Indian Journal of Engineering & Materials Sciences
Vol. 29, August 2022, pp. 519-525
DOI: 10.56042/ijems.v29i4.46362

# Exergetic and Enviroeconomic analysis of a novel PVT array with triangular duct for building application

Amit Sharma, Ravi Kumar*, & C S Rajoriya
Government Engineering College Bikaner, Rajasthan 334 001, India

*Received: 13 February 2021; Accepted: 1 September 2021*

Photovoltaic/thermal air collector has potential to execute electrical and thermal energy concurrently. This paper investigates carbon dioxide mitigation and enviroeconomic analysis on basis of overall, energy and exergy gain of semi-transparent PVT (SPVT), and opaque PVT (OPVT) arrays under natural convection in Bikaner, Rajasthan (India). The analysis has been carried out on an array configuration of opaque and semi-transparent arrays having 7 modules connected in series. Experimental work has been done in the month of September to December and comparison has been made on the basis of electrical and thermal gains. The results depict that average electrical, thermal and overall exergy gain of SPVT array is higher by 9.20%, 15.2% and 8.08% with respect to OPVT array. The CO2 mitigation for four months for semi-transparent array is higher by 0.67 tCO2 and 0.15 tCO2 as compared to OPVT array on the basis of overall thermal energy and overall exergy gain respectively. The environmental cost of SPVT array is higher by Rs. 710.53 and Rs. 160.50 than OPVT array for four months with respect to overall thermal energy and overall exergy gain.

**Keywords:** Photovoltaic air collector, Electrical efficiency, Thermal efficiency, Overall exergy gain, CO2 emission, enviroeconomic analysis.

## 1 Introduction

Before technological revolution, most of the human activities such as transportation, cooking etc. were depended on non-conventional energy resources therefore, carbon dioxide and greenhouse gases emission, global warming etc. problems have arisen[1]. However, in last few years, many researchers and engineers are working to invent technology and energy efficient system which are based on renewable energy resources. Renewable energy (RE) resources can easily meet the increasing global energy demand and can lower down the harmful emissions. Energy harnessed from the sun is that non-conventional source of energy which is converted into electricity by using of PV technology[2].

Now a days, many researchers are working on photovoltaic thermal technology that can provide electrical energy as well as thermal energy. Agrawal et al.[3] performed exergoeconomic analysis on base of energy preservation for glazed PV/T air collector and compared with conventional PV module. They also performed validation test for experiment and good co-relations were obtained between theoretical and experimental values. It is observed that uncertainty in the experiments obtained in December month is 11.6% and April month is 2.1%. Annual net energy preserve by glazed PV/T air collector is 234.7 kWh. Agrawal *et al.*[4] has been done comparative analysis of unglazed, glazed and conventional PV/T air collector on basis of overall thermal energy gain and carbon credit under climate of Shrinagar (India). It is observed that unglazed PVT array performance is higher when compared with other two arrays. Results shown that reduction in $CO_2$ emission per annum for unglazed and glazed arrays are 62.3% and 27.7 % in contrast with conventional PVT arrays on the basis of overall thermal gain. Arslan et al.[5] have proposed finned air fluid photovoltaic thermal collector to analyses energy and exergy performances by use of numerical and experimental technics. It was observed that PV panel electrical efficiency increased 0.42% by using of cooling. Rajoria et al.[6] has performed enviroeconomic analysis for two different configurations under four different climatic conditions of India. It is found that annual $CO_2$ mitigation result is higher for Bangalore. They also evaluated environmental cost on basis of energy and exergy. Tripathi *et al.*[7] have performed experiment and numeric computation to observe the overall PV degradation loss factors. Agrawal *et al.*[8] has presented enviroeconomic analysis and energy matric of glazed PV/T air collector for New Delhi under Indian climatic condition. The effect of annual uniform

*Corresponding author (Email: er.ravi.49@gmail.com)

cost, energy pay back and life cycle conversion efficiency have been determined for 8%, 10% and 12% interest rates. They observed that annual thermal energy and exergy gain is $ 36.97 and $ 8.55 respectively. Tiwari *et al.*[9] has derived improved analytical expression for electrical efficiency and cell temperature of semitransparent solar cell. It is found that electrical efficiency of solar cells is increased 0.97%. Rajoria et al.[10] has worked on exergetic and enviroeconomic analysis of SPVT array and also compared with opaque and solar cell tiles PVT array. They evaluated performance of PVT array for four different weather conditions to calculate the overall thermal and exergy gain. They indicated that semi-transparent performance is higher as compared toother two PVT array. Tripathi *et al.*[11] have fabricated and designed a single unit of fully coved concentrated photovoltaic thermal collectors to analyses thermal and electrical gain. The annual behavior of system was also studied by using fixed position technic as well as manual maximum power point tracking technic. Thermal energy and exergy gain is higher in M-MPPT technic. Agrawal *et al.*[12] analyzed annual cost of Glazed PVT air collector on the basis of the carbon credit earned and overall thermal and exergy gain for 30-year lifetime. They found that Rs 109,242 carbon emission reduction and Rs 25275.6 overall thermal and exergy gain. Tripathi *et al.*[13] has analyzed N partially PVT concentrating collector for energy, exergy and carbon credit. It is observed that they saved $ 153.90 per year on basis of overall thermal energy is saved by reduced $CO_2$ emission per annum for 25% PV coverage area and $ 22.25 per year on basis of overall exergy gain is saved for 100% PV coverage area. Rajoria *et al.*[14] has composed newer approach on cash flow diagram of PVT array system. They also investigated effect of energy payback time and earned carbon credit on annualized uniform cost of the different type PVT arrays such as opaque, semi-transparent, solar tiles. On the basis of energy and exergy, the annualized uniform cost has increased 7% to 16.5%. Higher value of annualized uniform cost is indicated better performance of system. Nazri *et al.*[15] has studied on energy economic analysis of PV/T-TE air collector. They observed that at mass flow rate of 0.1 kg/s the maximum efficiency is obtained 0.97% and yearly uniform cost is high for overall exergy and thermal energy gain yearly. Rejeb *et al.*[16] have developed novel photovoltaic thermal collector by using optical anti-reflective or low emissivity coating, thermal resistance and channel heat exchanger to reduce radiation, conduction and thermal losses. Results showed that proposed system has increase electrical and thermal efficiency by 15.4% and 73% respectively. Saadon *et al.*[17] has been analyzed semi-transparent BiPVT under nature ventilation for exergy, exergoeconomic and enviroeconomic. They observed that semi-transparent BIPV/T represented better exergy and energy efficiency as compared with opaque BIPV/T. Soltani *et al.*[18] has performed experimental analysis on photovoltaic thermal collector integrated with a thermo-electric module. It used five cooling approaches and observed that $SiO_2$-water nanofluid gave the maximum efficiency and is best coolant among all. Result shown that lower power generation, carbon mitigation and carbon credits are obtained by natural cooling with air comparatively with nanofluids.

By literature study, it has been observed that limited work is performed on air-based PVT array. In this paper, carbon mitigation and enviroeconomics is evaluated on the basis of overall thermal gain and overall exergy gain for air-based PVT system added with two types of PVT arrays such opaque and semi-transparent arrays. In this work, triangular duct has been used to extract heat and cooling in natural climate condition of Rajasthan.

## 2 Materials and Method

### 2.1 Experiment Setup

he system consists opaque and semi-transparent of PVT modules and an array has been composed by connecting 7 modules in series i.e. outlet from one PVT air collector has been connected to inlet of second collector and so on till the seventh PVT air collector. Each PVT air collector has an area of 1.9 m$^2$ having a triangular duct below each PVT air collector hence covering the whole array to extract heat from the bottom under natural convection mode. Specifications of both PVT module is shown in Table 1. The parameters are tested under standard conditions at 1000 W/m$^2$ and 25°C.

Table 1 — Specification PVT Array

| Array Type | $P_{max}$ ($W_p$) | $V_{oc}$ | $I_{sc}$ | $I_m$ | $V_m$ | Module area | Total Array area |
|---|---|---|---|---|---|---|---|
| Semi-Transparent | 270 | 37.80 V | 9.10 A | 8.66 A | 31.20 V | 1.9 m$^2$ | 13.3 m$^2$ |
| Opaque | 270 | 38.16 V | 8.96 A | 8.48 A | 32.46 V | 1.9 m$^2$ | 13.3 m$^2$ |

All the experimental work has been carried out on the system installed on the rooftop of Mechanical Department of Engineering College Bikaner, Rajasthan from September to December month. The main section of air-cooling duct is shown in Fig. 1 in which single inlet and outlet has been provided in circular section.

To ensure thermal insulation, the bottom and sides has been covered by wooden ply (6 mm), polyvinylchloride sheet (6 mm) and polystyrene (25.4 mm). Natural air has been circulated through the duct and air velocity is measured with hot wire anemometer. The inlet and outlet temperature of air has been measured by K type thermocouples. All measurement devices have been calibrated and checked according to requirement range. Daily climate data has been recorded by weather condition station in data logger.

### 2.2 Research Methodology

In this study, energetic, exegetic and enviroeconomic analysis has been evaluated by considering natural climate of Rajasthan for September month to December month. For calculating hourly performance of both system averaging data methodology [19-20] has been used to carry out performance parameter.

#### 2.2.1 Electrical Efficiency

Electrical efficiency of opaque and semi-transparent photo-voltaic array has been calculated by Eqs1 and 2.

$$P_{out} = FF*V_{oc}*I_{sc}\ (kW) \qquad \ldots (1)$$

Here $Fill\ Factor\ (FF) = \frac{Vm \times Im}{Voc \times Isc}$

$$P_{in} = I(t)*A_{pv}(kW) \qquad \ldots (2)$$

where, $P_{out}$ is electrical energy output, FF is fill factor, $V_{oc}$ is hourly average open circuit voltage, $I_{sc}$ is hourly average short circuit current, I(t) is hourly average solar radiation and $V_m$ or $I_m$ is maximum voltage and current. Then electrical efficiency (η) is shown in Eq. 3.

$$\text{Electrical efficiency } (\eta) = \frac{Pout}{Pin} \qquad \ldots (3)$$

#### 2.2.2 Thermal Efficiency

Thermal efficiency is greatly depended on mass flow rate and temperature gradient. For PVT collector, inlet and outlet energy is determined by Eqs 4 and 5.

$$E_{out} = \dot{m}c_p(T_{out} - T_{in})\ (kW) \qquad \ldots (4)$$

where, $E_{out}$ is the energy output of PVT array, $\dot{m}$ is mass flow rate of air (kg/s), $c_p$ is specific heat at constant pressure of air (kJ/kg.K), $T_{in,}$ and $T_{out}$ are inlet and outlet temperature of air (°C). $E_{in}$ input energy of PVT system is as

$$E_{in} = I(t)*A_{pv}\ (kW \qquad \ldots (5)$$

Then thermal efficiency ($\eta_t$) is shown in Eq. 6.

$$\text{Thermal efficiency } (\eta_t) = \frac{Eout}{Ein} \qquad \ldots (6)$$

#### 2.2.3 Overall Exergy Gain

In a PVT system, exergy is maximum rate at which solar energy is converted into useful work. It is referring to quality of energy.

$$\Psi = [\ 1 - \frac{4}{3}\frac{Ta}{Ts} + \frac{1}{3}(\frac{Ta}{Ts})^4] \qquad \ldots (7)$$

where, Ψ is efficiency conversion coefficient proposed by Petela as shown in Eq. 7, $T_a$ is the ambient temperature (K), and $T_s$ is the temperature of sun (5777 K).

$$\sum Ex_{out} = \sum P_{out} + \sum \dot{m}c_p(T_{out} - T_{in})*\eta_c\ (kW) \qquad \ldots (8)$$


Fig. 1 — Installed experimental setup, (A) opaque PVT Array, (B) semi-transparent PVT Array and (C) Inlet side view.

Here thermal energy is converted into electrical energy by utilization of Carnot cycle. $Ex_{out}$ and $Ex_{in}$ is output and input exergy as shown in Eqs 8 and 9.

$$Ex_{in} = \Psi * I(t) * A_{pv} \text{(kW)} \quad \dots (9)$$

Exergy efficiency of PVT system has been calculated by Eq. 10.

$$\Psi_{PVT} = \frac{\text{Exout}}{\text{Exin}} \quad \dots (10)$$

**2.2.4 Overall Thermal Gain**

It is useful heat gain by PVT system in which electrical energy is converted into thermal energy by using of power generation factor and value of factor is depend on coal quality. According to Indian coal quality, power generation factor is 0.38. Overall thermal gain is shown in Eq. 11[6].

$$\sum \dot{Q}_{overall} = \sum \dot{E}_{(out)} + \sum \frac{p_{out}}{\eta_{cpower}} \quad \dots (11)$$

Here $\eta_{cpower}$ is power generation factor

**2.2.5 Environmental cost**

This analysis is dependent on the price of $CO_2$ emission disseminated into the environment. Hence, $CO_2$ mitigation in a month from PVT array can be calculated from Eq. 12.

$$\Phi_{CO_2} = \frac{\text{Ɯ}_{CO_2} \times \dot{E}_{overall}}{10^3} \quad \dots (12)$$

where, $\Phi_{CO_2}$ is $CO_2$ mitigation per month ($tCO_2$/month), $\text{Ɯ}_{CO_2}$ is the equivalent $CO_2$ intensity for the generation of electricity from coal (2.0 $kgCO_2$/kWh), and $\dot{E}_{overall}$ is the overall energy/exergy generated (kWh) from the PVT array per month. The average value 14.5 \$/$tCO_2$ has been considered for the calculation of environmental cost that is depicted in Eq. 13.

$$\check{E}_{CO_2} = \check{e}_{CO_2} \times \Phi_{CO_2} \quad \dots (13)$$

where, $\check{E}_{CO_2}$ is the environmental cost parameter ($CO_2$ mitigation cost per month) (\$/month) and $\check{e}_{CO_2}$ is the cost of carbon per $tCO_2$ (\$/$tCO_2$).

## 3 Results and Discussion

In this investigation, the performance of OPVT and SPVT arrays have been evaluated on the criteria of energy and exergy. Experimental study has been conducted for four months September to December 2020 under natural climatic condition in Engineering College Bikaner, Rajasthan. Fig. 2 shows the hourly variation of solar radiation in these months.

From the study, it is found that solar radiation is maximum in September and continuously decrease in subsequent months. Table 2 shows the electrical and thermal attribute of OPVT and SPVT array. Electrical efficiency of SPVT arrays is found to be higher as compared with OPVT array due to direct radiation gain from unpacked surface area of SPVT arrays that results in less amount of heat retention in and around the solar cell. Average electrical efficiency of OPVT array and SPVT arrays is 12.77%, and 14.06% respectively for four months.

Monthly variation in electrical output and thermal output is exhibited in Figs 3 and 4. It is found that the electrical gain reaches a maximum in November due to less temperature of the modules which can be attributed to the dependence of electrical efficiency on temperature. The study shows that the thermal efficiency of the air-based PVT collector is greatly affected by solar intensity and mass flow rate of air.

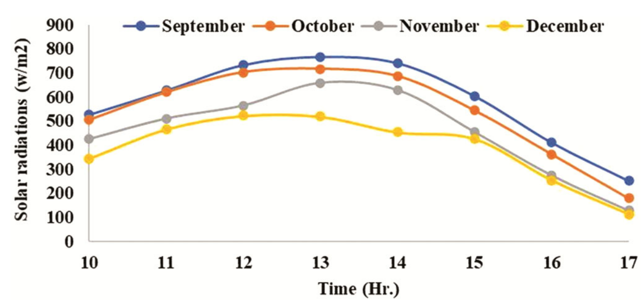


Fig. 2 — Hourly variation of solar radiation for four months.

Table 2 — Electrical and Thermal attribute of opaque and SPVT arrays

| Months | OPVT array | | | | SPVT array | | | |
|---|---|---|---|---|---|---|---|---|
| | Electrical Output (kWh) | Electrical efficiency (%) | Thermal Output (kwh) | Thermal efficiency (%) | Electrical Output (kWh) | Electrical efficiency (%) | Thermal Output (kwh) | Thermal efficiency (%) |
| September | 180.71 | 10.05 | 588.6 | 31.6 | 175.21 | 10.11 | 705.9 | 38.00 |
| October | 177.97 | 11.21 | 527.1 | 29.77 | 189.81 | 12.55 | 576.6 | 32.92 |
| November | 183.45 | 14.37 | 362.4 | 23.36 | 195.65 | 16.22 | 411.9 | 26.96 |
| December | 169.76 | 15.44 | 140.4 | 10.49 | 181.05 | 17.37 | 181.2 | 14.47 |

The Average thermal efficiency of SPVT system is increased 15.2% with respect of OPVT system due to heat dissipation rate of SPVT system is higher as compared with OPVT array. Fig. 5 displays the hourly variation of outlet temperature of air in SPVT array for four months. The monthly maximum air temperature is observed for the month of September and the peak temperature of air for all the month lies at 2:00 PM.

Table 3 shows the overall exergy and energy gain attribute of OPVT and SPVT arrays. It is noticed that the overall thermal energy gain in SPVT is greater than OPVT array for entire four months. In month of September, maximum thermal gain obtained from SPVT array. It has been recognized that under natural convection the heat extraction greatly depends on the velocity inside the duct.

The Exergy analysis based upon second law of thermodynamics and is a very important tool for system enhancement and its cost effectiveness. Monthly variations of overall exergy and efficiency is shown in Table 3. The results reveal that the overall exergy gain is higher by 9.03% in SPVT in contrast to OPVT array in the month of November because of the

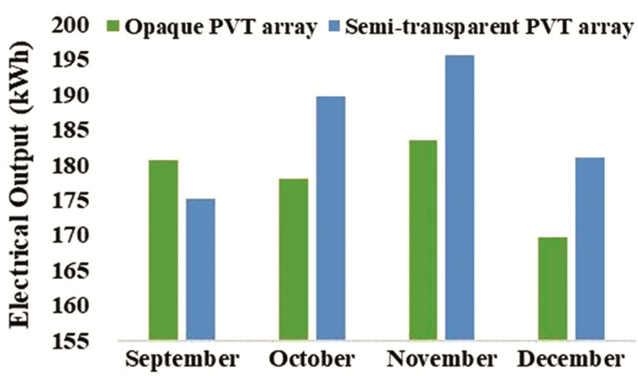


Fig. 3 — Variation in electrical output.

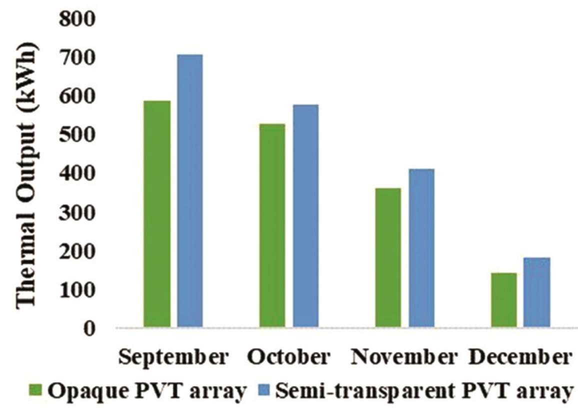


Fig. 4 — Variation in thermal output.

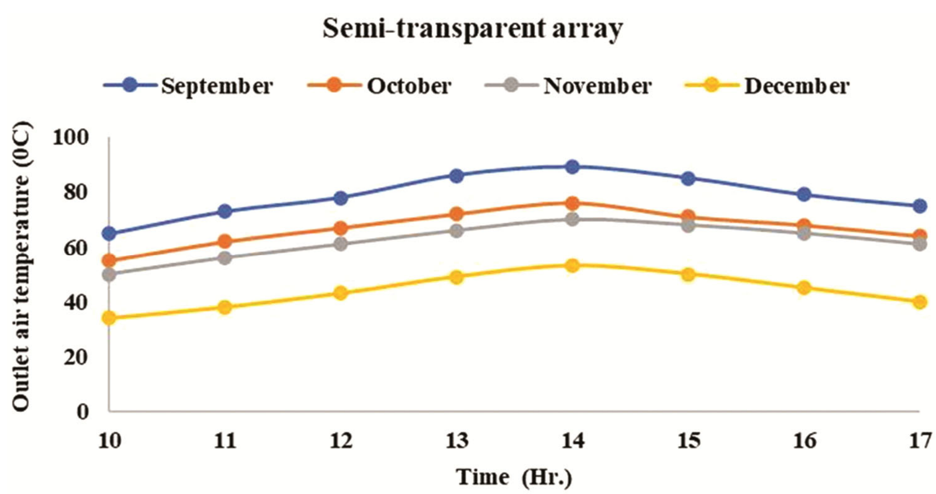


Fig. 5 — Hourly variation of outlet air temperature of SPVT array.

Table 3 — Overall exergy and energy gain attribute of opaque and SPVT array

| Months | OPVT array | | | | SPVT array | | | |
|---|---|---|---|---|---|---|---|---|
| | Overall exergy gain (kWh) | Overall exergy gain efficiency (%) | Overall thermal gain} (kwh) | Overall thermal gain efficiency (%) | Overall exergy gain (kWh) | Overall exergy gain efficiency (%) | Overall thermal gain (kwh) | Overall thermal gain efficiency (%) |
| September | 239.42 | 14.18 | 1064.17 | 62.57 | 257.29 | 15.59 | 1167 | 69.65 |
| October | 225.92 | 14.94 | 995.46 | 63.83 | 245.59 | 16.9 | 1076.12 | 71.01 |
| November | 216.84 | 17.73 | 845.17 | 65.75 | 238.37 | 20.44 | 926.79 | 74.86 |
| December | 179.64 | 17.30 | 587.14 | 54.83 | 196.38 | 19.90 | 657.66 | 64.53 |

Table 4 — Parameters of opaque and SPVT array

| Parameter | Basis | OPVT Array | SPVT Array |
|---|---|---|---|
| $CO_2$ mitigation in four months, ($tCO_2$) | Overall thermal energy | 6.98 | 7.66 |
| | Overall exergy | 1.72 | 1.88 |
| Enviroeconomic (environmental cost) parameter for four months, (Rs.) | Overall thermal energy | 7392.44 | 8102.97 |
| | Overall exergy | 1824.50 | 1985.00 |
| Average efficiency of four months, (%) | Overall thermal energy | 61.75 | 70.02 |
| | Overall exergy | 16.05 | 18.21 |

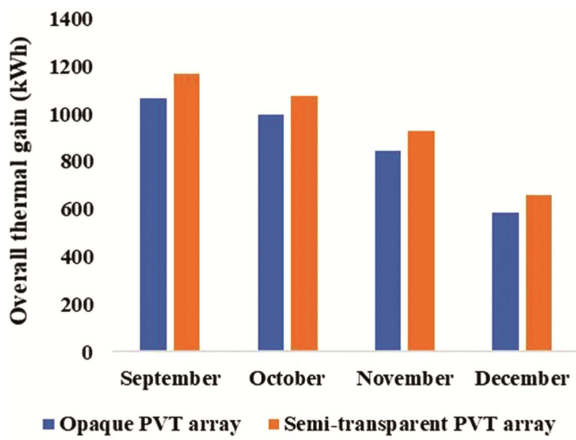


Fig. 6 — Variation in overall thermal gain.

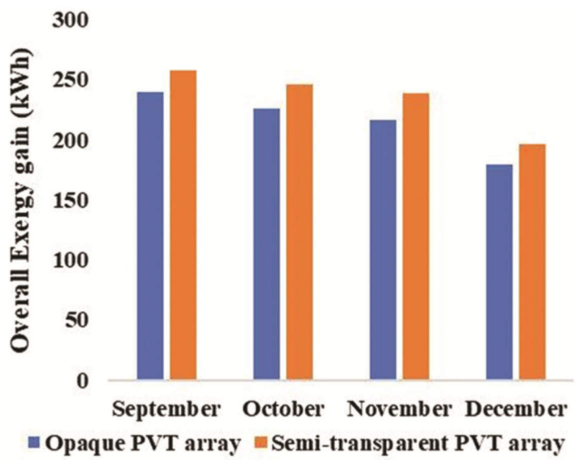


Fig. 7 — Variation in overall exergy gain.

reason that in this month, weather condition is most favorable for PVT system and heat extraction from triangular duct is maximum due to which a higher gain in electrical power of SPVT array is observed. The average overall exergy gains and exergy efficiency is incremented by 8.08% and 11.90% respectively in SPVT array in contrast to OPVT array. Overall thermal and exergy gain with respect to four months is displayed in Figs 6 and 7.

The enviroeconomic and $CO_2$ mitigation parameter for SPVT and OPVT array has been represented in Table 4. It has been examined that SPVT array provides a higher potential of mitigating $CO_2$ which has resulted in an increase of $CO_2$ mitigation by 8.7% on the basis of overall thermal energy and 8% on the basis of overall exergy gain with respect to OPVT array. The environmental cost of SPVT array is higher by Rs. 710.53 and Rs. 160.50 than OPVT array for four months on the same basis of comparison.

## 4 Conclusion

In the present study investigates the energy, exergy and enviroeconomic analysis of SPVT array and OPVT array. Experimental work is performed in September to December month under natural convection condition at Engineering College Bikaner (Raj.). Triangular duct is fabricated for heat extraction from the natural air flow. The performance evaluation has been carried out during 10:00 AM to 05:00 PM for both PVT array. Following are prime inferences drawn from analysis:

- The electrical efficiency and thermal efficiency of SPVT array is higher 9.20% and 15.24% respectively than OPVT array.
- Maximum thermal energy is obtained in September month and minimum thermal energy is found in December month but electrical performance is higher in December month.
- The overall exergy and thermal gain of SPVT array is elevated by 8.08% and 8.76% in contrast to OPVT array. Maximum exergy and thermal gain are obtained in month of November.
- SPVT array provides a potential for higher $CO_2$ mitigation resulting in a higher environmental cost on both the basis of investigation.
- The enviroeconomice analysis enables the comparison of price with respect to $CO_2$ emission which can prove to a basic tool for environmental cost assessment.
- The environmental cost of SPVT array is higher by 710.53 Rs and 160.50 Rs than OPVT array for four months with respect to overall thermal energy and overall exergy gain.

This analysis can provide behaviors of different type of PVT array in last four months of year. All analysis is performed under nature climatic condition. Now our aim in future is to control affecting parameter and evaluated optimum condition for both PVT array. The outcomes of the above analysis can be useful for integration in the new and existing building and other infrastructure to obtain thermal as well as electrical output. Also, it can be used as a façade for different air pass and configurations as per the building skin to achieve a zero-energy building.

## Acknowledgment

The authors acknowledged the financial support of CRS projects under TEQIP-III phase for the CRS ID 1-5763884671 and also RTU CRS ID-54.

## References


1 Kumar R, Rajoria CS, Sharma A, & Suhag S, *Mater Today Proc*, 46 (2020) 5322.
2 Rajoria C S, Kumar Ravi, Sharma Amit, Singh Dharmendra, & Suhag Sathan, *Mater Today Proc*, 46 (2021) 5342.
3 Agrawal S, & Tiwari GN, *Solar Ener*, 86 (2012) 2826.
4 Agrawal Sanjay, & Tiwari G N, *Ener Conv Manag*, 65 (2013) 628.
5 Arslan E, Aktas M, & Can OF, *J Clean Prod*, 276 (2020) 123.
6 Rajoria CS, Agrawal S, & Tiwari GN, *Solar Ener*, 88 (2013) 110.
7 Tripathi R, Sharma R, & Tiwari GN, *Green Ener Tech*, Springer, (2020) 685.
8 Agrawal S, & Tiwari GN, *Solar Ener*, 92 (2013) 139.
9 Tiwari A, Tripathi R, & Tiwari GN, *Adv Ener Res*, Springer, 1 (2020) 88.
10 Rajoria CS, Agrawal S, Tiwari GN, & Chaursia GS, *Solar Ener*, 122 (2015) 1138.
11 Tripathi Rohit, & Tiwari GN, *Solar Ener*, 146 (2017) 180.
12 Agrawal S, & Tiwari GN, *Solar Ener*, 115 (2015) 329.
13 Tripathi R, Tiwari GN, & Dwivedi VK, *Solar Ener*, 136 (2016) 260.
14 Rajoria CS, Agrawal S, Dash A K, Tiwari GN, & Sodha MS, *Solar Ener*, 124 (2016) 254.
15 Nazri NS, Fudholi A, Bakhtyar B, Yen CH, Ibrahim A, Ruslan MH, Mat S, & Sopian K, *Renew Sustain Ener Rev*, 192 (2018) 187.
16 Rejeb O, Gaillard L, Julien SG, Ghenai C, Jemni A, Bettayeb M, & Menezo C, *Renew Ener*, 146 (2020) 610.
17 SaadonS,GaillardL, Menezo C, & Girouxjulien S, *Renew Ener*, 105 (2020) 981.
18 Soltani S, Kasaeian A, Lavajoo A, Loni R, Najafi G, & Mahian O, *Ener Con Manag*, 218 (2020)112.
19 Ozakm AN, & Kaya F, *Solar Ener*, 197 (2020)199.
20 Sohel M I, Ma Z, Cooper P, Adams J, & Scott R, *App Ener*, 132 (2014) 216.