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Life Cycle Analysis of Thin-Film Photovoltaic Thermal Systems for Different Tropical Regions

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Abstract: Different energy solutions are required to satisfy the energy demand of the world's ever-growing population. Photovoltaic Thermal systems (PVT) could propose resolutions to tackle real-time issues regarding power generation. Life Cycle Analysis (LCA) is performed to compare the environmental impact and measure the energy across different PVT modules consisting of a-Si, CdTe, and CIS thin-film solar cells. The authors performed LCA to calculate the energy payback time (EPBT) and life-cycle CO_2 emissions of residential rooftop and open-field PVT systems. The primary energy needed to produce thin-film PVT modules of 1 m^2 cell area was considered in the present life cycle analysis studies operated using water as the working fluid. The annual net electrical energy savings at various Indian weather conditions, such as New Delhi, Jodhpur, and Ladakh, have been calculated. For the thin-film PVT systems, the calculated values of annual energy yield for three locations with average solar radiation levels and peak sun hours in the range of 600–1000 W/m^2 and 6–8 h were reported. Results show that the CO_2 emissions for rooftop installation of CdTe and CIS are around 200 and 156 kg/annually, which is lower than the open field installation of the same, where CO_2 emissions were found to be 295 and 250 kg/year.

Keywords: life cycle analysis; photovoltaic/thermal systems; energy payback time (EPBT); CO_2 emissions; CO_2 mitigations; carbon credit earned

1. Introduction

In most parts of the world, fossil fuels are still the primary source of electricity generation [1]. However, as the global population grows exponentially, it is expected that most of the population residing in rural areas will migrate to big cities in search of employment or other opportunities [2]. This will intensify the country's reliance on finite, non-renewable energy reserves to meet future energy requirements [3]. Furthermore, the usage of conventional energy sources results in CO_2 emissions and environmental damage to many aspects such as air, water, and land pollution as well as affecting human health [4]. As a result, research into alternative energy sources has already commenced safeguarding existing fossil fuel reserves [5]. Coal, oil, and natural gas justify around 33% of global greenhouse gas releases [6]. India's desire for energy is intensifying to meet the existing monetary advancement desires of the country [7]. According to the World Resource Institute's 2017 report, India is accountable for about 6.65% of total world carbon releases, ranking after China, the US, and the European Union [8]. Climate change can upset the world's environmental stability [9]. The Paris Agreement aimed to keep global warming under 2 °C [10]. The worldwide need for power will peak in the year 2030, according to the World Energy Council [11]. Coal and oil provide over 74 per cent of total energy needs [12]. The PVT hybrid solar collector is a system that combines a photovoltaic (PV) module for solar energy conversion and produces high thermal conversion efficiency with the help of thermal fluid [13]. This solar conversion technology improvement primarily aims to cool photovoltaic cells to increase electricity generation while also generating useful thermal energy from the working fluid, resulting in a cogeneration device [14]. The uses of PVT can be classified based on their differing magnitudes of temperature. Low temperature (0 °C to 50 °C), medium temperature (50 °C to 80 °C), and high temperature (over 80 °C). PVT collectors are suitable for a variety of applications that are dependent on the form of fluid used in the transfer of heat [15]. PVT liquid collectors can be used for space heating, water heating, desalination, and space cooling. PVT air collector has usage similar to that of the PVT liquid collector. PVT technologies have the potential to play an essential role in global energy generation and they can also be viewed as a viable choice for applications that deliver power, warmth, etc. [16].

Many researchers have performed studies on the LCA of PVT systems and CO_2 emissions that arise due to energy generation from conventional and renewable energy sources. Alejandro Calderon Diaz et al. [17] established a clear idea of how energy use is reduced today by comparing an older LCA analysis (1998) of Amorphous silicon with the results of an LCA obtained in 2009. It was found that energy consumption per meter square of the amorphous-Si module was 989 MJ/m^2 and the average Energy Payback Time (EPBT) was 2.6 years. Vineet et al. [18], from their environmental and economic analysis of several types of PV technologies used in a rural solar drying system, found that CdTe PV technology provides constant electricity but low efficiency. Overall efficiency was minimum in the case of a-Si. It was concluded that using CIGS's PVT system consumes less energy during manufacturing and gives out the best payback time of 0.39 years. Noah et al. [19] conducted a study in which the main objective was to juxtapose life-cycle greenhouse gas emissions, embodied energy, and monetary investment of solar panels that used mono-crystalline with solar panels that used a thin-film created with amorphous silicon. According to the findings, the thin-film panels provided a more significant net ecological gain than the other panel. PV panels minimize GHG emissions even if manufactured in a nation with high power emissions, such as China. Hundreds of LCA for various household and utility-scale PV systems have been completed and published during the last thirty years. These LCAs have produced a wide range of outcomes. In the NREL [20] LCA, in their Harmonization Project, a total of 400 papers were evaluated and screened, covering crystalline silicon (mono- and multi-crystalline) and thin-film (amorphous silicon, CdTe, and CIS). The harmonization was performed using the below crucial technical constraints:

- Solar irradiation, measured as kWh/m^2/year, is the average energy flow from the sun.
- The PV system and components' operational lifetime is in (years).
- Module efficiency refers to how much solar energy the module converts to direct current power.

From the above study, the module efficiencies of a-Si, CdTe, and CIS used were deemed to be 6.3%, 10.9%, and 11.5%. Next, Wu et al. [21] studied the potential application of Amorphous silicon PV technology. They suggested that flexible laminates created with amorphous thin-films will outperform rigid thin-film PV laminates at greater temperatures and low solar radiation. It was observed that the flexible amorphous thin-film PV laminates could have up to 20% greater performance in hot environments and up to 12% better performance in lower and diffused light circumstances.

Though many research findings are available on crystalline silicon-based PVT systems, as per the author's knowledge, the LCA on thin-film PVT systems is not reported yet. Additionally, minimal literature on performance analyses of PVT systems for tropical climatic regions such as India is available. Therefore, in this study, the life cycle analysis (LCA) of three different types of PVT systems, i.e., a-Si, CdTe, and CIS, employs water as the working fluid. In addition, the embodied energy, energy payback time, CO_2 mitigation, and carbon credit earnings have also been calculated for rooftop and open field installations.

2. Methodology

The methodology used in PV LCA studies is extended to current PVT modules also, which follow ISO standard 14044, shown in Figure 1. These ISO standards specify four steps for conducting an LCA: (a) definition of goals and scope; (b) life-cycle inventory (LCI); (c) life-cycle impact assessment (LCIA); and (d) interpretation. The first step requires a clear definition of the problem statement and the respective system boundaries used for analysis [22]. The inventory step quantifies the materials, energy, and emission flows during each PV system's life cycle stage. The environmental impact of energy consumption, resource consumption, pollutant emissions, and GHG emissions is quantified in the LCIA and the cumulative impact on the environment is estimated further. During the fourth and last step of the LCA, as defined by the ISO, the interpretation of the results is critical because different assumptions can produce different results.

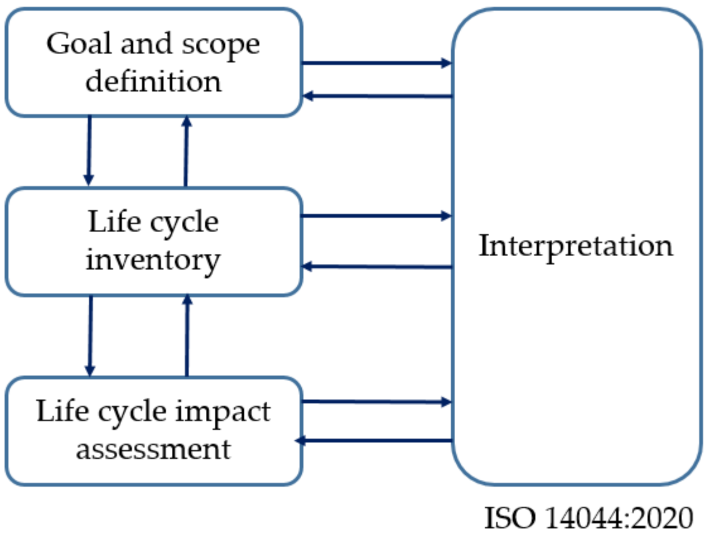

Figure 1. The four-step LCA analysis as per ISO 14044:2020/Amd 2:2020 adopted for PV systems [22].

In the present study, the value of the embodied energy of a system includes the amount of energy spent to manufacture each component of the system [23]. The list of components present in PV and PVT systems is given in Table 1, where a thermal absorber component is additionally present in the PVT system. A thermal absorber configuration composed of copper tubes and an aluminum sheet is assumed for the analysis affixed to the module's backside [24]. The Balance of System (BoS) for open field and rooftop installation are nearly identical, except that a hefty support assembly must be essential for open field installations. Extreme wind and structural solidity necessitate this massive support structure. The charge controller, battery, and inverter are among the components of the BoS, which are used to power AC loads in both types of installations.

Table 1. PVT components.

S.No	PV System	PVT System
1	PV Module (a-Si, CIS, CdTe)	PV Module (a-Si, CIS, CdTe)
2	BoS components (inverter, battery, etc.)	BoS components (inverter, battery, etc.)
3		Thermal absorber

3. Results and Discussion

As per the ISO 14044 methodology, the LCA of three thin-film PVT systems with open field and rooftop installation conditions was carried out. EPBT, CO_2 emission, and CCE analysis were calculated for the three PVT systems and their results are discussed hereunder.

3.1. Embodied Energy Analysis of a PVT System

The embodied energy of a PVT system reveals information about the total energy required starting from the manufacturing of the individual components till its installation at the site [22]. The calculated values of the embodied energy for various PVT modules with an area and packing factor of unity can be found in Table 2.

Table 2. Embodied energy for different PVT Modules of 1 m^2 area.

Type of PV Module	Cell Efficiency	Packing Factor	Temperature Coefficient of Power	Embodied Energy of PV System	Embodied Energy of PVT System	Module Life (Years)	Module Wattage, W_p/m^2
	(%)		(%/°C)	(kWh/m^2)	(kWh/m^2)		
a-Si	6.6	1	−0.2	625	762	5	64
CIS	12.0	1	−0.28	357	494	10	94
CdTe	10.0	1	−0.22	498	635	15	118

The embodied energy values for both PV and PVT considering rooftop and open field structures are shown in Figures 2 and 3. Figure 2 shows that the embodied energy calculations for rooftop installation of a-Si are highest at 762 kWh/m^2. In contrast, the CIS has the least embodied energy at 494 kWh/m^2, which is around 1.5 times lesser than the a-Si module. The embodied energy for CdTe was found to be 635 kWh/m^2, which is 1.2 times lesser than that of an a-Si module. In addition, Figure 3, shows that the embodied energy for the open field CdTe module is 935 kWh/m^2. This is around 1.2 times greater than the embodied energy of the CIS module, which was found to be 794 kWh/m^2. The reason for the higher energy consumption for manufacturing the a-Si and CdTe modules are the numerous processes involved in the extraction of various rare earth raw materials and the preparation of the modules. The embodied energy values are higher for open field installation than the corresponding rooftop installation due to the heavy structures required to support the PVT systems. Moreover, a-Si PVT systems do not suit well for open field applications due to their fast degradation characteristics and huge installation area requirements.

Several methods are available for reclaiming solar energy that is incident on the Earth's surface [25]. The incident solar energy is directly absorbed or channeled through a thermal absorber [26]. This absorbed energy can be used for heating or cooling rooms, generating thermal electricity, cooking, drying, etc. The electrical energy that is generated is used for a variety of purposes, including cooling and water pumping. As a result, in addition to reducing CO_2 emissions, significant fossil fuel savings have been documented in previous studies [27]. The module life cycle analysis involves determining the net energy offered by a PV module by subtracting the total power developed from the PV module's input energy. The input energy includes the process energy required by various elements used in the system, such as raw material extraction and the processing of the same, production of the components, its servicing, etc. [28]. This total energy demand is analyzed against the electrical and thermal yield of the PVT system (E_{out}).

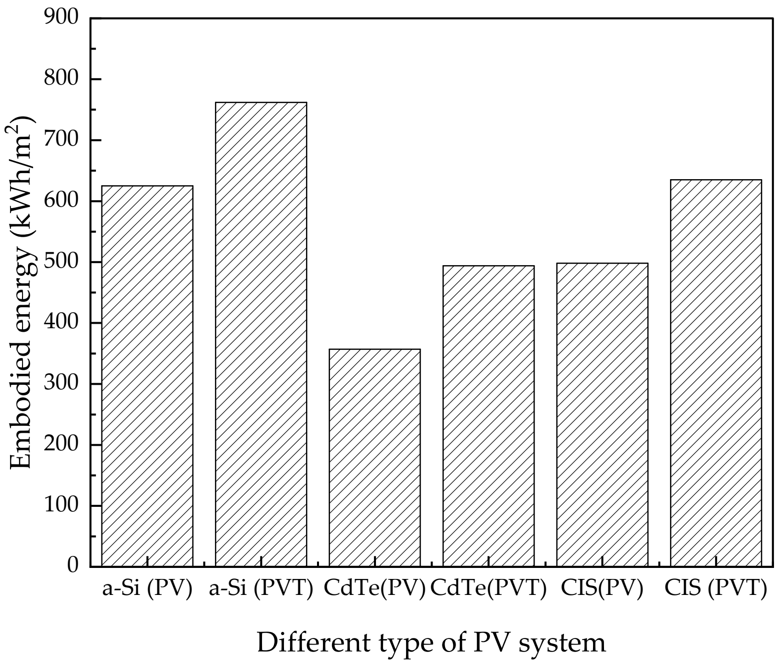

Figure 2. Comparison of embodied energy values of different thin-film PV and PVT modules under roof-top installation.

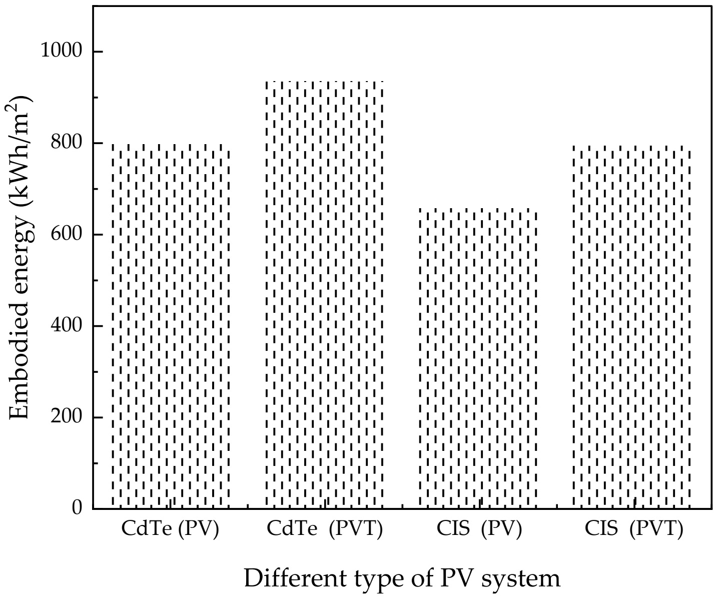

Figure 3. Comparison of embodied energy values of different thin-film PV and PVT modules under open field installation.

3.2. Annual Electrical Yield from PVT System

The annual PVT system's energy generation is determined by considering the amount of solar radiation and possible cell temperature prevailing over the specific location shown in Tables 3 and 4. The PVT system's electrical energy yield (E_{out}) was estimated using the average yearly solar radiation value for the three locations considered in the analysis using Equation (1).

$$\text{Yearly average Insolation } (\text{kWh/m}^2/\text{year}) = \text{Insolation on the panel } (\text{W/m}^2) \times \text{number of hours of peak sunshine} \times \text{number of days with clear sun in a year} \quad (1)$$

Table 3. Average solar insolation in W/m^2 for different locations [29].

Location	Climate Zone	PVT Module Inclination	Insolation (W/m^2)	Sunshine Hours	Latitude (ϕ)	Elevation above Mean Sea Level
New Delhi	Composite	Horizontal	636	8		
		Latitude (ϕ)	954	8	28.61° N	216 m
Jodhpur	Hot Dry	Horizontal	745	8		
		Latitude (ϕ)	1187	8	26.23° N	224 m
Ladakh	Cold	Horizontal	815	10		
		Latitude (ϕ)	1222	10	34.22° N	3542 m

Table 4. Annual average insolation on an inclined plane at a tilt angle of latitude for the regions.

Insolation Received on an Inclined Plane (W/m^2)	Duration of Sunshine Hours (6)	Number of Clear Sunny Days	Annual Average Insolation ($kW\text{-}h/m^2$)
600	6	300	1080
800	6	300	1440
1000	6	300	1800
600	8	300	1440
800	8	300	1920
1000	8	300	2400

E_{out} = The average annual insolation × electrical efficiency of the PVT module.

The cell efficiencies for a-Si, CdTe, and CIS PV modules have been considered as 6.6%, 10%, and 12%. Considering the packing factor of the cells in the PVT module, the efficiency of the module is given by Equation (2).

$$\text{PVT module efficiency } (\eta_{PVT}) = (\text{Packing factor}) \times (\text{solar cell efficiency}) \quad (2)$$

The packaging factor was taken as 1 for the present study for calculations. Furthermore, the combined electrical losses of 19% are commonly attributed to individual contributions by inverters, transformers, etc. Therefore, in this study, the assessment of the capacity of the PVT system BoS is computed using Equation (3).

$$\eta_{BoS} = (100 - \text{all electrical losses}) = 0.81 \quad (3)$$

The annual electricity output of an a-Si module of 1 m^2 area is given by Equation (4).

$$\begin{aligned} E_{out}\text{ (electrical)} &= \text{Annual insolation average} \times \text{efficiency of the solar cell} \times \text{packing factor} \times \text{BoS efficiency} \\ &= 1440 \times 0.066 \times 1 \times 0.81 \\ &= 76.982\ \text{kWh}/m^2/\text{year} \end{aligned} \quad (4)$$

Similar calculations have been repeated for CdTe and CIS, considering the efficiency of 10% and 12% module efficiencies. Over the module's lifetime, dust deposition, changes in humidity conditions, and cell deterioration impact the efficiency neglected in this study. The energy generation estimates for a-Si module for the sunshine hours of 6 and 8 h and different insolation levels are shown in Table 5.

Table 5. Annual energy output (electrical) for a-Si PV system @ ($\eta_{cell\,=}$ 6.6%).

Insolation on an Inclined Plane, (W/m^2)	Duration of Sunshine Hours	E_{out} Electrical, Watt
600	6	57.736
800	6	76.983
1000	6	96.228
600	8	76.983
800	8	102.643
1000	8	128.304

3.3. Annual Thermal Energy from PVT

The present analysis assumes the Bi-Symmetrical web flow thermal absorber configuration for PVT systems [30]. Hence, as per the literature, the typical thermal efficiency of this PVT configuration was reported as 45% with water as the working fluid [23]. Equation (5) provides the calculation for the amount of thermal energy generation possible from the PVT system.

$$\begin{aligned} E_{out}\ (\text{thermal}) &= \text{Mean daily insolation} \times \text{thermal efficiency} \\ &= 1440 \times 0.45 \\ &= 648\ \text{kWh/m}^2/\text{year} \end{aligned} \tag{5}$$

Since most of the energy in a PVT module exists as exergy energy, the electrical and thermal power outputs should be changed to exergy energy given by Equation (6) [31].

$$\begin{aligned} E_{out}\ (\text{Exergy}) &= E_{out}\ (\text{thermal}) \times \left[1 - \tfrac{25+273}{T+273}\right] \\ &= 648 \times \left[1 - \tfrac{25+273}{55+273}\right] \\ &= 59.268\ \text{kWh/m}^2/\text{year} \end{aligned} \tag{6}$$

where T is the fluid outlet temperature from the thermal absorber. For this study, T has been considered as 55 °C [23].

The collective sum of the electrical power and thermal energy output taken annually is the overall annual energy output.

$$\begin{aligned} \text{Total annual energy output} &= (\text{Electrical}) + (\text{Thermal Exergy}). \\ &= (76.982 + 59.268) \\ &= 136.25\ \text{kWh/m}^2/\text{year} \end{aligned} \tag{7}$$

The overall annual energy output for an a-Si module is represented in Table 6. Solar radiation availability can be understood to rise by approximately 1.6 times and the sun hours to increase to 8. The overall energy is almost twice that of 600 W/m^2 and 6 sunshine hours. Likewise, if the availability of solar radiation increases by approximately 1.3 times and the sun hours increase to 8, the overall energy is almost 1.7 times when likened to 600 W/m^2 and 6 sun hours.

Table 6. Total annual energy output from rooftop system for a-Si PV and a-SiPVT @ (η_{cell} = 6.6%).

Insolation on an Inclined Plane, (W/m^2)	Duration of Sunshine Hours	Total E_{out}, a-Si PV (Watt)	Total E_{out}, a-Si PVT (Watt)
600	6	57.737	102.188
800	6	76.983	136.250
1000	6	96.228	170.313
600	8	76.983	136.251
800	8	102.643	181.668
1000	8	128.304	227.085

3.4. Energy Payback Time (EPBT)

The energy payback time (EPBT) is calculated by dividing the embodied energy required (E_{in}) by the annual total energy output (E_{out}). The EPBT estimates how long it will require for twelve-monthly energy generations (E_{out}) to become equivalent to yearly energy expenditure. The ratio between the output and total energy needed for a given lifespan is known as the energy yield factor. This factor specifies the amount of energy attained for every energy investment unit [29].

$$\text{EPBT} = \frac{\text{Gross energy requirement}\ (\text{kWh/m}^2)}{\text{Overall energy output}\ (\text{kWh/m}^2/\text{year})} \tag{8}$$

$$\text{Energy yield factor} = \frac{\text{Lifetime energy output}\left(\text{kWh/m}^2\right))}{\text{Embodied energy }\left(\text{kWh/m}^2\right)} \quad (9)$$

$$\text{Energy yield } = \frac{\text{Lifetime of the total system}(\text{years})}{\text{Energy payback time (EPBT) (years)}} \quad (10)$$

For a photovoltaic thermal system, the annual energy yield factor must be larger than zero, which means that over a given lifespan, the PVT system's power output is compelled to be more than the embodied energy of the system. The EPBT of a PVT system is used to analyze the energy demand gap between the actual need and total energy produced; the lesser the EPBT, the better the PV system's alternative to fossil fuel-based energy production.

Figure 4 depicts the EPBT values for rooftop installation of all three PVT systems discussed. It is clear that a-Si has the largest EPBT which is 4.9 years (for 600 W/m^2) and CIS, with the lowest amount of 1.48 years (for 1000 W/m^2), which is around 3.3 times lesser than that of a-Si. The EPBT for CdTe values was found to be 2.16 years at a solar radiation value of 1000 W/m^2, which is 1.45 times greater than that of the CIS module. This figure shows that the CIS module is better suited at a solar radiation value of 1000 W/m^2 due to its low EPBT value.

Figure 5 shows the EPBT values for open-field installation for the three thin-film PVT systems. The EPBT value was again observed to be least in the case of the CIS module, coming out to be 2.39 years at a solar radiation of 1000 W/m^2. In contrast, the EPBT for the CdTe module was 1.33 times greater than that of the CIS module, calculated as 3.18 years for the same solar radiation value. The CIS module can be preferred due to its low EPBT value in open-field installations.

3.5. Carbon Dioxide Emissions

The mean CO_2 intensity per kWh for power plants run on coal is about 0.98 kg CO_2. Therefore, if 40% of the transportation and distribution are lost, 20% of domestic devices are lost.

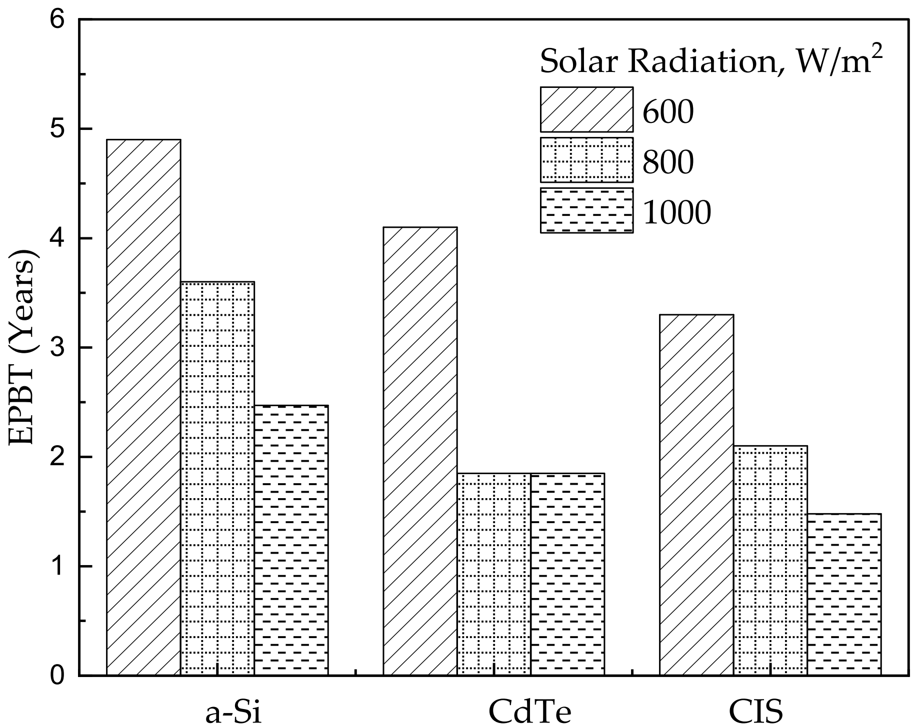

Figure 4. Rooftop EPBT values of different PVT systems for solar insolation levels of 600, 800, and 1000 W/m^2.

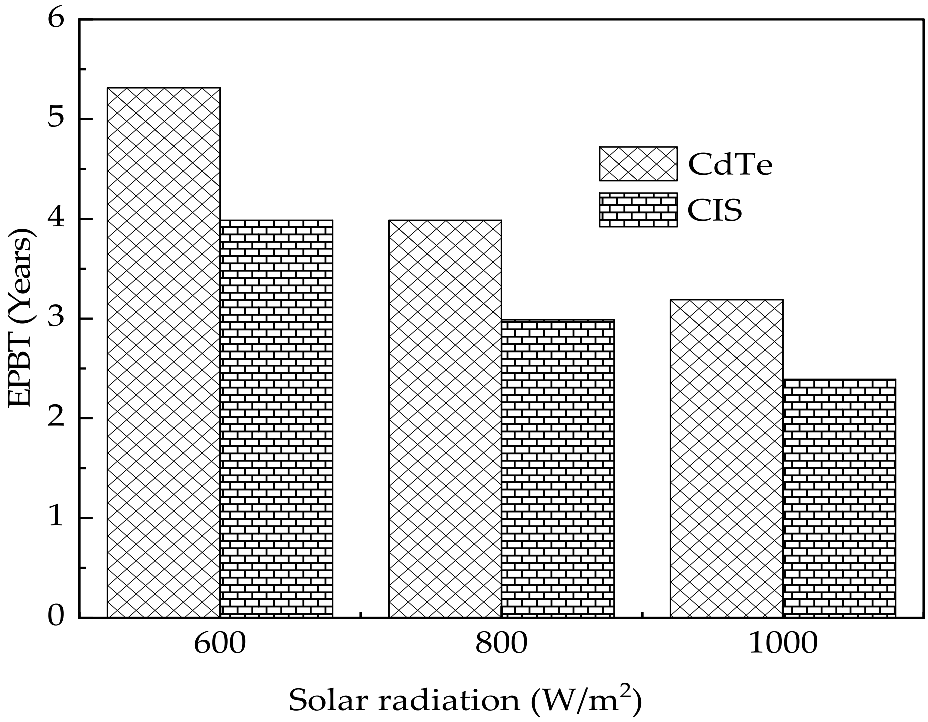

Figure 5. Open field EPBT values of the PVT systems for solar insolation levels of 600, 800, and 1000 W/m^2.

As a result, the average CO_2 intensity of conventional fuel-based power plants is observed to be around 1.58 kg CO_2 per kWh [32].

$$\text{Amount of } CO_2 \text{ emitted by the PVT system } (\text{kg/year}) = \frac{E_{in} \times 1.58}{LT} \quad (11)$$

where E_{in} denotes embodied energy and LT represents the lifespans of the PVT systems. The variation in annual CO_2 emissions for rooftop and open field installation conditions for five years are shown in Figures 6 and 7.

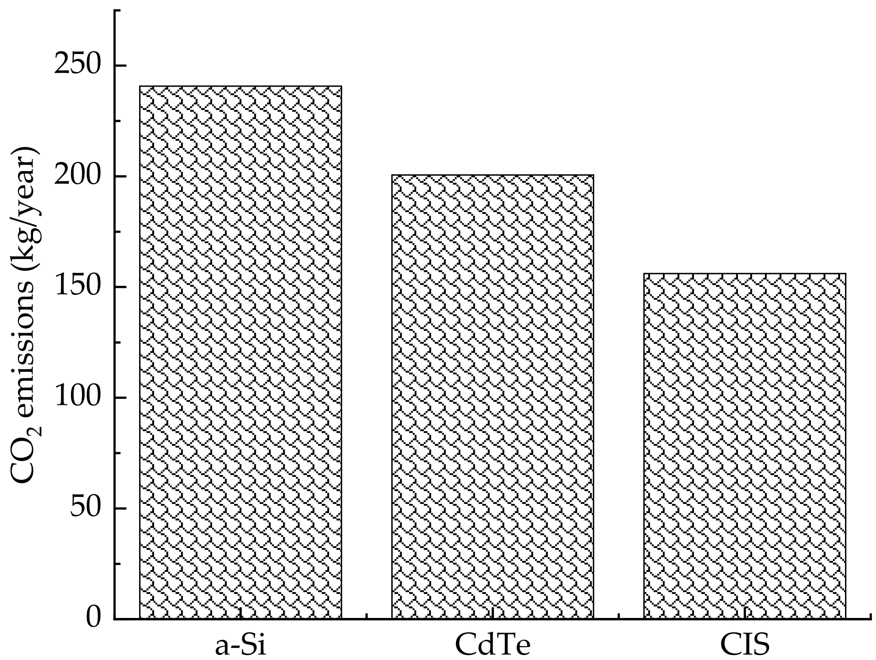

Figure 6. Annual foof-top CO_2 emissions of the Photovoltaic Thermal systems.

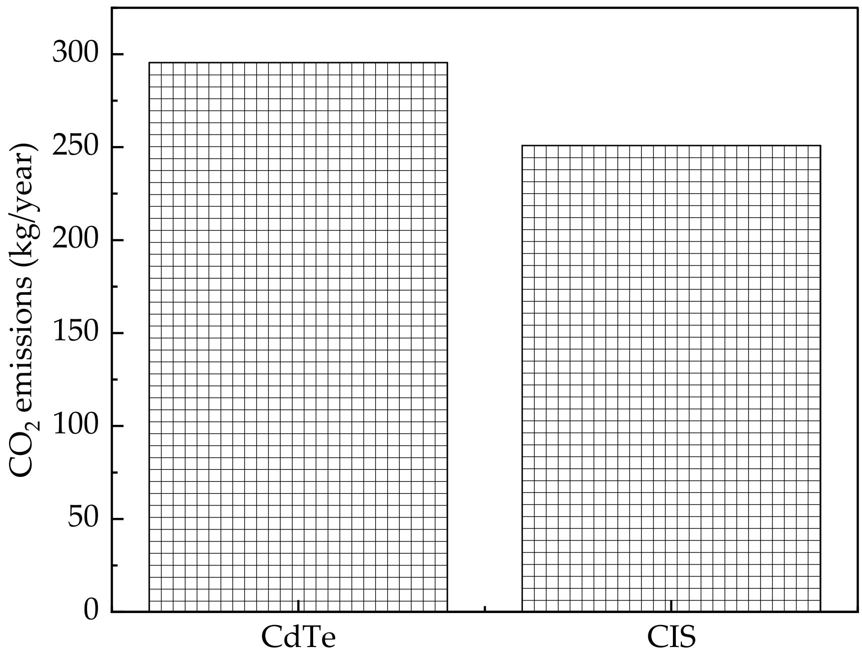

Figure 7. Annual Open field CO_2 emissions of the photovoltaic thermal systems.

The emission value obtained for the a-Si module was 240.79 kg/year, which is 1.54 times greater than the CO_2 emissions obtained for the CIS module, i.e., 156.04 kg/year. The CO_2 emissions for the CdTe module were found to be 200.66 kg/year, i.e.,1.28 times greater than that of the CIS module. It is clear that the annual CO_2 emissions of the CIS module were lowest in comparison to all three thin-film module PVT rooftop systems.

Figure 7 shows the annual CO_2 emissions for open field installation of CdTe and CIS PVT systems. The CO_2 emissions for CdTe were found to be around 295.46 kg/year over five year period, which is around 1.18 times higher than that of the CIS module (250 kg/year). In the case of the open field installation, the CIS PVT system has also achieved lower annual CO_2 emissions.

3.6. Carbon Dioxide Mitigations and Carbon Credit Earned (CCE)

The yearly carbon dioxide emissions of PVTs (kg of CO_2) equals $E_{out} \times 1.58$, where E_{out} signifies the PVTs annual energy gain [33].

$$CO_2 \text{ emission throughout the lifespan of the PVT system (kg)} = E_{out} \times 1.58 \times LT \quad (12)$$

For calculation, the lifetime for a-Si, CIS, and CdTe systems are assumed as 5, 15 and 10 years. Therefore, the total CO_2 emission/mitigation of the PVT systems throughout their lifetime in tons of Carbon dioxide is given by Equation (13).

$$\text{NCEM} = \frac{((E_{out} \times LT) - E_{in}) \times 1.58}{1000} \quad (13)$$

The cost of CO_2 reduction is currently appraised to be around USD 20 for every tonne [34]. CCE = NCEM × Price of CO_2 traded for every ton.

From the above tables, the CIS has the highest CCE value at USD 87.83 [1 ton of CO_2 = USD 20 (July 2022)]. This is 1.23 times the CCE value of the CdTe module, which amounts to USD 71.09 for rooftop installation at 1000 W/m^2 solar radiation with a lifespan of ten years. The net CO_2 emissions for rooftop installation were found to be 3.7 tonnes for the CdTe module, which is 1.13 times smaller than that of the CIS module (4.19 tonnes) at 1000 W/m^2 solar radiation.

For open field installation, the net CO_2 emissions for the CdTe module were calculated to be 3.08 tonnes at 1000 W/m^2 solar radiation. This value is 1.7 times less than the CIS module (5.24 tonnes). The Carbon Credit Earned was calculated to be USD 104.93 for the

CIS module at the same solar radiation value. This is 1.7 times higher than that of the CdTe module, which was found to be USD 61.61. Therefore, it concludes that the CIS module has a higher CCE and NCEM value at 1000 W/m^2 compared to the CdTe module for both rooftop and open field installations shown in Tables 7 and 8.

Table 7. Rooftop results for CO_2 emissions, NCEM and CCE for 800 and 1000 W/m^2 solar radiation for CdTe and CIS PVT systems for a 10-year life span.

PVT Module	Solar Radiation 800 w/m^2			Solar Radiation 1000 w/m^2		
	CO_2 Mitigation (Tonnes)	NCEM (Tonnes)	CCE (USD)	CO_2 Mitigation (Tonnes)	NCEM (Tonnes)	CCE (USD)
Cd-Te	3.70	2.62	52.56	4.63	3.55	71.09
CIS	4.19	3.34	66.84	5.24	4.39	87.83

Table 8. Open field results for CO_2 emissions, NCEM and Carbon Credit earned for 1000 W/m^2 solar radiation for CdTe and CIS PVT systems for a 10-year life span.

PVT Module	CO_2 Mitigation (Tonnes)	NCEM (Tonnes)	CCE (USD)
CdTe	4.63	3.08	61.61
CIS	5.24	5.24	104.93

Generally, based on the experimental data collected on the PVT system for overcast and sunny conditions, the performance varies with ambient and other operating conditions [24]. Since the regions selected for this study have varied diurnal conditions, the overall efficiency, i.e., the sum of electrical and thermal efficiency, will also vary. In the New Delhi region, during summer, the thermal absorber will help to reduce the cell temperature; hence, electrical efficiency increases with considerable thermal efficiency. Similarly, during winter, the region experienced the least ambient temperatures, so overall efficiency may drop due to lower thermal efficiency values. An analogous scenario also follows for the Jodhpur region and introducing a thermal absorber will increase the cell life [23]. Ladakh is a typical cold arid region with high incoming solar insolation levels, with an average value of 5 kWh/m^2/day; hence, higher solar cell temperatures might prevail. Therefore, PVT systems will be effective in attaining lower cell temperatures during summer months and thus a reliable overall efficiency can be ascertained.

3.7. Validation of Results

In this section, the outcomes of the present LCA analysis performed for different PVT systems are validated with LCA performed for PV-based systems available in the literature. Alsema and Raugei et al. [35,36] performed studies using ISO 14044 LCA methodology considering thin-films and CdTe PV systems in the past with module efficiencies of 10% and 9%. However, this study was analyzed based on the latest commercial module efficiency available for a-Si, CdTe, and CIS systems as 6.6%, 10%, and 12%, respectively, and other technical data for supporting components. The comparison tables for PVT system EPBT and CO_2 emission reduction outcomes obtained from the present analysis to that of the PV system reference values reported by [35,36] Alsema and Raugei et al. are shown in Tables 9 and 10.

The results show that the EPBT values of thin-film PVT systems are 26% and 6% lower than PV system results of Alsema et al. in open field and rooftop conditions. The reason for this variation is due to the increase in cell efficiency by 1% and a three-times reduction in the lower embodied energy of the PVT system in the current case. Similarly, the present research achieved 36.9 g-CO_2/kWh CO_2 emissions, which is 23% lower than the results of Raugei et al. for rooftop conditions.

Table 9. Validation results of EPBT for PVT systems under rooftop and open field conditions.

Module	Type of Solar Cell	Solar Radiation (kWh/m^2/year)	EPBT (Year) Rooftop	EPBT (Year) Openfield
PV [35]	Thinfilms	1700	2.1	4
PVT (Present Study)	a-Si	2400	3.35	-
		1800	4.47	-
	CdTe	2400	2.16	3.18
		1800	2.88	4.25
	CIS	2400	1.48	2.39
		1800	1.98	3.18

Table 10. Validation results of EPBT for PVT systems for CdTe PV system.

Module	Solar Radiation (kWh/m^2/year)	CO_2 Emissions (g-CO_2/kWh) Rooftop
PV [36]	1700	48
PVT (Present Study)	2400	36.9

4. Conclusion

This study analyzed estimates of energy payback time, CO_2 emissions, and CCE for three different PVT systems, i.e., a-Si, CdTe, and CIS, in two distinct installation conditions, i.e., rooftop and open field. In this study, diverse climatic locations such as New Delhi, Ladakh, and Jodhpur were considered to determine the best choice among a-Si, CdTe, and CIS PVT systems. The results observed that the payback period was estimated to be between 1.48 and 5.59 years for the PVT systems with productive energy output. This is because EPBT calculations reveal a considerable improvement in energy output per year from rooftop installation for all three individual PVT systems, where the values were lower than the open field conditions. Additionally, it was observed that as the average solar radiation at a location increases, the EPBT value gets lower. With reference to the CO_2 emissions, higher emissions were recorded for a-Si to be 212 kg/year. Additionally, for CdTe and CIS PVT systems, the annual CO_2 emissions were calculated as 108/85 kg (rooftop) and 155/132 kg (open field). Similarly, the highest carbon credits earnings of USD 104 were achieved using CIS thin-film PVT systems in open field conditions.

With the increased performance attributes of the thin-film-based PVT systems, predominantly in tropical areas, achieving fewer CO_2 emissions and NCEM is possible with the accomplishment of higher CCE. In the future, if the cell efficiency improves and the cost of energy per kWh utilized for embodied energy reduces, EPBT and CCE will continue to enhance, allowing for their expansion in domestic applications. The UN sustainable development goals can be easily achieved as these systems demand upkeep and will pave the way to improved societies as excess energy is transferred to the nearby grid via net metering.

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