Exergoeconomic and enviroeconomic analysis of semitransparent and opaque photovoltaic (PV) panels: a comparative study

R K Mishra1*, Gagan Chaudhary2, Rajesh Tripathi3 and Rajendra Prasad4

1, 3, 4Department of Applied Sciences (Physics) Galgotias College of Engineering and Technology, Greater Noida
2Department of Mechanical Engineering, HIET, Ghaziabad, UP
E-mail:bhu.rajeev@gmail.com

Abstract. In present communication the exergoeconomic and enviroeconomic analyses of two different stand-alone photovoltaic (PV) modules viz. semitransparent and opaque have been performed. The exergoeconomic examination is very useful way to investigate the correlation between capital cost and exergy losses. The enviroeconomic analysis describes the carbon dioxide mitigation by the system. The energy (electrical) produced annually by semitransparent and opaque PV panel is also evaluated. It is reported that the semitransparent panel shows better performance as for as energy saving are concern. Environmental cost reduction is found to be 128.7 Rs. /year and 125.95 Rs. /year for semitransparent and opaque PV modules, respectively.

Keywords: Exergoeconomic, enviroeconomic, PV module, exergy.

*Corresponding author

1. Introduction

All around the world there are lots of major consequences because of using conventional fuels. One of the basic reasons for the environmental pollution is the emission of hazard gases [1, 2]. Because of the bad environmental impact and poor stability of the economics the development in the PV sector is of great interest [3]. The annual energy from panel depends on the orientation of the panel [4, 5]. Performance of PV panel using full-scale mock-up model was studied by Song et al. [6] for South Korea. Author found that the photovoltaic module inclined at 30°, facing due south, gave around 2.5 times more power as compared with the PV panel placed vertically. The electrical efficiency of photovoltaic panel is also strongly dependent on temperature of the module. Park et al. [7] experimentally revealed that power was found to be decreased by 0.48–0.52% for one degree rise in temperature of the panel. The energy production from the PV module is affected by its temperature which changes as the property of glass changes. For designing and analyzing the energy systems, the thermodynamics and the cost accounting of the system should be combined. According to Rosen and Dincer [8] the unit cost based on energy is utilized in order to calculate the cost of energy conversion devices. Singh et al. [9] observed that the quantitative and qualitative losses are analyzed by exergy examination. The performance of energy systems is evaluated and improved using exergoeconomic analysis also termed as the exergetic cost analysis [10]. Environmental policies affecting the environmental cost analysis is termed as Enviroeconomic analysis. Badescu [11] analyzed that by using an electrical energy storage system connected with a photovoltaic array, the heat pump compressor can be driven. Ozgener and Hepbasli [12] observed a structured link between the total cost and loss in
exergy while investigating solar operated appliances. The exergoeconomic evaluation of hybrid photovoltaic thermal module air heater was carried out by Agrawal and Tiwari [13]. Author reported that the hybrid photovoltaic thermal (PVT) system saves more energy than a PV panel. Mishra and Tiwari [14] found that a photovoltaic thermal (PVT) solar collector is a viable option not only for fulfilling the need of hot water but also for getting DC power during daytime when sun is there. Sahota and Tiwari [15] while studying the energy and exergy of a solar still, found that the carbon dioxide released annually was estimated to be 14.95 tonnes and 3.17 tonnes hybrid system (without heat exchanger) and 24.61 tonnes and 2.36 tonnes for hybrid system (with heat exchanger). Elbar et al. [16] performed exergoeconomic and environmental estimation of new solar distillation unit integrated with photovoltaic panel (PV). The result showed that solar still system, used with PV as reflector, is the most efficient technology.

In this communication, the electrical energy production, exergoeconomic and enviroeconomic analyses of two distinct types of stand-alone PV panel namely semitransparent (Fig. 1a) and opaque (Fig. 1b) are evaluated for New Delhi India [17].

![Figure 1(a): Photograph of Semitransparent PV module.](image1)

![Figure 1(b): Photograph of opaque PV module.](image2)
2. Thermal modeling

(i) Semitransparent PV module (Fig. 1a)

For semitransparent PV panel [18]:

\[
\tau_g \alpha_c \beta_c \int I(t) \, dx = \left[ U_{im,a} (T_m - T_a) + U_b (T_m - T_a) \right] \int \, dx + \eta_e \tau_g \beta_c \int I(t) \, dx
\]

(1a)

From above Eq. (1a), the equation for \( T_m \) will be given as

\[
T_m = \frac{(\tau_g \alpha_c \beta_c - \eta_m) I(t) + U_{im,a} T_a + U_b T_a}{U_{im,a} + U_b}
\]

(1b)

where, \( \eta_m = \eta_e \tau_g \beta_c \)

The equation for electrical efficiency of a PV panel [19, 20]

\[
\eta_m = \eta_{m0} \left[ 1 - \beta_{ref} \left( \frac{T_m - T_{ref}}{T_{ref}} \right) \right]
\]

(1c)

where, \( T_{ref} = 25^\circ C \) for indoor testing conditions and \( T_{ref} = T_a \) (ambient temperature) for outdoor testing conditions.

From above Eqs. (1b) and (1c),

\[
\eta_m = \frac{1 - \beta_{ref} \tau_g \alpha_c \beta_c I(t)}{U_{im,a} + U_b}
\]

(1d)

(ii) Opaque PV module (Fig. 1b)

For opaque PV panel [19]

\[
\tau_g \left[ \alpha_e \beta_e + \alpha_f (1 - \beta_c) \right] \int I(t) \, dx = \left[ U_{im,a} (T_m - T_a) + U_b (T_m - T_a) \right] \int \, dx + \eta_e \tau_g \beta_c \int I(t) \, dx
\]

(2a)

From Eq. (2a),

\[
T_m = \frac{(\alpha \tau)_{G-T, eff} - \eta_m} {U_{im,a} + U_b} I(t) + U_{im,a} T_a + U_b T_a
\]

(2b)

where, \( \eta_m = \eta_e \tau_g \beta_e \)

From Eqs. (1c) and (2b)

\[
\eta_m = \frac{1 - \beta_{ref} (\alpha \tau)_{G-T, eff} I(t)}{U_{im,a} + U_b}
\]

(2c)

The electrical power produced can be given as [21]

\[
P(e) = \eta_m A_m I(t)
\]

(2d)

3. Net present value
Let us consider $P$ is present value, $S$ is the salvage value, $R_1$ is operational costs per year and $R_5$’s are painting and maintenance cost for the interval of five years. NPV can be written as [22]

$$\text{Net Present Value (NPV)} = P + R_1 \times \left[ \frac{(i+1)^n - 1}{i(i+1)^n} \right]_{i=0}^{i=n} + R_{5,1} \times \left[ \frac{1}{(i+1)^n} \right]_{i=0}^{i=n} + R_{10,2} \times \left[ \frac{1}{(i+1)^n} \right]_{i=0}^{i=n} + R_{15,3} \times \left[ \frac{1}{(i+1)^n} \right]_{i=0}^{i=n} + \cdots - S \times \left[ \frac{1}{(i+1)^n} \right]_{i=0}^{i=n}$$

(3)

4. Exergoeconomic evaluation

Because of irreversibility, exergy is lost during a process.

Energy in - Energy out = Energy accumulation

and

Exergy in - Exergy out - Exergy consumed = Exergy accumulated

From (4a) and (4b),

Energy out = Product energy out + Waste energy out

and

Exergy out = Product exergy out + Waste exergy out

The loss rates in terms of energy and exergy can be written as:

Energy loss rate ($L_{en}$) = $\sum$ Energy flux rates - $\sum$ Energy flux rates inputs products

(4e)

and

Exergy loss rate ($L_{ex}$) = $\sum$ Exergy flux rates - $\sum$ Exergy flux rates inputs products

(4f)

From Eqs. (1a), (4e) and (4f), for semitransparent panel

Energy loss rate ($L_{en}$) = $\sum \tau_g \alpha_c \beta_c I(t) bdx - \sum \eta_e \tau_g \beta_c I(t) bdx$

(4g)

and

Exergy loss rate ($L_{ex}$) = $\sum \tau_g \alpha_c \beta_c I(t) bdx - \sum \eta_e \tau_g \beta_c I(t) bdx$

(4h)

where

$I_{en}(t) = I(t) \times \left[ 1 - \frac{4}{3} \times \left( \frac{T_a}{T_s} \right) + \frac{1}{3} \times \left( \frac{T_a}{T_s} \right)^3 \right]$

where, $T_s$ is the sun temperature in K.

From Eqs. (2a), (4e) and (4f) for opaque PV panel

Energy loss rate ($L_{en}$) = $\sum \tau_g \alpha_c \beta_c (1 - \beta_c) I(t) bdx - \sum \eta_e \tau_g \beta_c I(t) bdx$

(4i)

and

Exergy loss rate ($L_{ex}$) = $\sum \tau_g \alpha_c \beta_c (1 - \beta_c) I(t) bdx - \sum \eta_e \tau_g \beta_c I(t) bdx$

(4j)

Following Rosen and Dincer [23] define,

$\frac{L_{en}}{NPV}$

and

(4k)
\[ R_{ex} = \frac{L_{ex}}{NPV} \]  

(41)

5. Enviroeconomic evaluation

The cost reduction parameter for environment can be given as [24]: 

\[ C_{CO_2} = c_{CO_2} \times x_{CO_2} \]  

(5)

where, \( C_{CO_2} \) is the cost reduction parameter for environment, \( c_{CO_2} \) is \( CO_2 \) emission reduction price for one t\( CO_2 \) and \( x_{CO_2} \) is reduction in \( CO_2 \) mitigation per year (t\( CO_2 \)/year).

(i) Glass to glass type PV module

Total electrical energy produced per annum = 79.18 kWh

Suppose that the unit power is used and reduction in energy because of bad quality of home devices is about 20%. The transferred power will be 1.25 units. Suppose there are 40% losses in the transmission and distribution channels.

The generated power in the plant is 

\[ \frac{1.25}{1-0.4} = 2.08 \text{ units} \]

The average \( CO_2 \) identical intensity for electrical energy from coal is approximately 0.98 kg of \( CO_2 \) per kWh at the source. Thus, for unit power used the amount of \( CO_2 \) emission will be \( 2.08 \times 0.98 = 2.04 \text{ kg} \).

The annual \( CO_2 \) emission reduction = 79.18 \times 2.04 kg \( CO_2 \) e

\[ = 0.16132 \text{ t}CO_2 \text{e} \quad (1 \text{ ton} = 10^3 \text{ kg}) \]

The price of international carbon was between 13 $/t\( CO_2 \) and 16 $/t\( CO_2 \) [24]. The average is 14.5 $/t\( CO_2 \).

From Eq. (5), environmental cost reduction per annum = 0.16132 \times 14.5 $ = 2.34 $.

(ii) Glass to tedlar type PV module

Total electrical energy produced per annum by glass to tedlar type PV module = 77.75 kWh

The carbon dioxide emission reduction per annum = 77.75 \times 2.04 kg \( CO_2 \)e

\[ = 0.1586 \text{ t}CO_2 \text{e} \quad (1 \text{ ton} = 10^3 \text{ kg}) \]

Using Eq. (5) environmental cost reduction per annum = 0.1586 \times 14.5 = 2.29 $.

6. Results and discussion

The detailed specifications of both types of PV panels are listed in Table 1. Figure 2 shows plot of sun intensity and environmental temperature for a clear day in June, 2019 for New Delhi, India. The changes of module surface temperature and experimental electrical efficiency on hourly basis for panel are given in Figure 3. Figure reveals that semitransparent PV panel gives more efficiency as compared with opaque PV panel. This is because of the reason that the solar energy falling on the area of the panel which is not packed by solar cell is directly pass through the glass cover of panel, but, in opaque PV panel all the radiations which falls on the area where solar cells are there is absorbed by the tedlar. So, cell temperature for opaque PV module is higher than temperature in semitransparent PV panel.
Table 1: Specifications of photovoltaic modules.

| Specifications                   | Values           |
|---------------------------------|------------------|
| b                               | 0.605 m          |
| $K_g$                           | 1.1 W/m K        |
| $K_T$                           | 0.033 W/m K      |
| $L_g$                           | 0.003 m          |
| $L_T$                           | 0.0005 m         |
| $\alpha_c$                      | 0.9              |
| $\alpha_T$                      | 0.5              |
| $PF$ for semitransparent         | 0.76             |
| $PF$ for opaque                 | 0.83             |
| $\beta_{ref}$                   | 0.0045/K         |
| $\eta_{m0}$                     | 0.12             |
| $\tau_g$                        | 0.95             |
| Life of PV module               | 30 Years         |

Figure 2: Plot of sun radiation and environmental air temperature for a clear day in June, 2019.
Figure 3: Plot of module surface temperature and efficiency for a clear day in June, 2019.

Figure 4 shows the hourly changes of the power obtained from semitransparent and opaque PV modules. It is observed that the power generated by semitransparent module is higher as compared to opaque module because of the higher electrical efficiency of semitransparent panel. The measured values of electrical parameters for semitransparent and opaque panels are given in Tables 2 and 3, respectively.

Figure 4: Plot of electrical power for a clear day in month of June, 2019.
Table 2: Parameters for semitransparent PV module June 18, 2019.

| Sr no | Time (hour) | I(t) (W/m²) | Ta (°C) | Tm (°C) | Isc (A) | Voc (V) | ηm (%) | Electrical power (W) |
|-------|-------------|-------------|---------|---------|---------|---------|---------|---------------------|
| 1     | 9           | 480         | 34      | 39      | 2.3     | 19.2    | 10.19   | 35.33               |
| 2     | 10          | 840         | 36      | 41      | 3.4     | 18.9    | 8.47    | 51.41               |
| 3     | 11          | 800         | 39      | 45      | 3.2     | 18.5    | 8.20    | 47.36               |
| 4     | 12          | 820         | 41      | 46      | 3.2     | 18.4    | 7.97    | 47.22               |
| 5     | 13          | 740         | 41      | 46      | 3.3     | 18.6    | 9.18    | 49.05               |
| 6     | 14          | 640         | 42      | 44      | 3.0     | 18.9    | 9.82    | 45.39               |
| 7     | 15          | 460         | 41      | 45      | 2.2     | 19.2    | 10.16   | 33.76               |
| 8     | 16          | 280         | 40      | 43      | 1.4     | 19.2    | 10.66   | 21.56               |

Table 3: Electrical parameters for opaque PV module for a June 18, 2019.

| Sr no | Time (hour) | I(t) (W/m²) | Ta (°C) | Tm (°C) | Isc (A) | Voc (V) | ηm (%) | Electrical power (W) |
|-------|-------------|-------------|---------|---------|---------|---------|---------|---------------------|
| 1     | 9           | 480         | 34      | 41      | 2.2     | 18.5    | 9.39    | 32.56               |
| 2     | 10          | 840         | 36      | 44      | 3.3     | 18.6    | 8.09    | 49.10               |
| 3     | 11          | 800         | 39      | 48      | 3.0     | 18.4    | 7.64    | 44.16               |
| 4     | 12          | 820         | 41      | 49      | 3.0     | 18.4    | 7.45    | 44.16               |
| 5     | 13          | 740         | 41      | 50      | 3.0     | 18.6    | 8.35    | 44.64               |
| 6     | 14          | 640         | 42      | 49      | 3.0     | 18.6    | 9.66    | 44.64               |
| 7     | 15          | 460         | 41      | 47      | 2.2     | 18.7    | 9.90    | 32.91               |
| 8     | 16          | 280         | 40      | 46      | 1.4     | 18.7    | 10.35   | 20.94               |

Eqs. (1d) and (2c) are used to calculate the theoretical values for PV panel. Monthly average electrical parameter of semitransparent and opaque PV modules for New Delhi, India are evaluated and the result is given in Figures 5 and 6 respectively. The annual average electrical efficiency of semitransparent and opaque PV module is found to be 10.17% and 9.92% respectively. Eq. (2d) is used to calculate the electrical energy of PV panel. Figures 7 and 8 show the monthly variation of average electrical energy produced by semitransparent and opaque PV module respectively. Figures reveal that the annual average electrical energy produced by semitransparent and opaque PV modules is 79.18 and 77.75 kWh respectively. Then the monthly average electrical efficiency and electrical power produced is calculated [15].
Figure 5: Electrical efficiency for semitransparent PV module.

Annual average = 10.17%

Monthly average electrical efficiency, %

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Figure 6: Month wise electrical efficiency for opaque PV module.

Annual average = 9.92%

Monthly average electrical efficiency, %

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Figure 7: Month wise electrical energy obtained from semitransparent PV module.

Figure 8: Month wise electrical energy obtained from opaque PV module.

Capital cost and salvages value for different component are shown in Table 4. The net present value of semitransparent and opaque PV module is calculated by using Eq. (3).

The rate of losses in energy and exergy for modules has been computed by using Eqs. (4g), (4h), (4i) and (4j). Eqs. (4k) and (4l) are used to calculate the parameters $R_{en}$ and $R_{ex}$. The detail results of exergoeconomic and enviroeconomic analyses for New Delhi is shown in Tables 6. From Table it is clear that ratio of loss rate to net present value ($R_{en}$ and $R_{ex}$) is lower and the cost reduction for environment per annum is higher for semitransparent PV module for both the climatic conditions. It indicates that in terms of saving of energy and environment effect, the semitransparent PV panel gives better results as compared with opaque PV panel.
Table 4: Capital cost and salvages value for different component of the systems.

| Components                             | Qty in kg | PV module With stand ($) | Salvage value ($S_S$) at the inflation rate of 5% (present values of Iron scrap @$0.36/kg) |
|----------------------------------------|-----------|---------------------------|--------------------------------------------------------------------------------------|
| Support structure @$1.45/kg            | 10        | 14.5                      | 11.8                                                                                 |
| PV module G-G @$290.9/75Wp             | 1 no.     | 290.9                     | 9.1                                                                                 |
| PV module G-T @$218.1/75Wp             | 1 no.     | 218.1                     | 9.1                                                                                 |
| Paint @$1.8/kg                         | 0.5 kg    | 0.91                      | *                                                                                   |
| Fabrication charges                    |           |                           | *                                                                                   |
| Capital cost ($)                       |           |                           |                                                                                     |
| G-G PV module                          |           |                           |                                                                                     |
| G-T PV module                          |           |                           |                                                                                     |

Table 5: The result for semitransparent and opaque PV module for New Delhi, India, climatic conditions.

| PV module                | NPV ($) | $L_{\text{Ten}}$ (kWh) | $R_{\text{en}}$ (kWh/$\text{-year}$) | $L_{\text{Tox}}$ (kWh) | $R_{\text{ex}}$ (kWh/$\text{-year}$) | $C_{\text{CO2}}$ ($$/\text{-year}) |
|--------------------------|---------|------------------------|--------------------------------------|------------------------|--------------------------------------|---------------------------------|
| Glass to glass           | 382.1   | 25239.43               | 2.2                                  | 25107.57               | 2.19                                 | 2.34                            |
| Glass to tedlar          | 309.5   | 23770.5                | 2.56                                 | 23238.57               | 2.50                                 | 2.29                            |

7. Conclusions

Following conclusions have been drawn:

(i) Electrical power generated by semitransparent PV module is higher as compared to opaque panel.

(ii) In terms of energy saving and effects on environment, the semitransparent PV panel is better as compared with opaque panel.
References

[1] Omer A M 2008 Energy environment and sustainable development Ren and Sus. En. Rev. 12 2265–300
[2] Tiwari G N and Mishra R K 2012 Advanced Renewable Energy Sources (RSC Publishing Cambridge UK)
[3] Chaar L E, Lamont L A and Zein N E 2011 Review of photovoltaic technologies Ren. and Sus. En. Rev. 15 2165–75
[4] Mishra R K and Tiwari G N 2013 Energy and exergy analysis of hybrid photovoltaic thermal water collector for constant collection temperature mode Int. J. Sol. En. 91 161–173
[5] Mishra R K, Tiwari S, Tiwari A and Tiwari G N 2017 Unit cost analysis for Sodha Bers Complex (SBC): An energy efficient building Th. Sc. Eng. Prog. 4 58–70
[6] Song J H, An Y S, Kim S G, Lee S J, Yoon J H and Choung Y K 2008 Power output analysis of transparent thin-film module in building integrated photovoltaic system (BIPV) En. and build. 40 2067–75
[7] Park K E, Kang G H, Kim H I, Yu G J and Kim J T 2010 Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module Energy 35 2681–7
[8] Rosen M A, Dincer I and Kanoglu M 2008 Role of exergy in increasing efficiency and sustainability and reducing environmental impact, En. Pol. 36 128–137
[9] Singh N, Kaushik S C and Misra R D 2000 Exergetic analysis of solar thermal power system Ren. En. 19 135–43
[10] Sahoo P K 2008 Exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming App. Th. Eng. 28 1580–8.
[11] Badescu V 2002 First and second law analysis of a solar-assisted heat pump based heating system En. Conv. and Mang. 43 2539–52
[12] Ozgener O and Hepbasli A 2005 Exergoeconomic analysis of a solar assisted ground-source heat pump greenhouse heating system App. Th. Eng. 25 1459–71
[13] Agrawal S and Tiwari G N 2012 Exergoeconomic analysis of glazed hybrid photovoltaic thermal module air collector Int. J. Sol. En. 86 2826–2838
[14] Mishra R K and Tiwari G N 2013 Energy and exergy analysis of hybrid photovoltaic thermal water collector for constant collection temperature mode Int. J. Sol. En. 90 58–67
[15] Sahota L and Tiwari G N 2017 Exergoeconomic and enviroeconomic analyses of hybrid double slope solar still loaded with nanofluids En. Conv. and Mang. 148 413–430
[16] Elbar A R A, Yousef M S and Hassan H 2019 Energy, exergy, exergoeconomic and enviroeconomic (4E) evaluation of a new integration of solar still with photovoltaic panel J. Clean. Prod. 233 665–680
[17] Dubey S, Sandhu G S, Tiwari G N 2009 Analytical expression for electrical efficiency of PV/T hybrid air collector App. En. 86 697–705
[18] Tiwari A and Sodha M S 2006 Performance evaluation of hybrid PV/thermal water/air heating system: A parametric study Ren. En. 31 2460–2474
[19] Schott T 1985 Operation temperatures of PV modules: A theoretical and experimental approach Proc. Sixth EC PV Sol. En. Conf. (London) p 392-396
[20] Evans D L 1981 Simplified method for predicting PV array output Int. J. Sol. En. 27 555-560
[21] Skoplaki E and Palyvos J A 2009 On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations *Int. J. Sol. En.* **83** 614-624

[22] Tiwari G N, Mishra R K and Solanki S C 2011 Photovoltaic modules and their applications: A review on thermal modelling *App. En.* **88** 2287-2304

[23] Rosen M A and Dincer I 2003 Exergoeconomic analysis of power plants operating on various fuels *App. Th. Eng.* **23** 643–58

[24] Den Elzen M G J, Hof A, Beltran D A M, Grassi R G, Van R M, Van V B and Van V J D P 2011 The Copenhagen accord: abatement costs and carbon prices resulting from the submissions *Env. Sci. & Pol.* **14** 28–39