and thermodynamic losses in a greenhouse heating system with solar-assisted ground-source heat pump and found a correlation between the capital cost and exergy loss but no relation was established between capital cost and energy loss [7]. Caliskan et al. [8] performed the energy, exergy, environmental, exergoeconomic, enviroeconomic, and sustainability analyses of the novel air cooler considering the nine different dead state temperatures at constant environment temperature. They found the maximum exergetic cost rate of 0.0228 kWh/$-year at a dead state temperature of 37.77°C. According to the enviroeconomic analysis, the novel air cooler has CO_2 emissions cost as 6.96$/year. Agrawal and Tiwari [9] have done the exergoeconomic analysis of a glazed PV thermal (PVT) module air collector and found that for energy saving point of view the glazed PVT module air collector is a better option compared to PV module. Prabhakant and Tiwari

[10] have carried out an analysis of carbon credit earned by each district in India, for supplying minimum subsistence electricity to each family (energy security).

We present here the exergoeconomic and enviroeconomic analysis of semitransparent and opaque PV modules based on four different types of solar cells, namely, c-Si, a-Si, CdTe, and CIGS. The schematic designs of semitransparent and opaque PV modules based on c-Si and thin film solar cells are shown in Figure 1, where panel (a) corresponds to semitransparent c-Si, panel (b) corresponds to semitransparent thin film, panel (c) corresponds to opaque c-Si, and panel (d) corresponds to opaque thin film solar cells. The detailed performance analysis of the same systems has been presented very recently [11]. For incidence of the maximum solar radiation, the PV modules in northern hemisphere were considered to be places south oriented, having inclination with horizontal surface (30°) equal to the latitude of the system's station [12–14]. The performance analysis was carried out for New Delhi which is located at 28.38N, 77.12E in India. We now present here the annual electricity and exergoeconomic and enviroeconomic computations of those PV modules having power 75 Wp by considering the following weather conditions [15]:

(a) clear days (blue sky);
(b) hazy days (fully);
(c) hazy and cloudy days (partially);
(d) cloudy days (fully).

2. Modelling

The efficiencies and operating temperatures of PV modules are calculated using energy balance equations. To write the energy balance equations for PV modules, the following assumptions have been made:

(i) the heat conduction is in one direction;
(ii) the system is in quasi steady state;
(iii) the ohmic losses in solar cells and PV modules are negligible.

2.1. Energy Balance Equations

2.1.1. For Semitransparent c-Si. The energy balance equation for the semitransparent c-Si PV modules is written as [11, 16, 17]

$$\begin{aligned}&[\text{Rate of absorbed solar radiation received by PV module}]\\&=[\text{Rate of thermal energy loss from PV module to ambient through top glass surface}]\\&+[\text{Rate of thermal energy loss from PV module to ambient through back glass surface}]\\&+[\text{Rate of electrical energy generated from PV module}],\\&\alpha_m\tau_g\beta_m I(t)=U_T(T_m-T_a)+U_b(T_m-T_a)+\eta_m I(t),\end{aligned}\tag{1}$$

where the expression for electrical efficiency of semitransparent c-Si PV module is given by [11]

$$\eta_m=\frac{\eta_0\beta_m\tau_g\left[1-\beta_0\left\{(T_a-T_0)+\left(\tau_g\alpha_m\beta_m/U_L\right)I(t)\right\}\right]}{\left[1-(\eta_0\beta_0/U_L)I(t)\right]},\tag{2}$$

and $U_L=U_T+U_b$.

2.1.2. For Opaque c-Si PV Modules. The expression for electrical efficiency of opaque c-Si PV module is given by [11]

$$\begin{aligned}\eta_m=\eta_0\tau_g\beta_m&\left[1-\beta_0\left\{(T_a-T_0)+\frac{\left\{\tau_g\alpha_m\beta_m+(1-\beta_m)\alpha_T\right\}}{U_L}I(t)\right\}\right]\\&\times\left[1-\frac{\eta_0\beta_0\tau_g\beta_m}{U_L}I(t)\right]^{-1},\end{aligned}\tag{3}$$

where $U_L=U_T+U_b$.

2.1.3. For Thin Film (a-Si, CdTe, and CIGS) PV Modules. For thin film PV modules the energy balance equation will be written as [11]

$$\begin{aligned}&[\text{Rate of absorbed solar radiation received by solar cells}]\\&=[\text{Rate of thermal energy loss from solar cells to ambient through top surface}]\\&+[\text{Rate of thermal energy loss from solar cells to ambient through back surface of glass/tedlar}]\\&+[\text{Rate of electrical energy generated by the solar cells of PV module}],\\&\alpha_m(1-R_E)I(t)=h_0(T_m-T_a)+U_b(T_m-T_a)+\eta_m I(t),\end{aligned}\tag{4}$$

where the expression for electrical efficiency for a thin film PV module is given by [11]

$$\eta_m=\frac{\eta_0\left[1-\beta_0\left\{(T_a-T_0)+\left(\alpha_m(1-R_E)/U_L\right)I(t)\right\}\right]}{\left[1-(\eta_0\beta_0/U_L)I(t)\right]},\tag{5}$$

and $U_L=h_0+U_b$.

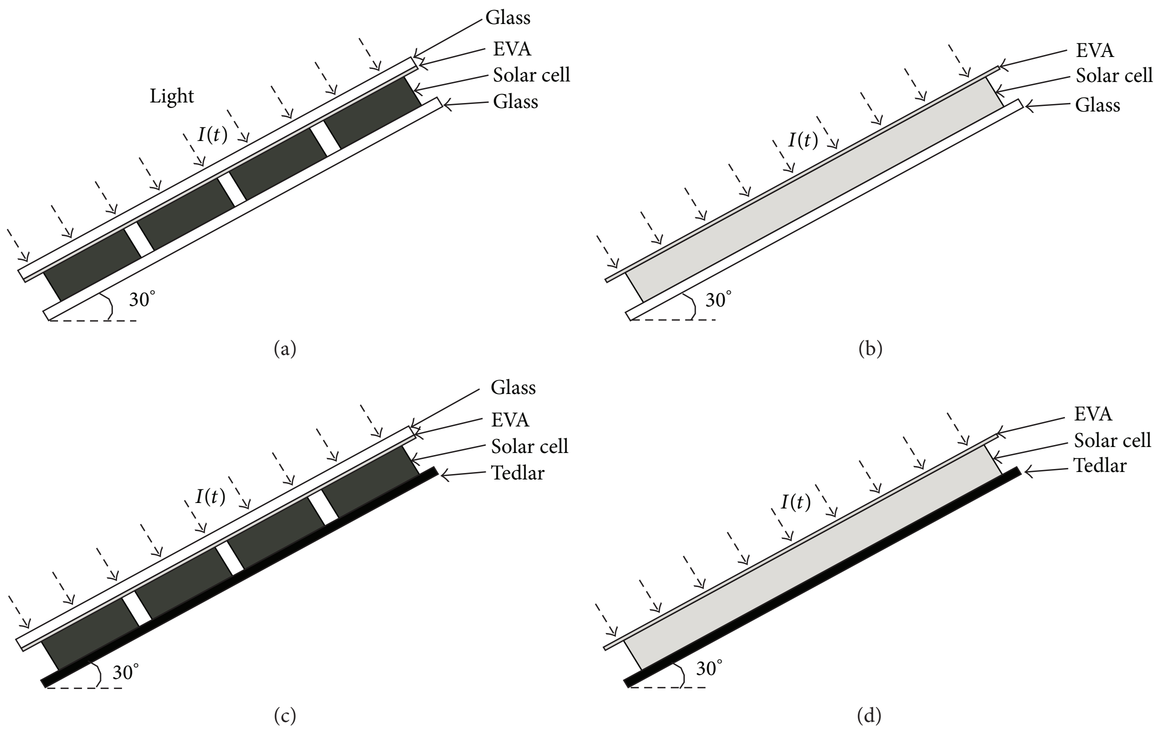

Figure 1: Schematic representation of (a) semitransparent c-Si, (b) semitransparent thin films (a-Si, CdTe, and CIGS), (c) opaque c-Si, and (d) opaque thin films PV modules, inclined at an angle of 30° from horizontal.

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 $\tau = 0$).

2.2. Annual Electricity. The hourly electricity of a PV module can be given by $E_{\text{el,hourly}} = \eta_m \times A_m \times I(t)$ [18]. And the daily electricity in kWh is obtained by $E_{\text{el,daily}} = \sum_{i=1}^{N_1}(E_{\text{el,hourly},i}/1000)$, where N_1 is the number of sunshine hours per day. The monthly electricity for the clear days (condition (a)) in kWh is calculated by the following expression:

$$E_{\text{el,monthly}} = E_{\text{el,daily}} \times n_1, \quad (6)$$

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

$$E_{\text{el,annual}} = \sum_{i=1}^{12} E_{\text{el,monthly},k}. \quad (7)$$

2.3. Net Present Value (NPV). For a PV system costing P and having service lifetime of n years, the net present value (NPV) can be calculated from

$$\begin{aligned} \text{NPV} = {} & \text{Present capital cost } (P) \\ & + \text{Operational and maintenance cost (OM)} \\ & \times \text{Unacost present value factor } \left(F_{RP,i,n}\right) \\ & + R_{5,1} \times \left(F_{SP,i,5}\right) \\ & + R_{10,2} \times \left(F_{SP,i,10}\right) + \cdots - \text{Salvage value} \\ & \times \text{Present value factor} \left(F_{SP,i,n}\right), \end{aligned} \quad (8)$$

where present capital cost of the PV system includes the cost of PV panel with stand, charge controller cost, battery cost, inverter cost, and wiring cost. $R_{5,1}, R_{10,2} \cdots R_{n,n}$ are the battery replacement costs that occurred every five years. We have

$$F_{RP,i,n} = \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right], \qquad F_{SP,i,n} = (1+i)^{-n}. \quad (9)$$

2.4. Exergoeconomic and Enviroeconomic Analyses

2.4.1. Exergoeconomic Analysis. From the well-known first law of thermodynamics, "energy can neither be created nor be destroyed," therefore, due to irreversibility of a process the exergy is consumed during the process. The energy balance equation for the components of a system was given by Lozano and Valero [19] as

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation}, \quad (10a)$$

$$\begin{aligned} & \text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} \\ & = \text{Exergy accumulation}. \end{aligned} \quad (10b)$$

The output terms in (10a) and (10b) can be given as

$$\text{Energy output} = \text{Energy input} - \text{Energy accumulation}, \tag{10c}$$

$$\text{Exergy output} = \text{Exergy input} - \text{Exergy consumption} - \text{Exergy accumulation}. \tag{10d}$$

Following Lozano and Valero [19], the energy and exergy loss rates can be obtained as

$$L_{en} = \sum_{\text{input}} \text{Energy flux rates} - \sum_{\text{output}} \text{Energy flux rates}, \tag{10e}$$

$$L_{ex} = \sum_{\text{input}} \text{Exergy flux rates} - \sum_{\text{output}} \text{Exergy flux rates}. \tag{10f}$$

From (10a), (10e), and (10f) the energy and exergy loss rates for PV module can be given as follows.

(i) For semitransparent c-Si PV module,

$$\begin{aligned} L_{en} &= \sum \tau_g \alpha_m \beta_m I(t) A_m - \sum \eta_m I(t) A_m, \\ L_{ex} &= \sum \tau_g \alpha_m \beta_m I_{ex}(t) A_m - \sum \eta_m I_{ex}(t) A_m. \end{aligned} \tag{11}$$

(ii) For opaque c-Si PV module,

$$\begin{aligned} L_{en} &= \sum \tau_g \left[\alpha_m \beta_m I(t) + (1-\beta_m) \alpha_m I(t)\right] \\ &\quad - \eta_m I(t) A_m, \\ L_{ex} &= \sum \tau_g \left[\alpha_m \beta_m I_{ex}(t) + (1-\beta_m) \alpha_m I_{ex}(t)\right] \\ &\quad - \eta_m I_{ex}(t) A_m. \end{aligned} \tag{12}$$

(iii) For thin film PV modules (a-Si, CdTe, and CIGS):

$$\begin{aligned} L_{en} &= \sum \alpha_m (1-R_E) I(t) A_m - \sum \eta_m I(t) A_m, \\ L_{ex} &= \sum \alpha_m (1-R_E) I_{ex}(t) A_m - \sum \eta_m I_{ex}(t) A_m, \end{aligned} \tag{13}$$

where $I_{ex}(t)$ is the Petela-Landsberg-Press factor [20] and can be calculated as

$$I_{ex}(t) = I(t)\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]. \tag{14}$$

Following Rosen and Dincer [21], a new parameter R is defined as the ratio of loss rate. For energy loss rates,

$$R_{en} = \frac{L_{en}}{\text{NPV}}. \tag{15}$$

For exergy loss rates,

$$R_{ex} = \frac{L_{ex}}{\text{NPV}}. \tag{16}$$

2.4.2. Enviroeconomic Analysis. Carbon dioxide (CO_2) emission trading is an administrative approach used to control the environmental pollution by providing economic incentives for achieving reductions in emissions of pollutants. So, the calculation of the cost associated with CO_2 emission is important to make an environmental assessment. The enviroeconomic (environmental cost) analysis is based on carbon price (or CO_2 emission price) and emitted carbon quantity. Establishing a carbon price is one of the most powerful mechanisms available to reduce national greenhouse gas emissions. The carbon price is an approach imposing a cost on the emission of greenhouse gases. Paying a price for carbon (CO_2) released into the atmosphere is a way of motivating people and countries to reduce carbon emissions. It also provides an incentive to invest and deploy renewable energy technology that does not emit carbon to the atmosphere. Also, the pricing method discourages people to generate electricity by the use of relatively more polluting coal, gas, and oil fired stations. Following Caliskan et al. [8], the enviroeconomic analysis based on CO_2 emission reduction and CO_2 emission reduction price can be given as

$$C_{co_2} = c_{co_2} \times x_{CO_2}, \tag{17}$$

where C_{co_2} is the environmental cost reduction parameter, c_{co_2} is CO_2 emission reduction price per tCO_2, and x_{CO_2} is reduction in CO_2 emission per year (tCO_2/year). If unit power is used by a consumer and the losses due to poor domestic appliances are around 20%, then the transmitted power should be 1 (1 − 0.2) = 1.25 units. If the transmission and distribution losses are 40%, which is common in Indian conditions, then the power that has to be generated in the power plant is 1.25 (1 − 0.4) = 2.08 units. The average CO_2 equivalent intensity for electricity generation from coal is approximately 0.98 kg of CO_2 per kWh at the source. Thus, for unit power consumption by the consumer the amount of CO_2 emission is 2.08 × 0.98 = 2.04 kg. We have

$$\begin{aligned} &\text{The carbon dioxide emission reduction per annum} \\ &\quad = \text{Annual electricity} \times 2.04\,\text{kg}\ CO_2\text{e}. \end{aligned} \tag{18}$$

Den Elzen et al. [22] mentioned the international carbon price between 13\$/tCO_2 and 16\$/tCO_2 for the low and high pledge scenario. So, this value is taken on average to be 14.5\$/tCO_2. Therefore,

$$\begin{aligned} &\text{Environmental cost reduction per annum} \\ &\quad = \text{Carbon dioxide reduction per annum} \times 14.5\$. \end{aligned} \tag{19}$$

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 were obtained from the Indian Metrological Department (IMD), Delhi. The following methodology has been used for the exergoeconomic and enviroeconomic analysis of the PV module.

Table 1: Design parameters of opaque and semitransparent PV modules.

Parameters	c-Si	a-Si	CdTe	CIGS
A_m (m^2)	0.65	1.17	0.72	0.72
α_c	0.9	0.85	0.8	0.8
β_c	0.89	1	1	1
β_0	0.006	0.001	0.002	0.003
η_{m0} (%)	14.20	6.40	10.40	10.42
α_T		0.50		
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)		$2.8 + 3.0\ v$; $v = 0.2$ m/s		
L_g (m)		0.003		
K_g (W/m K)		1.10		
L_T (m)		0.0005		
K_T (W/m K)		0.033		

Step 1. The hourly solar radiation on the PV modules (75 Wp), at the 30° inclination from the horizontal, was calculated using the Liu and Jordan method [23, 24].

Step 2. The designed parameters, for all the PV modules, used for calculations have been tabulated in Table 1.

Step 3. For the known climatic conditions and designed parameters, the electrical efficiencies of the PV modules of c-Si and thin film (a-Si, CdTe, and CIGS) have been evaluated using (2), (3), and (5), respectively.

Step 4. The monthly electricity for clear days (condition (a)) has been evaluated using (6) and the same process was adopted to calculate the monthly electricity for other climatic conditions (b), (c), and (d). The total electricity for each month was obtained by adding the electricity generations in the climatic conditions (a), (b), (c), and (d) in that month.

Step 5. The annual electricity was calculated using (7).

Step 6. Net present value (NPV) has been calculated by (8). Operational and maintenance cost has been considered to be 10%, whereas salvage value has been taken as 5% of the present capital cost (P) of the modules. Interest rate i has been taken as 8%.

Step 7. Energy loss rate and exergy loss rate for c-Si semitransparent, c-Si opaque, and thin film PV module have been calculated by using ((10a), (10b), (10c), (10d), (10e), (10f))–(13).

Step 8. For each PV module R_{en} and R_{ex} have also been calculated using (15) and (16).

Step 9. For each PV module carbon dioxide emission reduction per annum and environmental cost reduction per annum were calculated using (18) and (19), respectively.

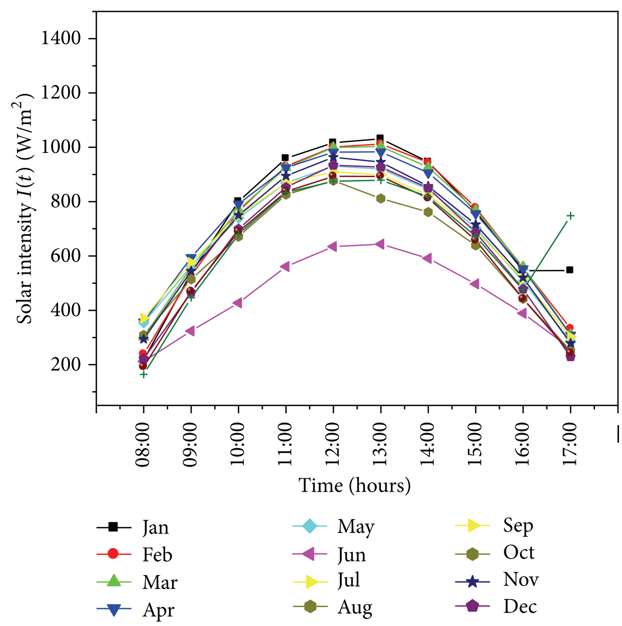

Figure 2: Hourly variation of solar intensity $I(t)$ for each month.

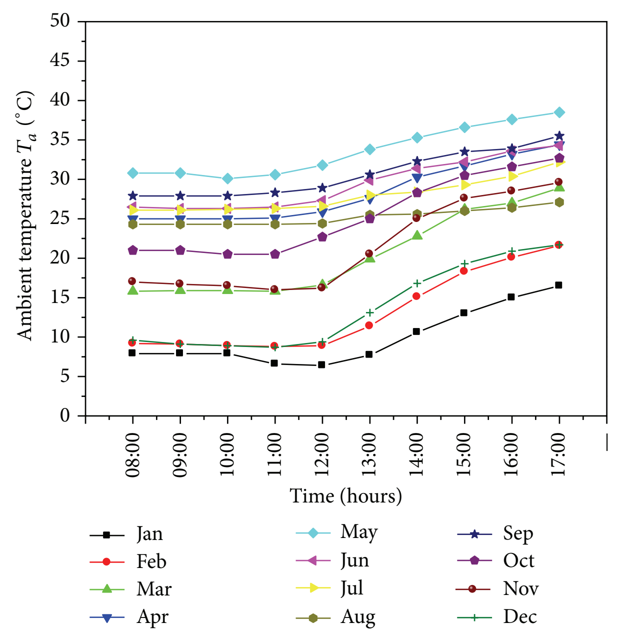

Figure 3: Hourly variation of ambient temperature (T_a) for each month.

4. Results and Discussion

To solve the mathematical equations, a computer program MathCad 8 has been used. The hourly variations of $I(t)$ at 30° inclination to the horizontal surface and ambient temperature (T_a) throughout the year are shown in Figures 2 and 3, respectively. The annual electricity for different semitransparent and opaque PV modules has been shown in Figure 4. For all the solar cell types, the semitransparent PV modules have shown higher annual electricity compared to the opaque ones. The maximum annual electricity is

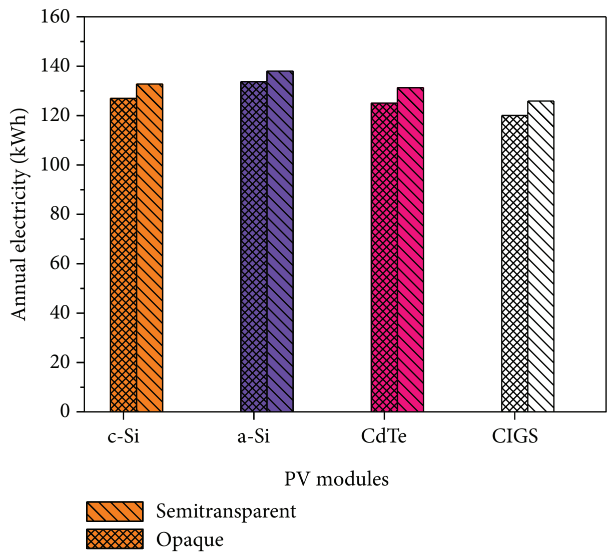

Figure 4: Annual electricity for different material semitransparent and opaque PV modules.

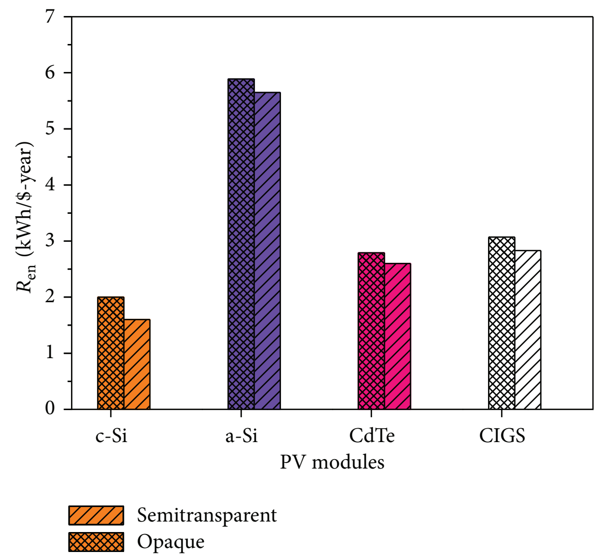

Figure 5: Ratio of thermodynamic energy loss rate to the net present value (R_{en}) for different material semitransparent and opaque PV modules.

observed for a-Si to be 139 kWh for semitransparent and 133 kWh for opaque PV module. CIGS modules have shown the minimum annual electricity which is 125.9 and 120 kWh for semitransparent and opaque, respectively. Table 2 shows the net present capital value of each type of PV modules. c-Si has shown higher net present value (542.67$) than the other PV modules. It is because of high capital cost (212.96$) due to shortage of availability of the material and expensive manufacturing process. For all the PV modules, kWh/kWp values are also calculated to show the energy generated divided by the STC rating. Table 3 compares the energy rating values of all the semitransparent and opaque PV modules in kWh/kWp, electricity per installed power. Semitransparent PV modules have higher kWh/kWp (~4%) than that of the opaque ones while among all the PV modules a-Si exhibited highest kWh/kWp and CIGS has lowest kWh/kWp. The reason behind this is the higher annual electricity of a-Si PV module and lowest annual electricity of CIGS. Table 4 shows the L_{en} and L_{ex} for each PV module. Irrespective of solar cell type, the semitransparent PV module exhibited less L_{en} and less L_{ex}. The reason behind this is that the semitransparent PV modules have shown the higher efficiencies throughout the year compared to the opaque ones as in case of c-Si PV modules; the packing factor is considered to be 0.89. In that case the solar radiation falling 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 film thicknesses some of the heat of the incident radiation is transmitted through the back glass sheet but in case of opaque modules it was absorbed by the tedlar sheet. The absorption of solar heat by the tedlar sheet results in increments in the module temperature, due to which the module efficiency decreases. Therefore, semitransparent PV modules exhibited higher energy flux rate products and higher exergy flux rates as compared to the opaque ones that causes lower L_{en} and L_{ex}. Among all the PV technologies in both cases (semitransparent and opaque) a-Si has shown higher L_{en} and L_{ex} because it exhibited higher energy flux rate products and higher exergy flux rate products because of higher efficiency.

The ratios of thermodynamic loss rate to net present value (R_{en}) for all the PV modules are shown in Figure 5. It was observed that semitransparent PV module exhibited lower R_{en} than the opaque ones for all the PV technologies. Similarly Figure 6 shows R_{ex} for all the PV modules and it was found to be lower for the semitransparent PV module. It is because of the lower energy and exergy flux rate products in semitransparent PV module. Table 5 shows the CO_2 emission reduction per annum (tCO_2e) and environmental cost reduction per annum ($) for all the PV modules. From Table 5 it is clear that, for all the PV technologies, the semitransparent modules have shown higher CO_2 emission reduction per annum (tCO_2e) giving higher environmental cost reduction per annum ($). The reason behind this is that the semitransparent PV module exhibited higher annual electricity. Among all the technologies it was found that a-Si PV module earns highest carbon credit and therefore higher maximum environmental cost reduction per annum compared to other PV modules. The reason behind this is the same as a-Si PV module having higher annual electricity.

5. Conclusions

On the basis of the present studies the following conclusions have been drawn.

Table 2: Net present value (NPV) for different material PV modules.

PV technology	Total investment cost ($)			Capital cost (P) (a + b + c) ($)	Lifetime (n) (years)	Salvage value (S) ($.) (~5% of P)	Operational and maintenance cost ($) (~10% of P)	NPV ($)
	Panel cost (a)	Stand cost (b)	Installation cost (c)					
c-Si	105	2.96	105	212.96	30	10.65	21.30	542.67
a-Si	60	3.70	105	168.70	20	8.43	16.87	405.47
CdTe	67.5	3.24	105	175.74	25	8.79	17.57	445.69
CIGS	60	3.24	105	168.24	20	8.41	16.82	542.67

Table 3: Energy rating values in kWh/kWp for different material semitransparent and opaque PV modules.

PV technology	Energy rating (kWh/kWp)	
	Semi.	Opaque
c-Si	1770.29	1693.05
a-Si	1839.99	1783.37
CdTe	1750.05	1667.53
CIGS	1678.83	1600.65

Table 4: Net energy loss rate and net exergy loss rate for different material semitransparent and opaque PV modules.

PV technology	Net energy loss rate (L_{en}) (kWh)		Net exergy loss rate (L_{ex}) (kWh)	
	Semi.	Opaque	Semi.	Opaque
c-Si	509.59	576.45	475.35	537.72
a-Si	1127	1129	1051	1054
CdTe	579.38	581.10	540.37	541.96
CIGS	582.90	584.50	543.79	545.20

Table 5: The values of CO_2 emission reduction per annum (tCO_2e) and environmental cost reduction per annum ($) for different material semitransparent and opaque PV modules.

PV modules	CO_2 emission reduction per annum (tCO_2e)		Environmental cost reduction per annum ($)	
	Semi.	Opaque	Semi.	Opaque
c-Si	0.27	0.25	3.93	3.76
a-Si	0.28	0.27	4.10	3.96
CdTe	0.27	0.25	3.88	3.69
CIGS	0.26	0.24	3.72	3.6

(i) Semitransparent PV modules exhibited higher annual electricity and higher kWh/kWp compared to the opaque ones, whereas among all the PV modules a-Si has shown the maximum annual electricity generation and maximum kWh/kWp.

(ii) Semitransparent PV modules exhibited lower L_{en} and L_{ex} giving lower R_{en} and R_{ex}, whereas among all the PV technologies, c-Si exhibited lowest energy rate and exergy rate.

(iii) Net CO_2 mitigation (tCO_2e) per annum was found to be maximum in semitransparent PV module giving higher environmental cost reduction per annum ($).

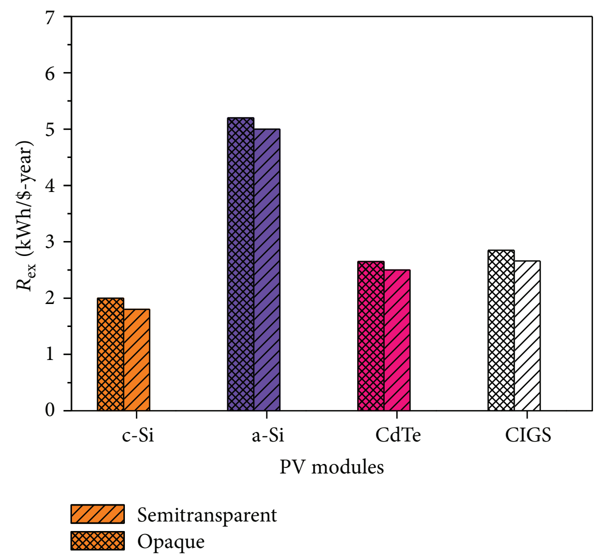

Figure 6: Ratios of thermodynamic exergy loss rate to the net present value (R_{ex}) for different material semitransparent and opaque PV modules.

Among all the technologies, a-Si PV module earns highest carbon credit and higher maximum environmental cost reduction per annum compared to other PV modules.

Therefore, as a whole for energy saving and impact on environment point of view, the semitransparent PV module is more beneficial than opaque ones.

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 (W/mK)
T: Temperature (K)
U_T: Overall top loss heat transfer coefficient from solar cell to ambient (W/m^2K)
U_b: Overall bottom loss heat transfer coefficient from solar cell to ambient (W/m^2K)
L: Length (m)

R: Reflectivity
v: Air velocity
L_{en}: Energy loss rate
L_{ex}: Exergy loss rate
T_s: Solar temperature.

Subscripts

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

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: Transmitivity.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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