



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

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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 arisen¹. 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 technology².

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 correlations 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 CO₂ 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 CO₂ 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 matrix of glazed PV/T air collector for New Delhi under Indian climatic condition. The effect of annual uniform

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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 to other two PVT array. Tripathi *et al.*¹¹ have fabricated and designed a single unit of fully covered concentrated photovoltaic thermal collectors to analyse thermal and electrical gain. The annual behavior of system was also studied by using fixed position technique as well as manual maximum power point tracking technique. Thermal energy and exergy gain is higher in M-MPPT technique. 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 CO₂ 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 natural 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 SiO₂-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

The 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 m² 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/m² 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, exergetic 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 methodology¹⁹⁻²⁰ 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.

$$P_{out} = FF * V_{oc} * I_{sc} \text{ (kW)} \quad \dots (1)$$

Here *Fill Factor (FF)* = $\frac{V_m \times I_m}{V_{oc} \times I_{sc}}$

$$P_{in} = I(t) * A_{pv} \text{ (kW)} \quad \dots (2)$$

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.

$$\text{Electrical efficiency } (\eta) = \frac{P_{out}}{P_{in}} \quad \dots (3)$$

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.

$$E_{out} = \dot{m} c_p (T_{out} - T_{in}) \text{ (kW)} \quad \dots (4)$$

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

$$E_{in} = I(t) * A_{pv} \text{ (kW)} \quad \dots (5)$$

Then thermal efficiency (η_t) is shown in Eq. 6.

$$\text{Thermal efficiency } (\eta_t) = \frac{E_{out}}{E_{in}} \quad \dots (6)$$

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.

$$\Psi = \left[1 - \frac{4}{3} \frac{T_a}{T_s} + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right] \quad \dots (7)$$

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).

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



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.

$$\Psi_{PVT} = \frac{Ex_{out}}{Ex_{in}} \quad \dots (10)$$

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. 11⁶.

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

Here η_{cpower} is power generation factor

2.2.5 Environmental cost

This analysis is dependent on the price of CO₂ emission disseminated into the environment. Hence, CO₂ mitigation in a month from PVT array can be calculated from Eq. 12.

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

where, Φ_{CO_2} is CO₂ mitigation per month (tCO₂/month), W_{CO_2} is the equivalent CO₂ intensity for the generation of electricity from coal (2.0 kgCO₂/kWh), and $\dot{E}_{overall}$ is the overall energy/exergy generated (kWh) from the PVT array per month. The average value 14.5 \$/tCO₂ has been considered for the calculation of environmental cost that is depicted in Eq. 13.

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

where, \check{E}_{CO_2} is the environmental cost parameter (CO₂ mitigation cost per month) (\$/month) and \check{e}_{CO_2} is the cost of carbon per tCO₂ (\$/tCO₂).

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.

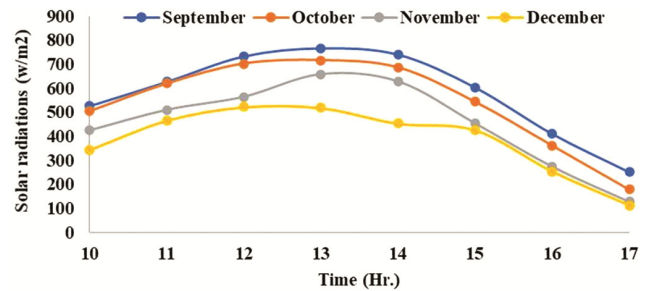


Fig. 2 — Hourly variation of solar radiation for four months.

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

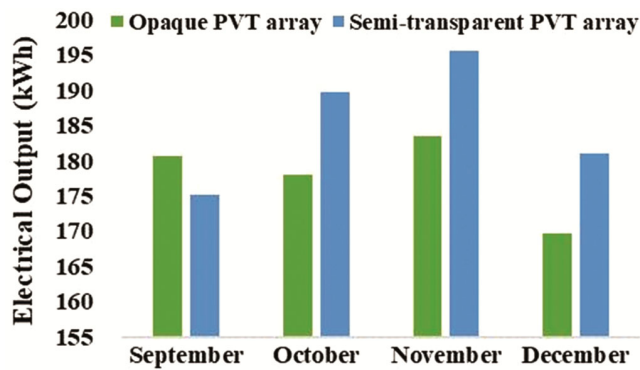


Fig. 3 — Variation in electrical output.

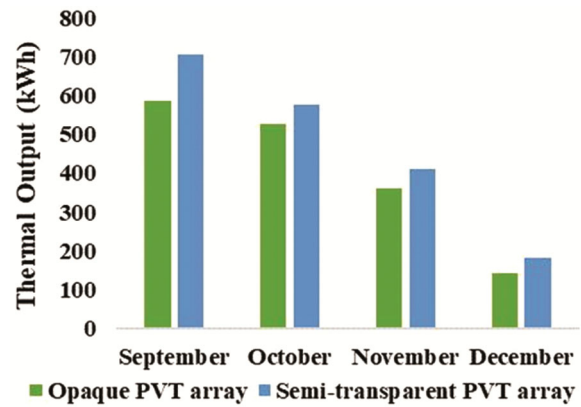


Fig. 4 — Variation in thermal output.

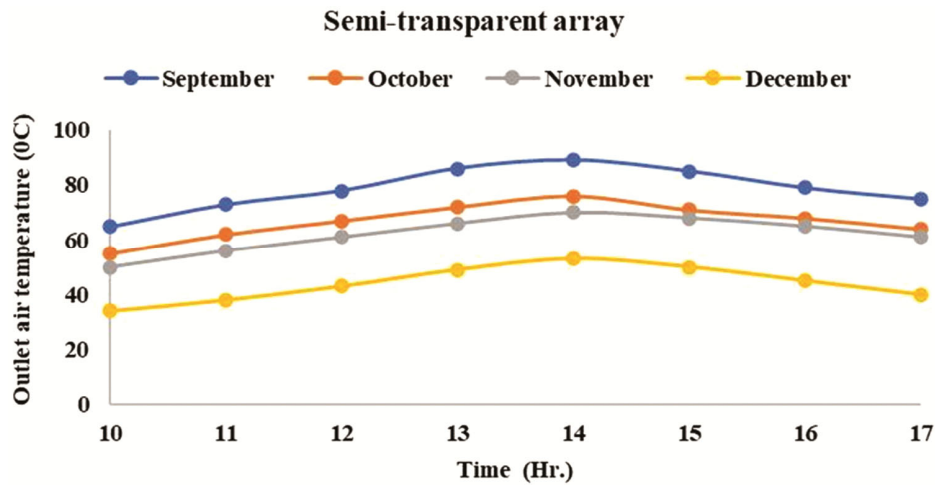


Fig. 5 — Hourly variation of outlet air temperature of SPVT array.

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

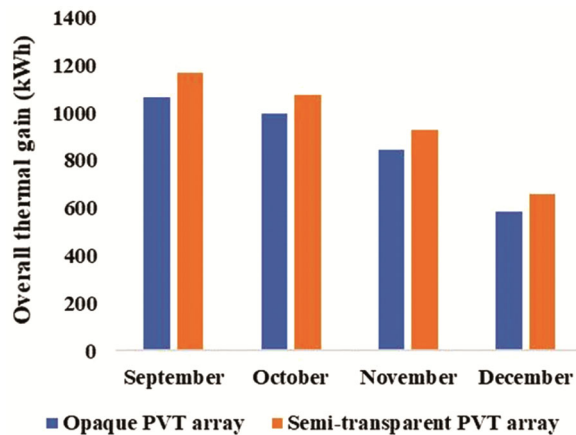


Fig. 6 — Variation in overall thermal gain.

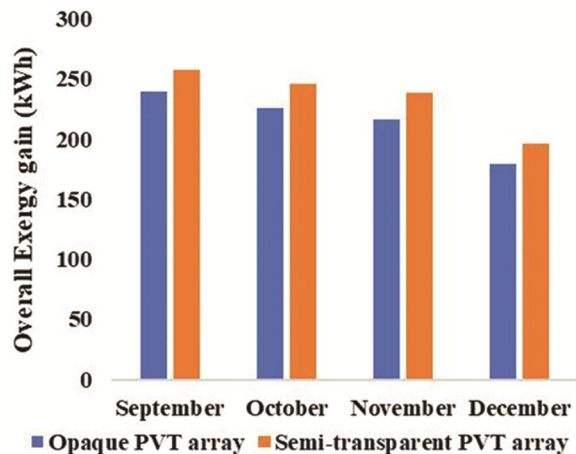


Fig. 7 — Variation in overall exergy gain.

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 CO₂ 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 CO₂ which has resulted in an increase of CO₂ 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 CO₂ mitigation resulting in a higher environmental cost on both the basis of investigation.
- The enviroeconomic analysis enables the comparison of price with respect to CO₂ 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.

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