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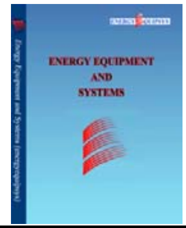

Significant factors for enhancing the life cycle assessment of photovoltaic thermal air collector

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ABSTRACT

Due to the rapid industrialization and development across the entire globe, there is the increasing demand for energy. However, the energy sources from fossil fuels are not abundant in every part of the world. India has to import fuel from other parts of the world which consumes a major portion of Government funds. So, currently improving solar energy technologies efficiency is one of the most promising researches in India. This study is mostly about life cycle assessment (LCA) of photovoltaic thermal (PVT) air collectors. All the important parameters like Energy payback time (EPBT), Energy production factors (EPF), Lifecycle conversion efficiency (LCCE), Embodied energy, Life cycle cost assessment (LCCA) and carbon emissions are investigated in this study as well. The role of these parameters in the LCA study is depicted in this study since LCA greatly impacts the effectiveness and cost of PVT air collector. Results revealed that the EPBT, GPBT, EPF, and LCCE are in the range of 0.8 to 14 years, 1 to 4 years, 0.4 to 22, and 0.10 to 2.86.

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1. Introduction

Development and energy are closely linked. The global energy demand is rapidly increasing with population fast growth, urbanization, and modernization. In the present scenario, the 32.94% of primary consumption of energy is supplied by oil, 29.20% by coal, 28.85 % by gas, 6.79% by hydro, 4.4 % by nuclear, 1.44% by wind while only 0.45 % are supplied by solar [1]. So, in order to increase the share of solar energy, a maximum focus is required. With the changes in the price of the fossil fuels and various other factors such as transportation, shortage of fossil fuel, greenhouse gas emission, the renewable energy demand is gaining attention day by day [3].

Solar energy has great potential as renewable energy can meet the growing demands of energy. The photovoltaic (PV) solar cell is a device that converts solar energy into electricity [4]. PV solar cells are mostly made up of silicon and non-silicon materials like monocrystalline, polycrystalline, cadmium telluride, copper indium gallium selenide, etc. [5]. The PV solar cell starts producing electricity when it is exposed to solar radiation. However, due to continuous heating of solar cell, its ability

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to produce electricity degrades and a large amount of heat gets accumulated at the back surface of the PV panel. Only 15-20% of solar radiation falling on PV cells is converted to electricity, and the rest is change to heat [8]. In Photovoltaic Thermal (PVT) air collector the heat from the back surface of the PV Panel is being collected. This heat can be used for several practical applications such as space heating, food drying, and consequently cooling the PV modules to enhance the efficiency of PVT air collector. However, this technology is not new (started in the 1970s) and by continual development, the technology is advanced for power generation [7]. The objective of harnessing energy effectively led to investigate the LCA study of PVT air collector.

A detailed classification of PVT air collector is shown in Fig.1. PVT air collectors are mainly classified depending on the flow above, below or both side of the absorber plate in a single or double pass flow, PVT with a concentrator and with energy storage has also been attempted in few of the earlier studies. A schematic diagram of the PVT air type collector is shown in Fig. 2(a) and Fig. 2(b). The main components are duct with inlet and outlet, absorber plate, PV cells, tedlar, and insulation. A duct is used to drive the flow of air beneath the PV module and above the absorber plate. PV module is supported with a tedlar. Low-temperature air from the environment enters through the inlet port and after absorbing heat from both tedlar, and the absorber plate come out through the outlet as hot air. The main advantage of using PVT air collectors over PVT water collector as a heat carrier is that there is less corrosion, no leakage, low weight, and easy installation [10]. Further, since the output air temperature is comparatively low, the hot air has got low-temperature application in different fields likes: drying of crops, space heating, etc.

LCA is a methodology for the assessment of the environmental impact of a product or service over its whole life cycle. Depending on the scope of the assessment, this may include all processes from the extraction of raw materials to the recycling or disposal [7]. With a view to assess and quantify the parameters like energy payback time (EPBT), energy production factor (EPF), life cycle conversion efficiency (LCCE), greenhouse gas emission, greenhouse gas payback time (GPBT) and life-cycle cost assessment (LCCA), various authors have conducted LCA study by employing the experimental and analytical work. In this paper, various studies on the PVT air collector to enhance the thermal efficiency, energy and exergy of the PVT system are addressed. However, the main focus of this paper is to study the various energy matrices of LCA of PVT air collectors like EPBT, EPF, LCCE, Greenhouse gas emission, GPBT, Annualized uniform cost (AUC) and LCCA. Also, in the present study, every energy matrices are discussed separately, and at the end, the trend of energy matrices last few decades is highlighted. The

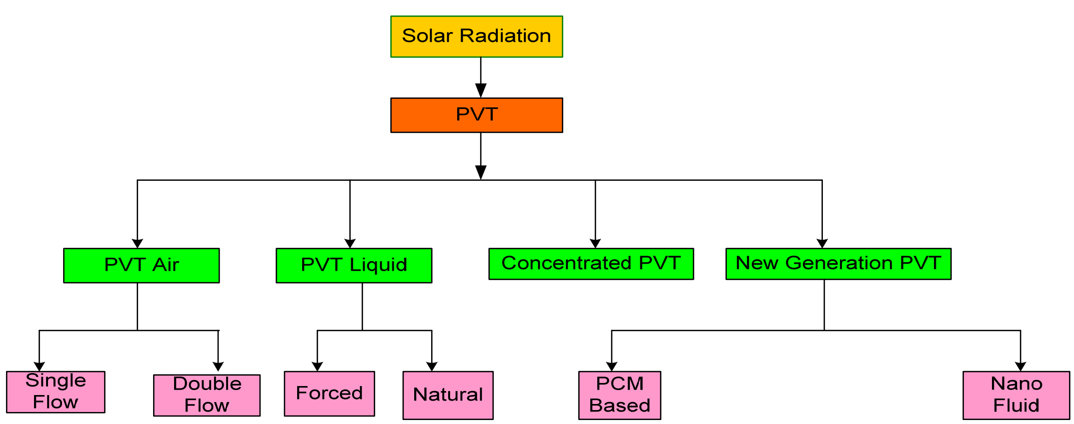

Fig.1. Classification of PVT system [4]

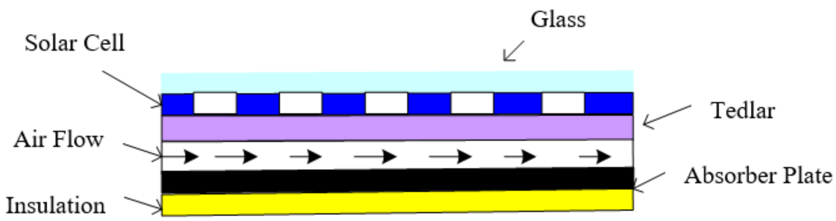

Fig. 2(a). The cross-sectional view of a conventional PVT air collector [4]

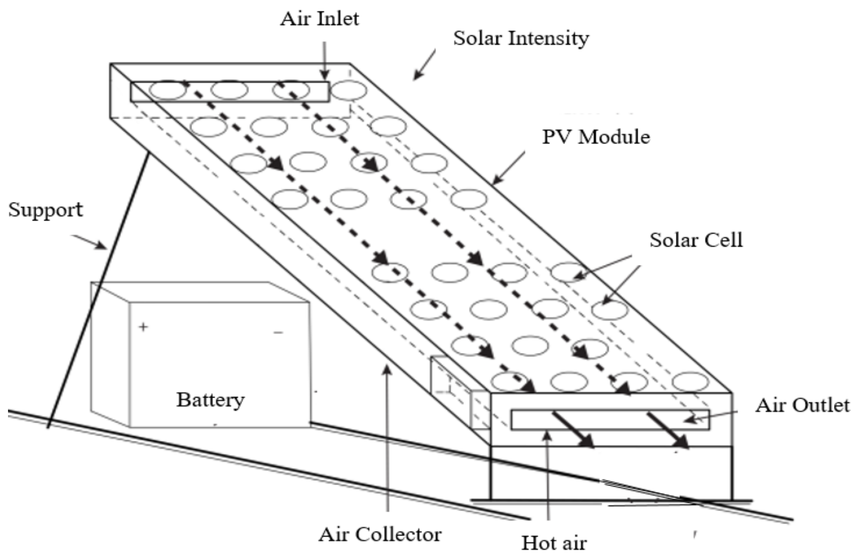

Fig. 2(b). Schematic diagram of the PVT air collector [4]

main advantage of using PVT air collectors over collector using water as a heat carrier is that there is less corrosion, no leakage, low weight, and easy installation [10].

Nomenclature

PV	Photovoltaic
PVT	Photovoltaic thermal
HPVT	Hybrid photovoltaic thermal
BIPVT	Building integrated photovoltaic thermal
BAPVT	Building added photovoltaic thermal
a-si	Amorphous silicon
mc-si	Multi-crystalline silicon
nc-si	nanocrystalline silicon
CdTe	Cadmium Telluride
CIGS	Copper indium gallium selenide
EPBT	Energy payback time
EPF	Energy production factor
LCCE	Life cycle conversion efficiency
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
$CO2_{eq}$	Carbon dioxide equivalent
tCO_2	Tons of carbon dioxide
kWh	kilowatt hour
Cu	Copper
Al	Aluminum
SAC	Solar air collector
SHS	Solar home system
EAHE	Earth air heat exchanger
RE	Renewable energy
SAPV	Stand-alone photovoltaic
ZEB	Zero energy building
GHGE	Greenhouse gas emission
T_a	Temperature of ambient air (k)
T_i	Inlet air temperature (k)
T_o	Outlet air temperature (k)
I(t)	Solar intensity (w/m^2)
B	The breadth of PV panel (m)
L	Length of the module (m)
$\dot{Q}$	Useful thermal energy (kWh)
T	Temperature (K)
t	Time (s)
n	Number of days

m_{ai}	Mass flow rate of air (kg/s)
C_{ai}	Specific heat of air (J/kg K)
U_L	The overall coefficient of heat transfer from PV cell to ambient (W/m^2 K)
h_{p1}	Penalty factor because of tedlar of PV panel
h_{p2}	Penalty factor because of interface present in between air and tedlar
E	Energy (kWh)
$\dot{E}$	Annual exergy output (kWh)
i	Interest rate per year
m	Years

Greek letters

η	Efficiency
β_r	Temperature coefficient at reference cell temperature
$(\tau\alpha)_{eff}$	Effective product of transitivity and absorptivity
χ	Energy production factor
$\O$	Life cycle conversion efficiency
ϕ	CO_2 mitigation per annum (t CO_2)
φ_{avgCO_2}	Average CO_2 equivalent intensity for electricity generation from coal

Subscript

th	Thermal
c	Solar cell
p	Plate
r	Reference
enin	Input energy (kWh)
enout	Output energy (kWh)
anoverall	Annual overall energy (kWh)

2. Life cycle assessments of Photovoltaic thermal air collector

There are important parameters which must be considered in LCA of PVT systems. Although the manufacturing of PV module, balance of system, installation, transportation disposal of system and recycling during the entire life cycle of the PVT system consumes a small amount of energy but it is one of the most important tools to analyze the overall efficiency and environmental impact of the system [11].

2.1. Thermal Efficiency

The thermal efficiency of the PVT air collector is defined as the ratio of the total useful heat collected by the collector to the total amount of solar intensity striking the collector surface during a specific period of time. Thermal efficiency is an important parameter to evaluate, how well the incident solar radiation to PVT air collector is converted into useful heat that can be used for various application like space heating, drying of products, etc.

The thermal efficiency(η_{th}) of PVT air collector is given by [26].

$$\eta_{th} = \frac{\sum_i^N \dot{Q}}{\sum_i^N I(t)\times B\times L}, \tag{1}$$

where N represents time in hour, $\dot{Q}$ is the useful thermal energy gained from the system in kWh, B and L are the breadth and length of PV module in meters (m) and I(t) is the incident solar intensity in W/m^2.

$$\eta_{overallth} = \eta_{th} + \frac{\eta_{electical}}{\eta_{cp}}, \tag{2}$$

where the range of η_{cp} lies in between 0.20 to 0.40 depending on the quality of coal and $\eta_{electical}$ is the electrical efficiency of the PV panel.

$\eta_{electical}$ can be expressed as [28]

$$\eta_{electical} = \eta_r \times [1\text{-}\beta_r(T_c - T_r)], \tag{3}$$

where, η_r is known as reference efficiency obtained at standard condition and β_r is known as the reference temperature coefficient which has a value of 0.00045/K for silicon cells, T_c is the reference temperature at a reference condition and, T_c is the operating temperature of the module in Kelvin (K).

Solanki et al. (2009) assessed the thermal efficiency of the PVT air collector with different mass flow rate. The set up consisted of three monocrystalline silicon, glasses to tedlar type PV modules. Thermal efficiency was found as 42%, whereas overall efficiency was found as 50% from the experiment. Othman et al. (2009) designed a hybrid photovoltaic-thermal solar collector and placed a del-grooved absorber plate in the air channel, which has the merit of producing heat and electricity simultaneously and compares its efficiency with that of hybrid photovoltaic thermal (HPVT) air collector without del grooved absorber plate. The result of the study shows that due to a del-grooved absorber plate, thermal efficiency enhances by 30 %. Tiwari et al. (2006) investigated the performance of PVT air collector integrated with air duct installed on the 6th floor of a building at the Indian Institute of Technology Delhi in India. The overall efficiency of the system was assessed by analytical expression by using the energy balance equation of each component in the PVT set up, and the obtained result was also validated experimentally. The results suggest that the overall efficiency of the system increases due to the reduction of the back surface temperature of the PV panel. Moreover, the thermal efficiency was found as 58.87%.

Tiwari and Sodha (2007) conducted a parametric study to the performance of HPVT air collector with and without tedlar. They concluded that the thermal properties of configuration without tedlar were found superior to the configuration with tedlar. Tripanagnostopoulos et al. (2002) performed an experimental test on PVT air collector of various configurations at the University of Patra, Greece. The PVT air collector was placed in a parallel row and kept at an adjustable spacing to avoid shading.

Further, adjustable diffuse reflectors were used to receive better radiation to collector surfaces. The thermal efficiency obtained was 69% depending on whether the reflectors were placed. Sarhaddi et al. (2010) performed a numerical simulation on PVT air collector by incorporating some changes on heat loss coefficient to improve the thermal properties of the PVT collector and compare the result with experimental studies. The study concluded that the thermal efficiency of the PVT air collector was found as 17.18%. Zakharchenko et al. (2004) made a theoretical and experimental analysis of hybrid PV-thermal system (unglazed type) in which the PV panel area was less than the solar collector. This research mainly contradicted the assumption that for higher thermal efficiency, the area of the PV panel and solar collector needs to be the same. Hegazy (2000) investigated PVT air collector with four configurations by solving the heat balance equation numerically. The flow of air over and below the absorber plates were two configurations whereas the flow of air on both the side of the absorber plate either in a single pass or double pass were the other two configurations. It was concluded from the study that the air flowing at the top of the absorber plate yields the highest overall efficiency of 55% with a mass flow rate of 0.04 kg/s. Salem et al. (2017) conducted a study on PVT collector with straight channels aluminum cooling plate in the climatic condition of Cairo, Egypt and compared the results with PVT air collector without a cooling plate. The outcomes show that the thermal efficiency rises from 31.6% to 47.2% due to straight channels mounted on the aluminum plate.

Nahar et al. (2017) set up an experimental model of PVT air collector in which the absorber plate was excluded. The study concluded that the thermal efficiency of PVT air collector with and without absorber plate were the same (80%). These results were validated with numerical study (84.4%). Agrawal and Tiwari (2010a) developed one dimensional transient building integrated photovoltaic thermal (BIPVT) model with four different configurations, namely:

case 1: All six rows of the BIPVT air collector were connected in parallel,

case 2: Three rows of the BIPVT air collector were connected in parallel and each having two rows in series,

case 3: Two rows of the BIPVT air collector were connected in parallel each having three rows in series and case 4: All the rows of the BIPVT air collector were connected in series.

The study concluded that the fourth case yields higher thermal efficiency equals to 53.7%. Mortezapour et al. (2012) conducted an analytical and experimental study to compare glass to glass and glass to tedlar PVT solar air collector in the city of Qaen in Iran. Glass to glass PVT solar air collector (SAC) has a higher outlet air temperature, cell temperature and thermal efficiency in comparison to glass to tedlar, due to higher absorption of solar energy through the black color absorber of glass to glass. Glass to tedlar PVT solar air collector has a higher back surface temperature and electrical efficiency because of thermal conduction in the solar cell from the back surface to tedlar. The maximum experimental electrical efficiency, thermal efficiency and overall efficiency for the glass to tedlar PV module were found as 10.35%, 57.9% and 84.5%, respectively. Zondag et al. (2002) developed an experimental prototype with a conventional sheet and thermal tube collector called combipanel PVT air collector. The thermal and electrical efficiencies for combipanel PVT air collector were found as 33% and 6.7 %. Yang and Athienitis (2014) developed an open loop air based building integrated BIPVT air collector with a single inlet and multiple inlet system. The thermal efficiency enhanced by 5% with two inlet system in comparison with single inlet system. The thermal efficiency enhanced by 10% because of additional wire mash packing in the collector. Joshi et al. (2009) evaluated the performance of PVT air collector with two PV modules glass to glass and glass to tedlar type and validated experimentally for the climatic condition of New Delhi, India. The study showed that in glass to glass PV module, the thermal efficiency initially increased and then decreased after attaining an optimum velocity of air through the duct, which was 3.2 m/s in this case. Kim and Kim (2012) conducted a study with glazed and unglazed PVT collector and concluded that glazed type collector has higher overall efficiency than the unglazed one. Kim et al. (2014) conducted an experimental analysis on air collector integrated with m-si PV module. The system was composed of 250 W of m-si PV module with 1.6 m^2 surface area. It was found from the study that an average of 15 % electrical and 22% thermal efficiency was obtained under outdoor test conditions. Singh et al. (2015) optimized the performance of PVT air collector by genetic algorithm. Parameters like the depth of duct and length, inlet air velocity, the thickness of tedlar and glass were optimized using the algorithm. The study showed an improvement of 13.14% and 4.6% in overall thermal and exergy efficiency. Kabeel et al. (2016) compared the performance of v-grooved and fined integrated photovoltaic thermal solar air collector (PVTSAC) experimentally and concluded that v-grooved has a better thermal advantage over flat PVTSAC due to better thermal contact between air flow and the absorber plate which enable better rate of heat transfer. Abuska et al. (2016) designed a PVTSAC with absorber plate integrated with a conical spring and compared its performance with the flat absorber plate. With a mass flow rate of 0.06 kg/s, the thermal efficiency of the absorber plate mounted with conical spring was 65.9% in comparison with 50.4 % for the flat absorber plate. Mojumder et al. (2016) investigated the performance of PVT air collector integrated with one to four numbers of fins. The study concluded that the increase of fins increases thermal efficiency. Haloui et al. (2016) conducted a study on PVT collector with CdTe PV module and compared its thermal efficiency with m-si PV module. The outcome showed that the overall efficiency of the PVT collector with CdTe module was higher than the PVT collector with m-si. Ooshaksaraei et al. (2017) compared the performance of single and double path flow design of air collector and concluded that the single path flow has higher electrical efficiency whereas thermal gain was superior in double path configuration. Slimani et al. (2017) investigated on double pass, conventional and glazed HPVT configuration on the climatic condition of Algiers, Algeria. The numerical investigation suggested that the daily thermal efficiency of conventional HPVT, glazed HPVT and double pass HPVT were 51.02%, 69.47% and 74% which shows that double pass has highest thermal advantage due to more thermal contact between the heat carrier and absorber plate. Ayaz et al. (2017) numerically simulated the tilt angle of the PV panel for the climatic condition of Burdur, Turkey, with MATLAB/Simulink to find the maximum energy generated by the panels. Results showed that 13, 9, 17, and 12 degrees were best-suited tilt angle during spring, summer, fall, and winter. Nahar et al. (2017) defined a model with pancake type collector just below the PV panel of PVT collector. They used COMSOL Multiphysics® analysis software for numerical study. It was concluded that power output increased by 2% due to the pancake type collector. Ahmed et al. (2017) conducted a computational study on PVT collectors by employing a phase change material (PCM) between the fins. Results revealed that PCM enhanced the electrical efficiency of the PV panel with an average value of 0.5 % during the period of maximum solar intensity for the day due to absorption of the appropriate amount of heat from PV panel which ultimately leads to cooling of PV panel.

Much research is conducted to enhance the thermal efficiency of the PVT air collector that can be understood from Fig. 3 which gives an impression that a continuous effort is made to increase the thermal performance of the PVT air collector, however, there is a significant variation on the values of thermal efficiency among included papers, and reasons for such discrepancy are the design methodology, locations and operating conditions that are different for various experiments. However, the air has low heat extraction capacity, and also more amount of electrical energy is required to have a higher mass flow rate of air to extract more amount of heat in order to cool the PV module. These are some drawback that prevents the adoption of PVT air collector from gaining much attention globally.

The factors by which the thermal efficiency of the PVT air collector can be enhanced as summarized from the above discussions are as follow:

- Modifying the design of absorber plate collector area, depth of duct, etc.
- Flowing the air above the absorber plate instead of below the absorber plate.
- Selection of the proper location where the system is completely exposed to solar radiation is also one of the important criteria.

2.2. Energy and Exergy Generation

Whenever, a solar ray contacts in the PV panel, it starts producing electricity, but at the same time, some extra heat is accumulated in the back surface of the PV panel due to continuous exposure of PV panel to the solar radiation. This heat that can be extracted from the back surface of the PV panel with the help of air collector is known as thermal energy. The importance of thermal energy extraction is that the cost of energy production per unit in a combination of electrical energy is economical than if the PV panel is only used for electricity production. The monthly useful thermal energy($Q_{monthly}$) obtained from the PVT collector can be expressed as [44]

$$Q_{monthly} = \frac{\sum_{i=1}^{n} \dot{Q} t_0}{1000} \text{ in kWh,} \tag{4}$$

where (5)

$$\dot{Q} = \frac{m_{ai} C_{ai}}{U_L} \left\{ h_{p1} h_{p2} (\tau\alpha)_{eff} I(t) - U_L (T_i - T_a) \right\} \times \left[1 - e^{\left(-\frac{-BU_L}{m_a c_a} \right) L} \right]$$

and

$\dot{Q}$ is the rate of usable thermal energy that can be achieve from the PVT air collector, m_{ai} is the mass flow rate of air in kg/s, C_{ai} is the specific heat of air in J/kg K, h_{p1} and h_{p2} are the penalty factor because of tedlar of PV panel and the interface present in

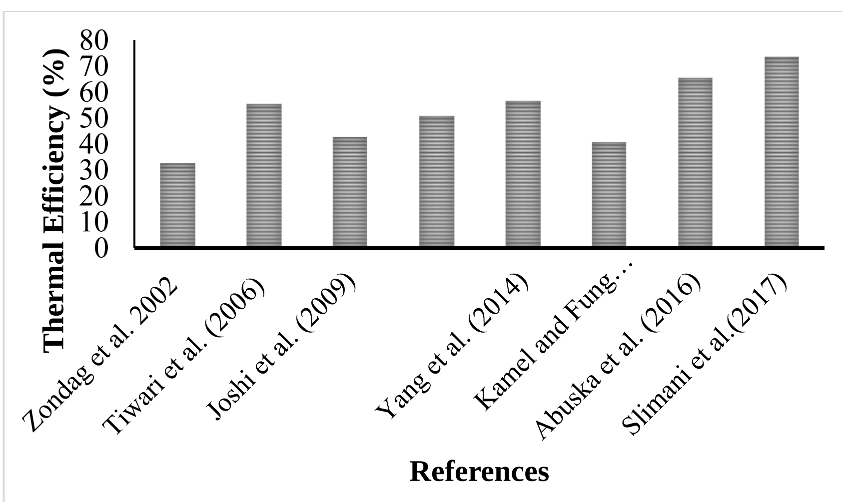

Fig. 3. Thermal efficiency of selected papers in 15 years

between air and tedlar, $\tau\alpha_{eff}$ is effective product of transitivity and absorptivity. U_L is the overall coefficient of heat transfer from PV cell to ambient in W/m^2 K, T_i and T_a is the inlet and ambient temperature of the air in kelvin (K).

Coventry (2003) defined exergy as the maximum useful theoretical work that can be achieved from the system when it returns to the equilibrium with the surroundings. The importance of exergy approach is that it provides a coherent value for various forms of energy such as heat, work, and electrical energy, etc.The annual exergy ($\dot{E}$) can be expressed as Bosonac et al. (2003)

$$\dot{E}= \dot{Q}\left[1-\frac{T_a+273}{T_o+273}\right] \text{ in kWh,} \tag{6}$$

where T_o is the outlet air temperature of PVT air collector in Kelvin (K)

Agrawal and Tiwari (2012) conducted an experimental study on glazed HPVT air collector in the climate of New Delhi, India. The HPVT consisted of three PV modules (monocrystalline) of glass to tedlar type with an effective area of 0.610 m^2. The annual overall energy and exergy generated were 1252.0 kWh and 289.5 kWh, respectively. Raman and Tiwari (2008) calculated the thermal energy and exergy generated by HPVT air collector for four Indian cities, namely Srinagar, Mumbai, Jodhpur and New Delhi with and without the balance of system (BOS). With BOS system, the calculated values of thermal energy were 625.99 kWh, 584.68 kWh, 649.34 kWh and 567.96 kWh for Srinagar, Mumbai, Jodhpur and New Delhi respectively and the exergy were152.8 kWh, 139.3 kWh, 157.22 kWh and 151.3 kWh for those cities. Jodhpur has the highest value for thermal energy and exergy because of high intensity of solar radiation. Prabhakant and Tiwari (2008) studied the effect of the carbon credit from hybrid photovoltaic thermal air collector HPVTAC located in solar energy park of Indian Institute of Technology Delhi, India. The HPVTAC system consists of two PV modules (effective area 0.605 m^2) with two wooden ducts in which two DC fan are fitted to suck the hot air from the lower surface of the PV modules for boosting the efficiency of PV modules. The result of the study suggested that the annual thermal energy and exergy obtained from the system were106.5 MWh and 2.692 MWh. Nayak and Tiwari (2009) analyzed the effectiveness of greenhouse with PVT air collector in the climatic condition of New Delhi, India during daytime and with earth air heat exchanger(EAHE) during the night. The temperatures of the greenhouse air in a day and night were compared. The system produces the energy and exergy of 24728.8 kWh and 1006.2 kWh annually during day and night, respectively.

Agrawal and Tiwari (2010) developed one dimensional transient BIPVT model with four different configurations , namely case 1: All six rows of the BIPVT air collector were connected in parallel, case 2: Three rows of the BIPVT air collector were connected in parallel each having two rows in series, case 3: Two rows of the BIPVT air collector were connected in parallel each having three rows in series and case 4: All the rows of the BIPVT air collector were connected in series at New Delhi, India. The study concluded that the fourth case had generated higher electrical, thermal energy and exergy.

Kamthania et al. (2011a) numerically calculated the performance of the double pass HPVT air collector system and compared with the single pass HPVT air collector for the climatic condition of Mumbai, India. The annual thermal energy and exergy of 2915.47 kWh and 818.61 kWh were obtained from double pass HPVT air collector whereas, 2463.72 kWh and 716.52 kWh were obtained from single-pass HPVT air collector. This shows that the double pass air collector has better thermal performance than single pass air collector due to higher heat extraction.

Rajoria et al. (2012) conducted a study on the climatic conditions of four cities of India (Bangalore, Jodhpur, Delhi and Srinagar) with four different configurations, namely case-1: four columns where each column having nine PV modules connected in series are in parallel connection , case-2: nine rows where each row having four PV modules connected in series, are in parallel connection, case-3: two integrated columns where each columns having eighteen PV modules connected in series are in parallel connection and case-4: three integrated rows where each row having twelve PV modules connected in series are in parallel connection. Out of the considered cases, the case-3, served the best purposed experimental setup as they produced the highest exergy than the other three cases. Bangalore has the annual thermal energy and exergy of 45400 kWh and 2700 kWh which were higher than the other cities due to maximum number of clear days coupled with maximum value of solar intensity.

Agrawal and Tiwari (2013) conducted a comparative analysis for three different types of HPVT air collectors in the climatic condition of New Delhi, India, namely glazed hybrid PVT tiles, unglazed hybrid PVT tiles and conventional HPVT air collectors and it was observed that the thermal energy and exergy for unglazed hybrid PVT tiles were higher by 27% and 29.3% by glazed hybrid PVT tiles and 61% and 59.8% higher by conventional HPVT air collectors, respectively. Rajoria et al. (2013) experimentally analyzed the generated energy and exergy for HPVT air collector with two different configuration, namely case-1: two numbers of integrated columns where each having eighteen PVT modules connected in series are in parallel connection and case-2: two numbers of integrated columns of eighteen modules where each having thirty six PVT tiles in the module is connected in series connection, for Delhi, Jodhpur, Bangalore and Srinagar in India.

The overall thermal energy gain collectively for Delhi, Jodhpur, Bangalore and Srinagar for case-2 was found as 18040.74 kWh and for case-1, it was 16345.91 kWh which shows that case-2 has highest thermal energy gain due to the fact that the design of the case-2 provides superior retention time for the air to carry the accumulated heat away from the system through outlet. Brideau and Collins (2014) studied the PVT air collector in the climatic condition of Waterloo, Canada, and made a comparison between impinging and parallel g jets of air. The results of the study show that for the same flow rate and channel depth, the heat transfer coefficient of the impinging jet was better than a parallel jet. Farshchimonfared et al. (2015) investigated an air distribution system for the residential building in the climatic condition of Sydney, Australia for optimizing the collector area and mass flow rate of PVT air collector to maximize the thermal energy generation. The optimum values of depth of duct were in the range of 0.09-0.026 m, whereas optimum mass flow rate of air per unit area of the collector was 0.021 kg/s m^2 as found from the study.

Pauly et al. (2016) designed a HPVT air collector in which the inlet has larger area than the outlet and compared the result with the literature by means of numerical investigation and concluded that the novel design has 20% enhancement of overall thermal performance than the system with the same inlet and outlet area due to more amount of thermal energy extraction from the outlet. Yang et al. (2015) analyzed PVT air collector with one and two inlet configurations at Concordia University, Canada. The system consisted of two PV modules, and the second inlet was provided in between them. It was observed that two inlet configuration improves the thermal efficiency by 5% than one inlet configuration as the second inlet allows the ambient air to enter inside the duct and mixes with air that has entered through the first inlet and enhances the outlet air temperature due to the enhancement of heat transfer rate. Dimri et al. (2017) proposed a design where the thermoelectric cooler was integrated with PVT collector and compared its performance with the semitransparent PVT collector on the climatic condition of New Delhi, India. It was found that the thermoelectric cooler with PVT collector has generated 4.723% higher electrical energy than semitransparent PVT collector due to more amount of thermal energy extraction by PVT air collector with thermoelectric cooler than semitransparent PVT air collector and hence the solar cell temperature of the PVT air collector with thermoelectric cooler cools faster than semitransparent PVT air collector. Khaki et al. (2017) optimized the mass flow rate of BIPVT air collector in the climatic condition of Kermanshah, Iran by genetic algorithm, by varying the collectors' areas as 10, 15, 25 and 30 m^2, and length to width ratio as 0.5, 1, 1.5, and 2 m to assessed the optimum mass flow rate for the system to yield maximum thermal energy and exergy. It was concluded that for collector's areas of 10, 15, 25 and 30 m^2 BIPVT air collector yielded 0.815 kWh, 16.224 kWh, 27.04 kWh and 32.44 kWh of overall annual energy. Mojumder et al. (2017) designed and experimentally analyzed the PVT air system in indoor conditions with the help of solar simulator with fins and without it. Because of rectangular fins, the heat transfer rate increases by 18.39%, which leads to the cooling of the PV cell temperature.

PVT air collector will be more economical if the thermal energy and exergy are achievable to a greater extent [5]. By considering various studies, it can be stated that to obtain maximum energy generation; the following parameters must be carefully considered:

- A proper location.
- PV cell materials selection.
- Optimization of duct depth packing factor and mass flow rate.
- Proper insulation of the system.

Further, it is found that the connecting number of PVT air collector in series configuration also leads to a higher thermal energy [48].

2.3. Energy Pay Back Time (EPBT)

Energy payback time is defined as the ratio of the total spent energy in the manufacturing of each component, fabrication and installation to the total output energy received from the PVT air collector. It is a measure by the time required by the system to recover the spent energy on manufacturing the system. It is defined as the ratio of input energy to output energy [27]

$$\text{EPBT} = \frac{E_{enin}}{E_{enout}} \text{ in years} \quad (7)$$

where E_{enin} and E_{enout} are the input and output energy in kWh of PVT air collector.

Crawford et al. (2006) conducted a life-cycle energy analysis of conventional c-si BIPV system and two BIPVT air collector integrated with a c-si and a-si solar cell. Results suggested the energy payback time for the above mentioned three installations were in the range of 12–16.5 years, 4–9 years, and 6–14 years, respectively. Also, with two BIPVT air collector installations, there was a 50% reduction of EPBT. Tripanagnostopoulos et al. (2006) conducted a study on the HPVT air collector to assess the economic viability of the system at the University of Patras, Greece. The study performed on different PVT air collector like glazed, unglazed PVT air collector and with a flat metallic sheet (TFMS) inside the setup along the path of air flow placed at the rooftop of the building. The results showed that PVT/Glazed type system has the lowest environmental impact whereas PVT/TFMS has more advantages from an economic aspect as presence of flat metallic sheet enhances the heat transfer rate which leads to higher extraction of thermal energy. The value of EPBT for 12-month air heating system was found as 1 year. Raman and Tiwari (2008) calculated the EPBT of HPVT air collector in four Indian cities, namely Srinagar, Mumbai, Jodhpur and New Delhi with and without BOS. With the BOS system the calculated values of EPBT were 2.42, 2.59, 2.34 and 2.90 in years for Srinagar, Mumbai, Jodhpur and New Delhi, respectively and without BOS were 1.78, 1.91, 1.72 and 2.14 years for these cities which suggested that Jodhpur has the lowest value of EPBT as intensity of solar radiation is highest than Srinagar, Mumbai and New Delhi. Tiwari et al. (2009) experimentally evaluated the EPBT of hybrid PVT air collector with and without BOS. PV module was made of monocrystalline silicon. It was observed that the value of EPBT with BOS was 1.59 years and without BOS was 1.16 years.

Kumar and Tiwari (2009) performed an LCA of single slope passive solar still and PVT active solar stills in a solar energy park of Indian Institute of Technology Delhi, India. The EPBT was found as 2.9 years and 4.7 years for passive and active PVT solar stills. Nayak et al. (2012) developed a dryer integrated with PVT air collector with DC fan for drying of agricultural product. They conducted a techno-economical analysis of the system to calculate the EPBT of the system. The results showed that EPBT was 5.6 years, which was much less than the expected lifespan of the dryer. Agrawal and Tiwari (2013a) conducted an enviro-economic analysis for HPVT air collectors in the climate of New Delhi, India. It was observed that the values of EPBT were 1.7 years and 7.8 years for energy and exergy. Nayak et al. (2014) evaluated the annual energy and exergy performance of a hybrid PVT air collector (New Delhi, India) by adopting several silicon and non-silicon-based PV modules. EPBT values in terms of thermal energy production for c-si, mc-si, nc-si, a-si, CdTe and CIGS were 2.12, 2.05, 1.97, 2.01, 1.91, and 1.66 in years and EPBT for exergy gain was 21.45, 23.64, 24.55, 34.48, 28.95 and 17.26 years. Kamthania and Tiwari (2014) evaluated the EPBT of m-si, a-si, p-si, and CdTe system for semi-transparent PVT double pass facades system in India. It was found that the EPBT for m-si, a-si, p-si and CdTe system were 2.30, 1.57, 1.92, and 1.34 years, respectively, for thermal energy and 8.85, 7.09, 7.36, and 5.29 years, respectively, for exergy. Chauhan et al. (2015) conducted an experimental work on hypothetical PVT air collector where a duct made of glass was provided above the PV module, and the experiment was performed on all the four cities, namely Bangalore, New Delhi, Jodhpur and Srinagar in India for a lifespan of 20, 30 and 40 years based on thermal energy and exergy.

The highest and lowest value of EPBT were found for Srinagar and Bangalore for thermal energy and exergy production, for all lifespans. Agrawal and Tiwari (2015) conducted a study on EPBT based on the effect of carbon credit for the lifespan of 30 years. For the PVT air collector, the EPBT for thermal energy and exergy were 1.8 and 7.8 years for 30 years lifespan. Rajoria et al. (2016) performed an LCA on three cases, namely case-1: opaque type PVT array, case-2: solar cell tile (SCT) array and case-3: semitransparent array by including an approach of cash flow to investigate the effect of EPBT time on LCA. It was found from the study that the minimum value of EPBT for energy and exergy were found as 0.70 and 1.84 years for case-3 and the maximum were found as 0.84 and 2.17 years for case-1, respectively. Angrisani et al. (2016) analyzed the performance of the solar assisted air conditioning device with the desiccant wheel installed in the two separate locations of Italy (Benevento and Milan). The variation of the collector area and tilt angle were studied. The EPBT for the system were found as 8 years and 6 years for Milan and Benevent, respectively. Abuska et al. (2017) performed an experimental analysis of PVTSAC with protrusions made up of Copper and Aluminum in v-grooved shaped. The EPBT were resulted in between 4.3 and 4.6 years on a yearly basis.

Figure 4 shows that the EPBT time reduced significantly in between the years, 2005 to 2016 due to continuous effort made in the advancement of technology, however, there is a significant variation on the values of EPBT among included papers, and reasons for such discrepancy are the type of solar cell used, system configurations and the most important factor are the location and operating conditions that are different for different cities and countries. However, the following conclusions can also be drawn from the above discussions:

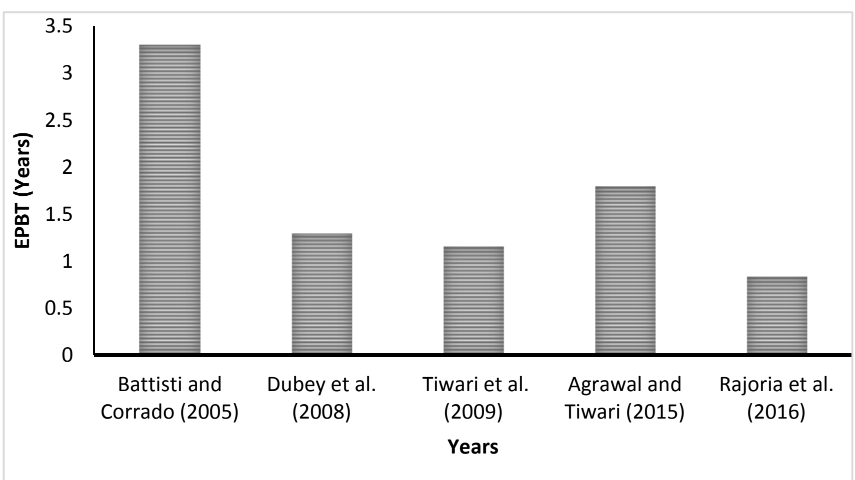

Fig. 4. Energy payback time during the last decade

- EPBT depends on how and where the system is produced.
- EPBT depends on the performance of the system on the basis of energy and exergy gain.
- To make the PVT system, operational EPBT needs to higher than the expected lifespan of the system. In general EPBT of PVT varies in the range of 1.4 to 34.1 years.

The importance of EPBT gives a measurement for the time required by the system to recover the spent energy on manufacturing the system. Though the EPBT should be as low as possible, and this can be happened by well-performing energy efficient PVT air collector. EPBT of silicon (c-si, mc-si,nc-si and a-si) and nonsilicon (CdTe and CIGS) type solar cell are depicted in Table 1. It is observed that the values of energy payback time are lower for non-silicon solar cell.

2.4. Embodied Energy

The embodied energy defined as the energy, which is associated with the production process, constituting even a small relative proportion, absorbs in all activities of material or component manufacturing. This energy also includes the energy consumed in the installation and maintenance of each component [53]. The embodied energy can be estimated for each component by multiplying the energy density of a particular component with the total weight of that component. It is measured in terms of kWh. The detailed values of embodied energy for various components used in the construction of Hybrid PVT air collector (glazed type) was given by Agrawal and Tiwari (2012) while the primary energy consumption for processing of ribbon, multi and mono-crystalline silicon used in PV module was given by Alsema and de Wild-Scholten (2005). A similar study was performed by Barnwal and Tiwari (2008), where a detailed value for processing of various grades of crystalline silicon was presented. The breakup values of the embodied energy are tabulated in Table 2.

The concept of embodied energy can be further understood by the results of EPBT as it is defined as the ratio of total energy consumed in the production and installation of the system to the total energy available at the output [95]. It was observed that the EPBT was lower when the experiment was performed by Raman and Tiwari (2008) without BOS. Because the BOS system mainly consisted of high energy density materials. It is observed that the high input energy components increase the EPBT as most of the studies used mild steel as a support structure. It is also found from the study that embodied energy can be correlated to the functional unit for the characteristics and performance of the system or the product, to ensure the results of different studies are compared.

2.5. Energy Production Factor (EPF)

EPF (χ) measure the performance of the PVT air collector, and it can be defined as the ratio of output energy to input energy [27]

$$\chi = \frac{E_{enout}}{E_{enin}}. \tag{8}$$

The above equation gives EPF on an annual basis.

Raman and Tiwari (2008) calculated the EPF of HPVT air collector for four Indian cities, namely Srinagar, Mumbai, Jodhpur and New Delhi with and without BOS.

Table 1. The energy payback time for different solar cell [75]

Silicon and Non-Silicon Solar Cell	EPBT (Years)
c-Si	2.12
mc-Si	2.05
Nc-Si	1.97
a-Si	2.01
CdTe	1.91
CIGS	1.61

Table 2. The break up values of the embodied energy

Publications	Sl.No.		Components	Quantity (kg)	Energy Density of component (kW h/kg)	Total Embodied Energy(kWh)
Agrawal and Tiwari (2012)	1.		Mild Steel Structure			
		(i)	Steel angle	30	8.89	266.7
		(ii)	Screw	0.5	8.89	4.45
		(iii)	Bolt and Nut	1.5	8.89	13.33
	2.		PVC sheet	5.11	25.64	131.02
	3.		Paint	1	25.11	25.11
		(i)	Aluminum	0.390	55.28	21.56
		(ii)	Iron	0.220	8.89	1.96
		(iii)	Plastic	0.120	19.94	2.33
		(iv)	Copper wire	0.050	19.61	0.98
					Total	2260.8
Barnwal and Tiwari (2008)	1.		Purification and processing of silicon			
		(i)	Metallurgical grade silicon (MG-Si) Processed from the silicon dioxide (quartz, sand)	1		20
		(ii)	Electronic grade silicon (EG-Si) Processed from From the MG-Si	1		100
		(iii)	Czochralski Silicon (Cz-Si) Processed from the EG-Si	1		210

With BOS system, the calculated EPF values were 0.41, 0.39, 0.43 and 0.34 for Srinagar, Mumbai, Jodhpur and New Delhi and without BOS were 0.561, 0.524, 0.582 and 0.468 for these cities, respectively. Jodhpur has the highest EPBT, since it has high solar intensity. Dubey et al. (2008) studied the thermal energy and exergy of the HPVT air collector by means of energy matrices. The EPF of the system was calculated by considering the lifetime of the system as 10, 20 and 30 years. The study suggested that EPF increases with an increase in lifetime of the PVT. Tiwari et al. (2009) experimentally evaluated the EPF of HPVT air collector with and without BOS. PV module was made of monocrystalline silicon. It was observed that the value of EPF were 0.63 with BOS and 0.86 without BOS. Prabhakant and Tiwari (2009) assessed the EPF for PVT air collector integrated with stand-alone photovoltaic (SAPV) power system installed at the energy park of Indian Institute of Technology Delhi, India. For 30, 40, and 50 years of lifespan, the EPF were 11.05, 14.73 and 18.42. Agrawal and Tiwari (2013a) conducted an enviro-economic analysis for the lifespan of 20, 30, and 40 years for HPVT air collectors in New Delhi, and it was observed the value of EPF were11, 16.5, and 22 for energy generation and 2.4, 3.6, and 4.8 for exergy generation at an interest rate of 10% for the lifespan of 20, 30 and 40 years. Nayak et al. (2014) evaluated the annual thermal and exergy performance of a hybrid PVT System in New Delhi, India, by adopting several silicon and non-silicon-based PV modules. EPF in terms of thermal energy for c-si, mc-si, nc-si, a-si, CdTe and CIGS were 14.1, 14.5, 15.2, 9.8, 7.84, and 12.2 and for exergy were 1.38, 1.26, 1.22, 0.58, 0.51, and 1.15. Agrawal and Tiwari (2015) conducted a study on EPF based on the effect of carbon credit for the lifespan of 30 years and suggested that due to carbon credit earned, EPF for a PVT air collector drastically reduced. For the PVT air collector, the EPF for thermal energy and exergy were 0.55 and 0.12. Chauhan et al. (2015) conducted experimental work on hypothetical PVT air collector with a provision of duct above opaque type PV module in Bangalore, New Delhi, Jodhpur and Srinagar for the lifespan of 20, 30 and 40 years. The highest and lowest EPF were obtained for Bangalore and Srinagar in terms of thermal energy and exergy for all lifespans because of high and low solar radiation at these two places. Shyam and Tiwari (2016) performed LCA for PVT air collector connected in series with an inlet which was covered with a semi-transparent PV module. The setup consists of two PVT air collector with an area of 2 m^2 and 0.605 m^2 of both PVT air collector were covered by 75W semitransparent PV module made of monocrystalline silicon. The values of EPF were found as 26.8 and 3.90 in terms of thermal gain and exergy gain. Rajoria et al. (2016) performed LCA of three cases, namely case-1: opaque type PVT array, case-2: SCT array and case-3: semitransparent array by including an approach of cash flow to investigate the effect of EPBT on LCA. The minimum value of EPF for energy and exergy were 1.19 and 0.46 for case-1 and the maximum for case-2 with 1.42 and 0.54 for energy and exergy, respectively. Detail variations of EPF observed by previous researchers are depicted in Fig. 5. It can be concluded that:

- The EPF can be enhanced by replacing the components/material with less embodied energy.
- The EPF increases with the increase in lifespan of the PVT air collector.
- It is found that the EPF are in the range of 0.4 to 22 in terms of thermal energy gain, and 0.41 to 1.38 in terms of exergy gain.

2.6. Life Cycle Conversion Efficiency (LCCE)

LCCE (Ø) is defined as the net energy production from PVT air collectors depending on incident solar radiation, which can be expressed as [27]

$$Ø_{\text{Lifespan}} = \frac{E_{enout} \times T_{year} - E_{enin}}{E_{solar} \times T_{year}}, \quad (9)$$

where T_{year} represents the life span of PVT air collector in years.

Raman and Tiwari (2008) calculated the LCCE of HPVT air collector for four Indian cities, namely Srinagar, Mumbai, Jodhpur and New Delhi, with and without the BOS. LCCE were 0.110, 0.110, 0.111 and 0.108 for Srinagar, Mumbai, Jodhpur and New Delhi, respectively and without BOS were 0.113, 0.112, 0.113 and 0.112 for these cities. Jodhpur has the highest LCCE due to high solar radiation intensity. Dubey et al. (2008) studied the thermal energy and exergy the of HPVT collector. The values of LCCE of the system were calculated as 0.317, 0.34, and 0.349 by considering the lifetime of the system as 10, 20 and 30 years.

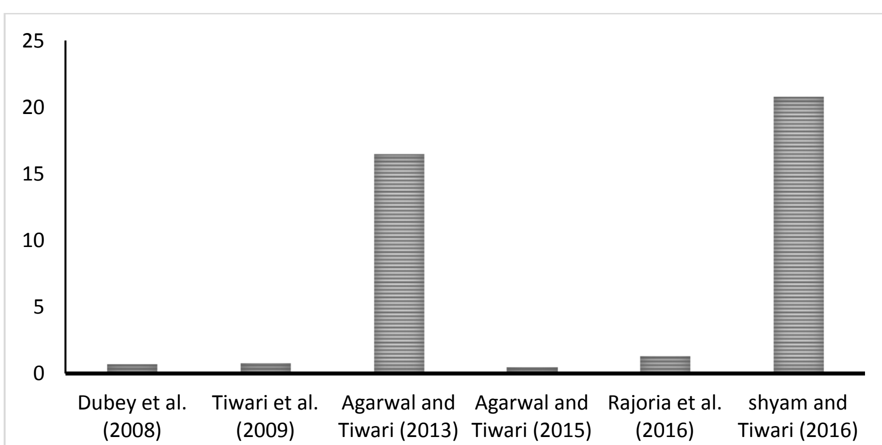

Fig. 5. The trend of EPF of PVT with time

The study revealed that LCCE increases with an increase in lifetime of the system. Tiwari et al. (2009) experimentally evaluated the LCCE of hybrid PVT air collector under standard test condition and outdoor condition with and without BOS, with one and two numbers of fans. PV module was made of m-si. The LCCE has no effect on BOS irrespective of the life of the hybrid PVT air collector. There was a notable difference in LCCE of hybrid PVT air collector under the standard and outdoor condition. Agrawal (2010) calculated LCCE of the various types of solar cells like m-si, p-si, a-si, r-si, CdTe and CIGS used in BIPVT air system for a span of 60 years, separately. LCCE of m-si was highest (0.349) while that of a-si silicon was the lowest (0.132). Nayak and Tiwari (2010) evaluated the LCCE for PVT air collector coupled with a greenhouse for New Delhi, Srinagar, Bangalore, Jodhpur and Mumbai. It was observed from the LCA study that Srinagar has maximum LCCE, and it increases with the life of the system. Agrawal and Tiwari (2013a) conducted an enviro-economic analysis for the lifespan of 20, 30, and 40 years for HPVT air collectors in New Delhi and it was observed that for 20, 30, and 40 years of lifespan, the values of LCCE in terms of thermal energy gain were 0.56, 0.58, 0.59, respectively and for the exergy gain, were 0.08, 0.10, 0.11, respectively. Nayak et al. (2014) evaluated the thermal energy and exergy of a hybrid PVT System (New Delhi, India) by adopting several silicon and non-silicon-based PV modules. The LCCE in terms of thermal energy for c-si, mc-si, nc-si,a-si ,CdTe and CIGS were 2.86, 2.80, 2.75, 2.47, 2.45 and 2.80 and for exergy were 0.084, 0.055, 0.042, 0.116, 0.173 and 0.038. Chauhan et al. (2015) conducted experimental work on hypothetical PVT air collector with a provision of duct above opaque type PV module for the climatic condition of Bangalore, New Delhi, Jodhpur and Srinagar for a lifespan of 20, 30, and 40 years based on thermal energy and exergy. The highest and the lowest value of LCCE were obtained for Bangalore and Srinagar in terms of thermal and exergy for all lifespan due to high solar radiation at Bangalore and low solar radiation at Srinagar.

From the LCCE study, the following points can be concluded:

- The LCCE increases with the increase in the lifespan.
- The LCCE greatly depends on the type of PV cells.
- For high LCCE, the PVT air collector needs to be installed in a region of high solar intensity.
- It is found that the LCCE is in the range of 0.10 to 2.86 in terms of thermal energy gain and 0.08 to 0.17 in terms of exergy gain.

2.7. Greenhouse Gas Emission (GHG)

One of the major GHG from PVT air collector is CO_2. The CO_2 mitigation from PVT air collector per annum is expressed as (Rajoria et al., 2013).

$$\phi = \frac{\varphi_{avgCO_2} \times E_{anoverall}}{10^3}, \qquad (10)$$

where ϕ is CO_2 mitigation per annum and is estimated in terms of t (tones) CO_2/annum, φ_{avgCO_2} is the average CO_2 equivalent intensity for electricity generation from coal and $E_{anoverall}$ is the annual over all energy in kWh.

Gaiddon and Jedliczka (2006) conducted a study on CO_2 mitigation and concluded that 1 kW of a single module of PV panel earned a reduction of 40 tons of CO_2 during its lifespan. Prabhakant and Tiwari (2008) studied the effect of the carbon credit of HPVTAC located in solar energy park at Indian Institute of Technology Delhi, India. The HPVTAC system consists of two PV modules of effective area 0.605 m^2 with two wooden duct in which two DC fan was fitted to suck the hot air from the lower surface of the PV modules to increase the efficiency of PV modules. The results concluded that the mitigation of CO_2 as per thermal and exergy gain of the HPVTAC system per year was 99.3 tons and 2.5 tons. Purohit (2009) estimated the potential of CO_2 mitigation for the solar home system (SHS) in India. It was found that approximately 97 million of potential SHS system existed during the study. Kamthania et al. (2011) estimated the energy, exergy and CO_2 mitigation analysis for HPVT (double pass) collector with air as heat carrier for Delhi, Bangalore, Jodhpur, Mumbai and Srinagar. Jodhpur has the highest energy, exergy, and CO_2 mitigation potential for the system due to high value of solar radiations. Rajoria et al. (2013) experimentally analyzed the CO_2 mitigation per annum for HPVT air collector with series and parallel configuration for the Delhi, Jodhpur, Bangalore and Srinagar. For series configuration, CO_2 mitigation per annum for Delhi, Jodhpur, Bangalore, and Srinagar were 84.52, 88.47, 90.85, and 81.31 t CO_2 whereas 94.05, 97.80, 99.81, and 88.31 t CO_2 for parallel configuration, which shows that CO_2 mitigation per annum is less for series configuration. Agrawal and Tiwari (2013) conducted an enviro-economic analysis for HPVT air collectors in New Delhi. The CO_2 mitigation in terms of CO_2 equivalent was 2.55 tons for energy gain and 0.59 tones for exergy gain. Kamthania and Tiwari (2014) evaluated the CO_2 mitigation of m-si, a-si, p-si and CdTe solar cells used in semi-transparent PVT double pass facades system in India. The CO_2 mitigation over system lifetime for m-si, a-si, p-si and CdTe system were found to be 260.63 t, 321.41 t, 196.33 t and 49.32 t for thermal energy gain and 30.14 t,102.1 t, 37.29 t and 57.31t for exergy gain. Nayak et al. (2014) evaluated the annual thermal and exergy performance of an HPVT System (New Delhi, India) by adopting several silicon and non-silicon based PV modules. CO_2 emission in terms of thermal energy for c-si, mc-si, nc-si, a-si, CdTe and CIGS were175.95 t, 172.42 t, 168.95 t, 104.92 t, 80.65 t, and 112.35 t and for exergy were 11.32 t, 13.99 t, 12.9 t,5.69 t,5.02 t and 6.43 t. Agrawal and Tiwari (2015) analyzed the CO_2 mitigation of glazed HPVT air collector due to the effect of carbon credit earned on the basis of annual thermal energy and exergy gain for the climatic condition of New Delhi. For the lifespan of 30 years, the carbon emission reduction was found as (the US) $ 1.739, US $ 3.861 and US $ 403.322 on thermal energy and exergy basis. Louwen et al. (2015) studied LCA of PVT collector in which PV module was made of silicon heterojunction (SHJ) cells and compared with PVT collector having m-si solar cell. The study concluded that the greenhouse gas emission for SHJ cell was 32 gCO_2-eq/kWh and 38 gCO_2-eq/kWh for m-si solar cell for a solar radiation of 1700 W/m^2. Studies suggested that nonsilicon PV module contributes less GHG than silicon PV modules.

2.8. Greenhouse Gas Payback Time (GPBT)

Battisti and Corrado (2005) performed LCA on multi-crystalline PV module by SimaPro 5.1 software in the climatic condition of Rome, Italy. A GPBT of 1.6-2.81 years was obtained from the numerical analysis for the climatic condition of Rome, Italy Tripanagnostopoulos et al. (2006) conducted a study on the HPVT system to assess the economic viability of the system at the University of Patras, Greece. The study performed on different PVT air collectors like glazed, unglazed PVT air collector and PVT air collector with a thin flat metallic sheet (TFMS) inside the duct along the path of air flow placed at the rooftop of the building. The results suggested that the PVT/Glazed type system has the lowest environmental impact, whereas PVT/TFMS has more advantages from an economical aspect. GPBT of 1.02 year was obtained for PVT/Glazed type system, which was lowest than the other two configurations. Good (2016) reviewed the published papers on LCA of PVT technology with air, water and another nanofluid as a heat carrier with PV modules made up of various silicon and non-silicon technologies. The study summarized various experimental and numerical simulations attempted by the previous researchers to overview the various parameters of PVT technologies. Results suggested that the GPBT for air as heat carrier was found in the range of 0.8 to 4 years. It is found from the conducted study that the value of GPBT depends greatly on the location, installation and orientation (Good, 2016).However, the range of GPBT time is in the range of 1 to 4 years.

2.9. Life Cycle Cost Assessment (LCCA)

Humphreys (1991) given an expression to estimate the future cost of PVT air collector:

$$\text{Future cost} = \text{Present cost} \times \text{CIF} - \text{Salvage value} \quad (11)$$

where CIF is compound interest factor.

Raman et al. (2008) performed LCA study and compared the LCCA for air and water HPVT collector and found that PVT air collector has the highest cost/kWh than water air collector on all the location selected for the experiment. Agrawal and Tiwari (2010) performed LCCA of BIPVT air collector installed on the rooftop of the building of Indian Institute of Technology Delhi. BIPVT air collector consists of 6 ducts connected in series to extract thermal energy from the PV modules with the help of air blower which consumed 0.72 kW of electrical energy produced from the PV panel to circulate air with a mass flow rate of 1kg/s, which enables to replace batteries and consequently lowers the electricity price. LCCA of BIPVT air collector with different solar cell performed by MATLAB 7 and compared with the similar BIPV system. Results suggested that the 0.1009 US $/kW was required for unit power generation for BIPVT air collector. Agarwal and Tiwari (2013) evaluated the carbon credit on the basis of thermal energy and exergy for Srinagar, India. The mathematical models of various types of air collector, namely conventional HPVT air collectors, glazed hybrid PVT tiles and unglazed HPVT tiles, were computed numerically by the MATLAB software. The study concluded that the net cost savings by reduction of CO_2 were $ 11.14(US), $ 14.18.1 and $ 18.030 annually for thermal energy and $ 3.97, US $ 4.87 and $ 6.34 for exergy for conventional hybrid PVT air collector, glazed hybrid PVT tiles, and unglazed hybrid PVT tiles. Shyam and Tiwari (2016) performed an LCCA of PVT air collector connected in series with two cases, one being an inlet was covered with a semitransparent PV module, and the other was outlet covered with semi-transparent PV module. The setup consisted of two PVT air collector of area 2 m^2 of which 0.605 m^2 of both PVT air collectors were covered by 75W semitransparent PV module of crystalline silicon. It was estimated that for a lifetime of 30 years with interest rate of 4%, the unit cost of electricity was 0.016 US $/kWh for thermal energy saving and 0.109 US $/kW h for exergy saving. Tripathy et al. (2017) performed an LCA study on BIPVT air collector on Indian climatic condition by considering shadow effect and estimated the LCCA for the system. Cost of energy production for BIPVT air collector depending on the climatic condition of the place was found in the range of 1.61 US $ /kWh and 3.61 US $ /kWh.

LCCA is one of the most important energy matrices for PVT air collector, which is widely acceptable. This parameter deals with the total cost involved in the system. This can be an interesting area of research in the current scenario of PVT market across the globe.

2.10. Annualized Uniform Cost (AUC)

There are various cost parameters that are to be involved in the cost analysis like initial cost, operation cost, maintenance cost and replacement cost. The annualized uniform cost (AUC) can be estimated by the given expression [27]

$$\text{AUC} = \text{present cost} \times \text{capital recovery factor (CRF)}, \tag{12}$$

where $\text{CRF} = \frac{i(1+i)^m}{(1+i)^m - 1}$, and m is in year.

Agrawal and Tiwari (2010) estimated the annualized uniform cost for BIPVT air collector installed on the rooftop of the building at the Indian Institute of Technology Delhi. BIPVT air collector consisted of 6 ducts connected in series to extract thermal energy from the PV modules with the help of air blower which consumed 0.72 kW of electrical energy produced from the PV panel to circulate air with a mass flow rate of 1kg/s, which enables to replace batteries and consequently lowers the electricity price. It was found from the study that the AUC for BIPVT air collector was US $ 785.66. Nayak et al. (2012) developed a dryer connected with PVT air heater system integrated with DC fan for drying of the agricultural product. The techno-economic analysis of the system was conducted to evaluate the AUC of the system. It was found from the study that the AUC for the system was US $ 19.01. Agrawal and Tiwari (2015) conducted a study to estimate the AUC based on the effect of carbon credit for the lifespan of 30 years and suggested that due to carbon credit earned there was a significant amount of reduction in AUC of PVT air collector. The AUC for thermal energy and exergy gain were found as 0.238 US $/kWh and 0.054 US $/kWh.

3. Conclusions

Efficient collection and effective utilization of solar power are significant for the exponential increase in energy demand and tranquilizing environmental concern. Continuous efforts are made to make the harnessing of solar power economically sustainable without any subsidy. The overview of some past studies about LCA of PVT air collectors shows the higher effect of various design parameters such as position and type of absorber material, packing factor, and mass flow rate of air on the performance of PVT air system. Performance variation for similar designed PVT is highly influenced by the climatic condition. In addition, since PV panels have a significant role in PVT air collector performance, the type of PV panels also affects the LCA of PVT air collector on both energy and environment. The energy matrices of the PVT air collector are the important parameters for the LCA of the PVT system. Through the discussion of each section, the strategies to improve the effectiveness of LCA of PVT air Collector system can be concluded as follow:

- A suitable location should be the first choice where solar irradiation is higher than 800W/m^2 to have a higher efficiency of the system.
- Design of any PVT air collector needs to be an application specific, i.e., the ratio of thermal and electric power needs to be clear. Literature reveals that the thermal output of the PVT air collector is generally lower than that of individual thermal output for the same size.
- Demand specific design is the next important criteria, and the important parameters that need to be standardized are collector area, duct depth, packing factor, mass flow rate, etc.
- Modified absorber plate-like corrugated or with extended surface provides economical PVT air collector as it gives a better thermal yield.
- PV panel with efficient non-silicon cell should be preferred over silicon-based as it is environmentally friendly.
- Embodied energy should be as low as possible, but the structure should be durable.

It is can be concluded that the EPBT, GPBT, EPF, and LCCE are in the range of 0.8 to 14 years, 1 to 4 years, 0.4 to 22, and 0.10 to 2.86 The study also reveals that a lifespan of PVT system is 20 to 30 years, so EPBT and GPBT are usually shorter than the expected lifespan of the system. Though the proper energy return on investment can leads the system to be an environmentally friendly and reasonable option for energy sustainability. The studies on LCA of PVT air collector is fewer than numbers of studies conducted only for the thermal efficiency improvement, energy and exergy analysis of the PVT air collector. Also, in the future, the study LCA of PVT air collector can be compared with/without fins, baffle plates with/without PCM to find more details about each technology.

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