Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues

Chr. Lamnatou*, D. Chemisana

Applied Physics Section of the Environmental Science Department, University of Lleida, c/Pere Cabrera s/n, 25001 Lleida, Spain

*Corresponding author: Chr. Lamnatou: lamnatou@macs.udl.cat

ABSTRACT

The present article is a review about PVT (photovoltaic/thermal) investigations with emphasis on studies which include environmental issues about PVT technology. The references analyzed are presented according to certain criteria (e.g. the type of the system: BA (building-added), BI (building-integrated), CPVT (concentrating PVT), etc.). The literature review shows that most of the investigations examine EPBT (energy payback time) and CO_2 emissions. In terms of the types of the systems, most of the studies are about BA PVT/water installations for domestic applications and thereby, more studies (which include environmental issues) are needed e.g. about BIPVT, CPVT, BICPVT and PVT systems for different applications (apart from the building sector), for example industrial. In addition, a separate section with factors which influence PVT from environmental point of view (PV cell material, heat transfer fluid, concentrators, alternative materials, etc.) is included. A critical discussion about these factors is also provided, explaining how they influence the profile of a PVT system from environmental point of view. Moreover, explanations about different methods and indicators which provide (or which can provide as a future prospect) useful information for PVT (from environmental point of view) are also presented.

Keywords: Life Cycle Assessment (LCA); Environmental issues; Photovoltaic/thermal (PVT) systems; Building-added, building-integrated and other configurations; Applications for buildings; Industrial applications

SYMBOLS / ABBREVIATIONS

BA	Building added
BI	Building integrated
BICPV	Building integrated concentrating photovoltaic
BICPVT	Building integrated concentrating photovoltaic/thermal
BIPV	Building integrated photovoltaic
BIPVT	Building integrated photovoltaic thermal
BOS	Balance of system
Cd	Cadmium
CdS	Cadmium sulfide
CdTe	Cadmium telluride
CED	Cumulative energy demand method
CIGS	Copper indium gallium diselenide
CIS	Copper indium diselenide
CML-IA	CML-IA method
CO_2 PBT	Payback time based on CO_2 emissions
CPV	Concentrating photovoltaic
CPVT	Concentrating photovoltaic thermal
CR	Concentration ratio
EI99	Eco-indicator 99 method
EPBT	Energy payback time
EPF	Electricity production factor
EVA	Ethylene vinyl acetate
FC	Fuel cell
GHG PBT	Greenhouse gas payback time
GHG	Greenhouse gas

GSHP	Ground source heat pump
GSHP-FC	Hybrid system with ground source heat pump and fuel cell
GSHP-PVT	Hybrid system with ground source heat pump and PVT
GWP PBT	Payback time based on global warming potential
GWP	Global warming potential
HIT	Heterojunction with intrinsic thin-layer
HVAC	Heating ventilation and air-conditioning
ILCD	International reference life cycle data system
ILCD 2011	ILCD 2011 method
IMPACT 2002+	IMPACT 2002+ method
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCCE	Life cycle conversion efficiency
LCIA	Life cycle impact assessment
PBT	Payback time
PCM	Phase change material
PV	Photovoltaic
PVT	Photovoltaic/thermal
PVT/air	PVT system with air as working fluid
PVT/bi-fluid	PVT system with two working fluids
PVT/liquid	PVT system with liquid as working fluid
PVT/PCM	Photovoltaic/thermal system with phase change material
PVT/water	PVT system with water as working fluid
R&D	Research and development
ReCiPe	ReCiPe method

ReCiPe PBT	Payback time based on ReCiPe
Si	Silicon
SiO_2	Silica
Te	Tellurium
TFMS	Thin flat metallic sheet

1. INTRODUCTION

Photovoltaic (PV) systems consist of PV cells which convert solar radiation into electricity. However, the absorbed solar radiation that it is not converted into electricity increases PV cell temperature, leading to a reduction of PV conversion efficiency. Thereby, PV cooling is necessary in order to keep the electrical efficiency at a satisfactory level and it can be conducted for example by means of water or air heat extraction [1]. Natural or forced air circulation is a simple and low-cost technique to remove heat from PV panels, but it is less effective at low latitudes where the ambient air temperature is higher than 20^oC for many months over the year. Water heat extraction is more expensive than air heat extraction; nevertheless, it can work effectively. In order to avoid pressure and electrical problems, the usual solution for PV cooling by means of water is to use water circulation through a heat exchanger in thermal contact with the PV panel rear surface [1]. If the heat removal fluid is used not only for PV cooling but also for other practical applications (e.g. domestic), hybrid PVT solar systems are obtained. In PVT devices, the PV modules and the thermal units are mounted together and the systems convert the solar radiation into electricity and heat (simultaneously). The PVT systems offer higher energy output than the standard PV modules and they can be cost effective if the additional cost of the thermal unit is low [1].

Regarding the classification of the PVT systems, it can be based for example on the working fluid. In this way, there are different PVT configurations, e.g. PVT/air, PVT/water [1], PVT/bi-fluid (air and water) [2, 3]. Another classification can be based on the type of circulation (natural or forced) of the working fluid [1]. Additional types of PVT can be found in the study of Tripanagnostopoulos et al. [1] where multiple PVT configurations are presented (with/without glass cover, with/without reflector, etc.). A general classification of PVT collectors is illustrated in Fig. 1 [4], based on criteria such as the working fluid and the type of the absorber.

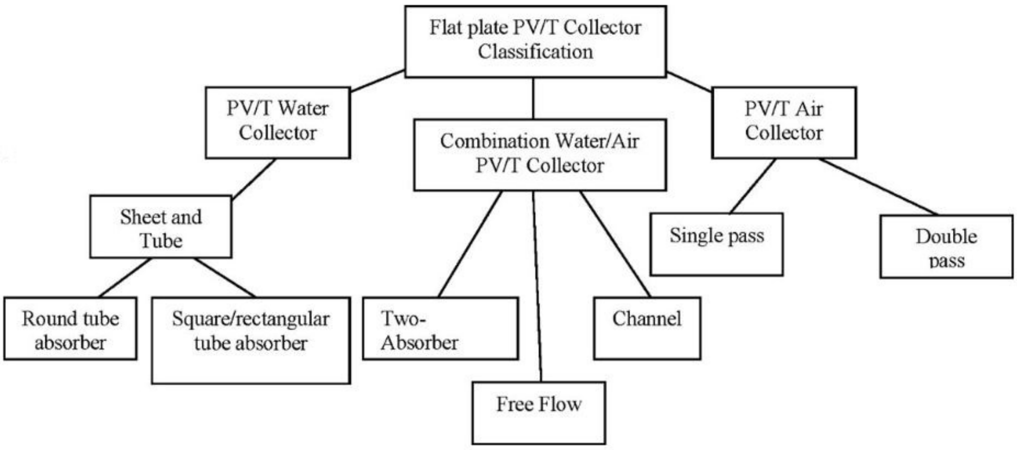

Figure 1. Classification of flat-plate PVT collectors (Source: [4]).

With respect to market and research activities related to PVT, there has been an increasing interest during the last years [5]. The market is still very small compared to PV and solar thermal markets; however, a number of commercial products are now available and different types of PVT configurations have gained ground [5]. Concerning the research on PVT, several investigations have been conducted, revealing the number of possible PVT concepts and the research/development problems for optimizing both electrical and thermal efficiency of a device (simultaneously). Multiple aspects can be optimized such as the spectral characteristics of the PV cells, their solar absorption and the internal heat transfer between the cells and the heat-collecting system [6].

Another aspect which has to do with PVT is the possible application. The output of both electricity and heat shows that PVT technology can be adopted in the building sector, especially when the available area for installation is limited [5]. Over the last years there is a new tendency for integration of solar systems into the building. These systems are known as BI and they include several configurations: BI solar thermal, BIPV, BIPVT, etc. It should be noted that BI solar systems replace a building component (e.g. façade) and they are not added on the building as the traditional BA configurations. In this way, BI solar systems offer multiple advantages (in comparison to the BA configurations), for example from aesthetic point of view [7, 8]. For the specific case of BIPVT, several studies have been presented, for multiple configurations, for example façade-integrated Fresnel-transmission PVT concentrator [9], two-inlet air-based BIPVT [10], BIPVT systems which combine roof-integrated with façade-integrated configurations [11].

At this point it should be noted that except of PVT applications for buildings (e.g. for domestic water heating: [2]), PVT systems also provide other types of applications such as desalination [12] and drying of agricultural products [13].

In terms of review studies about PVT systems, in Table 1 representative references are presented. From Table 1, it can be seen that most of the reviews focus on the recent PVT developments and the different types of PVT while few of these reviews include information about PVT from LCA (life cycle assessment)/environmental point of view. Based on the above mentioned gap of the literature and taking into account that PVT systems offer multiple benefits for the environment (e.g. energy and CO_2 savings in the building sector and in the industry), it can be seen that there is a need for a review study which focuses on PVT from environmental point of view. In the frame of this concept, the present article presents a literature review on PVT with emphasis on investigations which include PVT environmental issues (the references are classified e.g. according to the type of the PVT system and the working fluid). Moreover, the present article presents separate sections with: 1) information about methods and indicators which provide (or which can provide as a future prospect) useful information about PVT from environmental point of view, 2) factors which influence PVT from environmental point of view (materials of certain components, etc.), along with a critical discussion.

Table 1. Selected review studies about PVT.

REVIEW STUDIES	STUDIED ISSUES
Chow et al. [14]	PVT developments in the twentieth century Recent developments in flat-plate PVT and concentrator-type design Miscellaneous developments over the last years
Good et al. [5]	PVT collector technologies PVT in the building sector PVT market, market drivers and barriers
Tyagi et al. [15]	Solar thermal collectors (evacuated-tube, etc.) PV technology (types of solar cells, etc.) PVT technology (PVT/air, etc.) Novel applications of PVT
Zhang et al. [16]	The concept of PVT and the theory behind PVT operation Standards for PVT evaluation from technical, economic and environmental point of view R&D progress and practical application of PVT and opportunities for further studies
Zondag [17]	PVT history Issues about PVT/air and PVT/liquid systems Ventilated BIPV with heat recovery PVT market
Reddy et al. [18]	PVT air cooling, water cooling, unconventional cooling methods Efficiency by different cooling methods
Chow [19]	Developments in PVT technology Advancements over the recent years (e.g. BIPVT, concentrator-type PVT) The future work required
Sharaf and Orhan [20, 21]	CPVT: fundamentals, design, current technologies, design considerations, PV cells, solar thermal collectors, solar concentrator optics, concentrated solar energy [20] CPVT: implemented systems, performance assessment and future directions, high- and low-concentration CPVT [21]
Amanlou et al. [22]	CPVT: optics, different types of concentrators, experimental device, experimental results
Besheer et al. [23]	PVT/liquid, PVT/air, BIPVT Discussion about manufacturing, module efficiencies (thermal and electrical) Applications and cost
Charalambous et al. [24]	PVT collector types Performance of PVT collectors Qualitative evaluation of thermal/electrical output
SCI-NETWORK [25]	PVT/air, PVT/liquid, PVT concentrators Recommendations for procurers
Daghigh et al. [26]	Classification of PVT liquid collectors Refrigerant-based PVT collectors PVT water collectors, PVT hybrid water/air collectors

	Other types of liquid PVT collectors Economic analysis of PVT water collectors Performance analysis of PVT collectors by using energy and exergy analysis The direction of water- and refrigerant-based PVT systems, future research and development
Ibrahim et al. [4]	PVT collector design and performance evaluation Future developments for PVT collectors: BIPV, BIPVT
Avezov et al. [27]	PVT/air collectors and PVT/water collectors
Good [28]	Environmental impact assessment of PVT

2. METHODS AND INDICATORS WHICH PROVIDE INFORMATION FROM ENVIRONMENTAL POINT OF VIEW

In section 2 and in Table 2, information about representative methods and environmental indicators is provided, before the presentation of the literature studies which include environmental issues about PVT (section 3).

Table 2. Different methods which provide information for several environmental issues [29][1].

METHODS	EXPLANATIONS
CML-IA	Midpoint approach [29]
IMPACT 2002+	Combined midpoint/damage approach [29]
ReCiPe	Combination of the problem-oriented approach (midpoint) with the damage-oriented approach (endpoint) [29]
CED (cumulative energy demand)	CED includes characterization factors for the energy resources divided into 5 impact categories: non-renewable, fossil; non-renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; renewable, water [29]
Greenhouse gas protocol	An accounting standard of greenhouse gas emissions [29]
IPCC 2013	IPCC 2013 provides information about GWP (global warming potential) in a timeframe of 20, 100 and 500 years [29]

From Table 2, it can be seen that there are different methods (that can be adopted in the frame of studies about PVT) which provide information for multiple environmental issues such as energy demand, GHG (greenhouse gas) emissions, midpoint and endpoint impact categories. In the following paragraphs some explanations (related with the methods of Table 2) are provided.

Primary energy (also known as energy sources) is the energy that is embodied in the natural resources (some examples: coal, crude oil, natural gas) and it has not

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[1] In Table 2 are presented some of the methods of the report [29]. More information about additional methods can be found in [29].

undergone any anthropogenic conversion. This primary energy should be converted (and transported) in order to become usable energy. Embodied energy represents the energy utilized in order to produce a material substance (e.g. processed metals or building materials), considering the energy utilized at the manufacturing facility, the energy utilized for the production of the materials that are used in the manufacturing facility, and so on [30].

By knowing the primary energy demand related with the life-cycle of a system, the energy metric of EPBT (energy payback time) can be found. EPBT presents the time needed for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was utilized to produce the system itself [31]. Based on the concept of EPBT, the GHG PBT (greenhouse-gas PBT) [32, 33] can be also evaluated, by considering the $CO_{2.eq}$ emissions over system life-cycle (instead of the primary energy quantities which are taken into account for the calculation of the EPBT). On the other hand, ReCiPe is a newly-developed LCIA (life cycle impact assessment) method, it provides information for different impact categories [29] and based on this method another PBT (ReCiPe PBT [32]) can be also evaluated.

At this point it should be noted that specifically for the case of BI solar systems, the EPBT and the GHG PBT can be also calculated by taking into account that there is material replacement [33]. This alternative way of calculation of the PBTs is related with the fact that a BI system replaces the materials of a building component, for example the materials of a wall.

With respect to methods which are based on midpoint and endpoint approaches, it should be mentioned that a midpoint-based assessment presents a transparent analysis of environmental impacts with relative low uncertainties. Nevertheless, midpoint categories are relative difficult to interpret (for the people that are not experts) while the endpoint categories are very easy to understand but the results are less detailed and they have higher uncertainty [34].

In terms of the impact categories that are included in the midpoint approach of ReCiPe [29] these are: Ozone depletion, Human toxicity, Ionizing radiation, Photochemical oxidant formation, Particulate matter formation, Terrestrial acidification, Climate change, Terrestrial ecotoxicity, Agricultural land occupation, Urban land occupation, Natural land transformation, Marine ecotoxicity, Marine eutrophication, Freshwater eutrophication, Freshwater ecotoxicity, Fossil fuel depletion, Minerals depletion, Freshwater depletion. At the endpoint level of ReCiPe [29], most of these midpoint impact categories are multiplied by damage factors and then they are aggregated into the following endpoint categories: Human health, Ecosystems, Resource surplus costs. In the same way, IMPACT 2002+ includes 14 midpoint categories (Human toxicity, Respiratory effects, Ionizing radiation, Ozone layer depletion, etc.) which are aggregated into four damage categories (Human health, Ecosystem quality, Climate change, Resources) [29].

3. STUDIES WHICH INCLUDE ENVIRONMENTAL ISSUES ABOUT PVT SYSTEMS: A LITERATURE REVIEW

In the present section the studies are presented classified into subsections according to the type of system in terms of its integration into the building (BA vs. BI systems). This is because BI configurations are associated with material replacement, a factor which (as it was previously explained in section 2) can influence BIPVT profile from environmental point of view. On the other hand, PVT systems with sunlight concentration are presented as a separate category (subsection 3.3). Finally, in subsection 3.4 other types of systems for different applications (drying, etc.) are presented (as a separate category).

3.1. Building-added (BA) PVT systems

In Table 3 references (which include environmental issues) about BA PVT configurations are presented and it can be seen that most of these studies:

- Are for domestic applications.
- Have water as working fluid.
- Adopt crystalline PV cells.
- Have been studied for several climatic conditions (including Mediterranean countries).
- Examine EPBT, CO_2 emissions and cost issues.
- Adopt a lifespan of 20 years.

Specifically for the issue «applications», it can be observed that most of the studied cases are about active PVT/water systems which produce water at temperatures appropriate for domestic water heating. Thereby, for most of the cases the PVT systems cover the domestic energy demand, contributing to the reduction of CO_2 emissions in the building sector.

Moreover, it should be noted that some authors propose the utilization of reflectors [1, 35] and small modifications (e.g. TFMS (thin flat metallic sheet) [35]) of the reference system in order to improve PVT performance. For example, Tripanagnostopoulos et al. [35] proposed PVT configurations which use aluminium as diffuse reflector material and galvanized iron for the reflector installation. It was noted that all the experimental models were combined with stationary flat diffuse reflectors, placed among the parallel rows of the systems for the horizontal roof installation. The diffuse reflectors were investigated (instead of specular reflectors) since they offer almost uniform distribution of the reflected solar radiation on PV module surface [35].

In addition, there are studies which include a comparison of PVT with PV installations [1, 35, 43, 45, 49] and the results show that the PVT configurations show better performance (e.g. from environmental point of view) in comparison to the PV systems. With respect to BA PVT EPBTs, from Table 3 it can be observed that these values range from around 1 to 4 years, depending on the studied configuration.

Table 3. Literature studies which include environmental issues about BA PVT systems.

REFERENCE/YEAR OF THE STUDY	TYPE OF PV CELLS	WORKING FLUID	TYPE OF SYSTEM, APPLICATION, ETC.	REGION/ COUNTRY	ENVIRONMENTAL ISSUES STUDIED	LIFESPAN	RESULTS	ADDITIONAL INFORMATION/ FINDINGS
Tripanagnostopoulos et al. (2006) [35]	Multi-crystalline silicon	Air	PV vs. PVT systems for building roof (horizontal and titled; glazed and unglazed; with/without reflectors; with/without TFMS)	Patra, Greece	EPBT, CO_2 PBT, cost PBT, etc.	30 years	EPBTs and CO_2 PBTs for the scenario of 12-months air heating: 0.9-1.5 years for the PVT systems; 2.5-3.2 years for the PV systems	Glazed type PVT systems showed optimum performance in terms of energy, cost and LCA results
Raman and Tiwari (2008) [36]		Air	PVT for buildings (with/without BOS)	India: Srinagar, Mumbai, Jodhpur, New Delhi, Banglore	EPBT, life-cycle cost analysis, etc.	20 years; 30 years; 40 years; 50 years	EPBT of the PVT without BOS: around 2 years	The EPBT can be further reduced for higher solar radiation, longer sunshine hours and number of clear days
Finocchiaro et al. (2016) [37]		Air	Compact desiccant evaporative cooling system with PVT; residential sector, small office buildings	Palermo, Italy	ILCD 2011; CED	15 years	Production phase: predominant in most of the indicators; use phase: lower impacts for all the categories by 96% in comparison to a conventional system	The solar batteries show a considerable impact in human toxicities, freshwater toxicity and abiotic potential-minerals indicators
Tiwari et al. (2007) [38]	Single crystal silicon	Water	Scenarios with/without BOS for open-field and rooftop systems; optimum inclined PVT system	Different climatic zones in India	EPBT, CO_2 emissions, etc.		PVT EPBT is reduced due to the additional thermal energy available	The potential for mitigation of CO_2 emissions and the importance of PVT systems for sustainable development were also highlighted
Dubey and Tiwari (2008) [39]		Water	PVT solar water heater; domestic	Four types of weather conditions of New Delhi, India	EPBT, carbon credit, life-cycle cost analysis, etc.	10 years; 20 years; 30 years	If the system is installed at 10% of the total residential houses in Delhi, the total carbon credit earned annually in terms of thermal energy is Rs. 105.6 cores (in terms of exergy is Rs. 10.2 cores)	The cost/kWh is higher based on exergy when compared to the cost/kWh based on thermal energy
Kalogirou and Tripanagnostopoulos (2006) [40]	Polycrystalline silicon; amorphous silicon	Water	PVT systems for domestic hot water applications: passive (thermosyphonic) and active	Nicosia (Cyrpus), Athens (Greece), Madison (Wisconsin)	Life-cycle cost analysis, etc.	20 years	For higher solar radiation (Nicosia, Athens), the economics show better figures; although amorphous silicon modules are much less efficient than polycrystalline	General conclusion: as the overall energy production of the units is increased, the hybrid configurations show better chances of success (this is also strengthened by the improvement of the economic viability of the

							ones, they show better figures due to their lower initial cost	systems, especially for applications of low-temperature water e.g. for domestic use)
Dubey and Tiwari (2009) [41]		Water	PVT flat-plate water collectors connected in series; residential houses	Five different cities (New Delhi, Bangalore, Mumbai, Srinagar, Jodhpur) of India	CO_2 mitigation, cost analysis, etc.	30 years	For a system installed at 10% of the total residential houses in Delhi: total carbon credit by PVT water heating (thermal energy) USD $144.5 million/year	Collectors partially covered by PVs are beneficial for the users whose primary requirement is hot water production; Collectors fully covered by PVs are beneficial for the users whose primary requirement is electricity production
Canelli et al. (2015) [42]		Water	Conventional system with boiler and chiller, conventional system in load sharing operational mode, GSHP system, hybrid GSHP-FC and hybrid GSHP-PVT	Napoli, Italy	$CO_{2.eq}$ emissions, economic analysis, primary energy savings, etc.		Reduction of $CO_{2.eq}$ emissions equal to 15.8% and 52.0% for the GSHP-FC and for the GSHP-PVT, respectively	The better performance (from energetic and environmental point of view) of the GSHP-PVT is because of the use of a significant amount of renewable energy
Herrando et al. (2014) [43]	Mono-crystalline	Water	PVT systems for electricity and hot water in the UK domestic sector	London, UK	$CO_{2.eq}$ emissions, brief economic analysis, etc.	20 years 25 years	A PVT system can save up to 16.0 t of CO_2 (lifetime: 20 years) which is higher than the 11.8 t of CO_2 saved with a PV-only system	All the studied PVT systems outperformed the PV-only configuration in terms of the emissions and it was concluded that hybrid PVT systems offer a notably improved proposition over PV-only configurations
Herrando and Markides (2016) [44]	Mono-crystalline	Water	PVT systems for electricity and hot water in a typical house in London	London, UK	CO_2 emissions, techno-economic analysis, etc.	20 years; 25 years	System reduction in CO_2 emissions: 16.0 t over a lifetime of 20 years	For low solar irradiance and low ambient temperatures, a higher coverage of total household energy demands and higher CO_2 emission savings can be achieved by the complete coverage of the solar collector with PVs and a relatively low collector cooling flow rate
Tripanagnostopoulos et al. (2005) [1]	Multi-crystalline silicon	Water	PV vs. PVT systems for building roof (horizontal and titled; glazed and unglazed; with/without reflectors)	Patra, Greece	EPBT, CO_2 PBT, cost PBT, etc.	15-25 years	PVT systems (for replacing electricity only): EPBT 0.8-3.8 years and CO_2 PBT 0.8-3.5 years	PVT systems are cost effective and show better behavior (from environmental point of view) compared to standard PV modules
Dualsun [45]	Mono-crystalline	Water	PVT system for electricity and hot water e.g. for buildings	France	Reduction of energy consumption in buildings, etc.		PVT shows better performance in comparison with a standard PV	

Hassani et al. (2016) [46]	Si single-crystalline	Water/nanofluid	Several PVT configurations for domestic applications (with/without concentration, etc.)		Life cycle exergy analysis, exergy PBT, etc.	25 years	The nanofluid-PVT offers emission savings of around 448 kg $CO_{2,eq}$ per m^2 per year	The life-cycle exergy analysis showed that the nanofluid-PVT system has better performance in comparison to standard PV and PVT
Shyam et al. (2016) [47]	Semitransparent crystalline silicon	Water	PVT collectors partially covered by PVs; domestic applications	New Delhi, India	CO_2 mitigation, energy gain, exergy gain, EPBT, carbon credit, etc.	10 years; 20 years; 30 years	EPBT: 1.50 and 14.19 years based on the overall thermal energy and exergy, respectively	Carbon credits earned in a year: Rs. 6321.70 for overall thermal energy gain (Rs. 667.30 for exergy gain)
Wang et al. (2015) [48]			Hybrid combined cooling heating and power system (solar energy, natural gas): it includes PV and/or heat collector	Beijing, China	GWP, acidification potential, etc.	20 years	Following-thermal-load strategy is superior to following-electrical-load strategy (taking into account the environmental compensation of surplus products from the hybrid combined cooling heating and power system)	
Ozturk et al. (2012) [49]			A flat-plate collector, a PV and a PVT were studied: electricity and heat for domestic applications		EPBT, CO_2 PBT, etc.		EPBTs and CO_2 PBTs varied between 2, 12, 3.8 and 1.6, 3.6 and 1.8 years (for the flat-plate collector, the PV and the PVT, respectively)	Energy, exergy analysis and LCA were conducted

3.2. Building-integrated (BI) PVT systems

For the specific case of BIPVT configurations, there are considerably less studies (which include environmental issues) in comparison to BA PVT. Based on these references (Table 4) it can be observed that several types of PV cells have been examined, by adopting air as working fluid (for façade- and roof-integrated applications). Moreover, these investigations are for variable climatic conditions (Australia, India and Italy) and the adopted lifespans range from 5 to 30 years, depending on the system. Furthermore, the major part of these studies is about EPBT, CO_2 emissions and economic issues. The results (Table 4) show EPBTs varying from around 2 to 14 years, depending on the configuration.

Table 4. Literature studies which include environmental issues about BIPVT systems.

REFERENCE/YEAR OF THE STUDY	TYPE OF PV CELLS	WORKING FLUID	TYPE OF SYSTEM, APPLICATION, ETC.	REGION/ COUNTRY	ENVIRONMENTAL ISSUES STUDIED	LIFESPAN	RESULTS	ADDITIONAL INFORMATION/ FINDINGS
Agrawal and Tiwari (2015) [50]		Air	Glazed PVT: it can be integrated into a building (space heating) or into a dryer (crop drying)	New Delhi, India	EPBT, CO_2 emissions, techno-economic analysis, etc.	30 years	EPBT (based on energy): 1.8 years	Net CO_2 mitigation over lifetime: 76.5 t $CO_{2.eq}$ on overall thermal energy
Crawford et al. (2006) [51]	Crystalline silicon; amorphous silicon	Air	BIPVs with/without heat recovery and other scenarios	Sydney, Australia	EPBT, embodied energy, etc.	20 years	EPBT for BIPVs with heat recovery: 4-9 years (amorphous), 6-14 years (crystalline)	The use of heat recovery in combination with a BIPV system reduces the EPBT of a typical BIPV system
Kamthania and Tiwari (2014) [52]	Silicon and non-silicon based (CdTe; CIS; HIT; CIGS, etc.)	Air	Semi-transparent hybrid PVT double pass façade	Four weather conditions of Srinagar, India	EPBT, CO_2 mitigation, etc.	Several scenarios (5-30 years) based on PV-cell type	CO_2 mitigation, carbon credits earned: maximum for HIT and minimum for CIGS	HIT-type PV module was recommended for the proposed system due to its low EPBT, high EPF and LCCE
Battisti and Corrado (2005) [53]	Multi-crystalline silicon	Air	PV and PVT systems (roof-integrated; for space heating or domestic hot water)	Rome (Italy); Sydney (Australia)	EPBT, $CO_{2.eq}$ PBT, etc.	15-30 years	All the studied configurations showed environmental PBTs considerably lower than their expected lifespan (3–4 years vs. 15–30 years)	From energetic and from environmental point of view, PVs are more interesting when the module is used as dual-output: heat recovery for domestic hot water reduced the environmental PBTs more than 50%
Agrawal and Tiwari (2010) [54]	Mono-crystalline silicon; poly-crystalline silicon; ribbon crystalline silicon; amorphous silicon; CdTe; CIGS	Air	BIPVT system fitted as rooftop: generation of electrical energy and thermal energy for space heating	New Delhi, India	Life cycle cost assessment, etc.		The cost of unit power generation by the amorphous silicon BIPVT systems was US $ 0.1009 per kWh (quite close to the cost of power generation by the conventional grid)	Although the mono-crystalline BIPVT system is more suitable for residential consumers based on its energy and exergy efficiencies, the amorphous silicon BIPVT was found to be more economical
Rajoria et al. (2013) [55]		Air	Case 1: two integrated columns each having 18 PVT modules; case 2: two integrated columns of 18 modules each having 36 PVT tiles in the module	Four different cities of India: Delhi, Jodhpur, Bangalore, Srinagar	CO_2 mitigation, enviro-economic assessment, etc.		CO_2 mitigation for Bangalore in terms of overall thermal energy gain for case1 and 2 was 90.85 t CO_2/annum and 99.81 t CO_2/annum, respectively	Comparing to case 1, case 2 showed lower cell temperature (19.0%), higher electrical efficiency (6.5%) and higher average outlet air temperature (18.1%)
Rajoria et al. (2016) [56]		Air	Opaque (case A); solar cell tiles (silicon) (case B); semi-transparent (case C)	New Delhi, India	EPBT, carbon credit, life-cycle cost analysis, etc.	20 years; 25 years; 30 years	Case C showed the minimum EPBT in terms of energy and exergy (0.70 and 1.84 years, respectively)	Case A showed the maximum EPBT

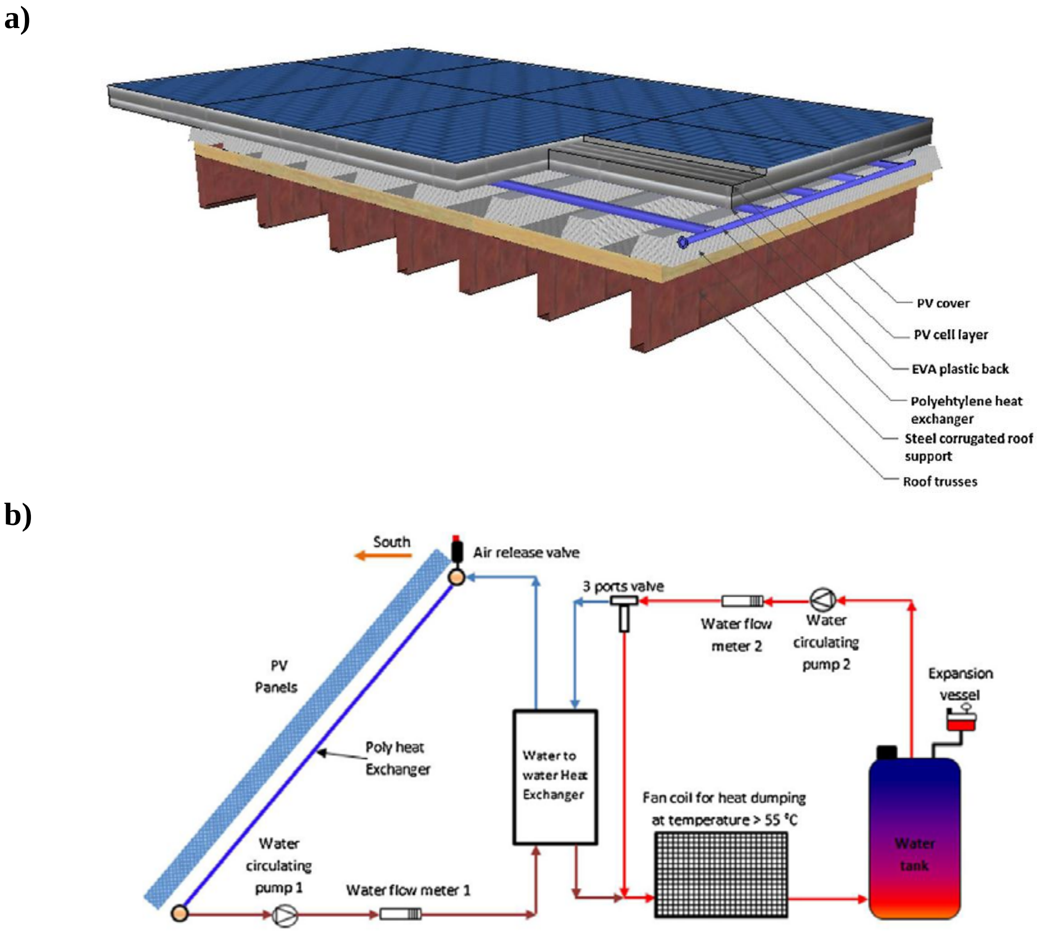
It should be mentioned that in the literature there are also some studies (that include environmental issues) which examine both BA PVT and BIPVT systems (Table 5). Most of these investigations give emphasis on EPBT and CO_2 emissions and they are about air-based configurations. The results reveal that for some cases the BA systems are better (from environmental point of view) than the BI configurations. For example the BA PVT and the BIPVT installations studied by Chow and Ji [33], presented EPBTs 2.8 and 3.8 years, respectively.

Table 5. Literature studies which include environmental issues about BA PVT and BIPVT systems.

REFERENCE/YEAR OF THE STUDY	TYPE OF PV CELLS	WORKING FLUID	TYPE OF SYSTEM, APPLICATION, ETC.	REGION/ COUNTRY	ENVIRONMENTAL ISSUES STUDIED	LIFESPAN	RESULTS	ADDITIONAL INFORMATION/ FINDINGS
Tiwari et al. (2009) [57]	Mono crystalline	Air	PVT: scenarios with and without BOS (for BA and BI (roof or wall) applications)	New Delhi, India	EPBT, LCCE, etc.	15 years; 30 years; 50 years	EPBT (outdoor conditions without BOS): 3.00-3.96 years, for 2004-2007 (the EPBT can be further reduced for higher insolation, etc.)	EPBT shows significant reduction by taking into account the increase in annual energy availability of the thermal energy in addition to the electrical energy
Agrawal and Tiwari (2013) [58]	Mono-crystalline silicon	Air	Unglazed hybrid PVT tiles, glazed hybrid PVT tiles and conventional hybrid PVT air collectors	Srinagar, India	CO_2 emissions, thermal energy gain, etc.	30 years	CO_2 emissions reduction/annum, based on overall thermal energy gain of unglazed and glazed PVT tiles, was higher by 62.3% and 27.7%, respectively, compared to the conventional PVT	The overall annual thermal energy and exergy gain of the unglazed PVT tiles was higher by 27% and 29.3%, respectively, compared to the glazed PVT tiles and by 61% and 59.8%, respectively, compared to the conventional PVT
SolarWall [59]		Air	Several configuration of BA PVT and BIPVT systems		CO_2 emissions, PBT, etc.		Considerable reduction in CO_2 emissions was presented as one of the benefits (since displacing the heating load usually means displacement of natural gas or heating oil)	The heat energy captured by the PV panels is ducted into building HVAC system where it is used to displace the conventional heating load
Chow and Ji (2012) [33]	Single-crystalline silicon	Water	BIPVT (vertically mounted) and BA PVT (free stand) systems	Hong Kong	EPBT, GHG PBT, cost PBT, etc.	15-30 years, in general	EPBTs: 2.8 years for the BA PVT at the best angle of tilt and 3.8 years for the BIPVT	GHG PBTs: 3.2 years for the BA PVT and 4.0 years for the BIPVT

By taking into account the references presented in Tables 4 and 5, it can be seen that BIPVT systems are a research topic with increasing interest. In addition, for most of the cases (Tables 4 and 5) the configurations are BIPVT/air. On the other hand, the proposed applications take into account the thermal/fluidic performance of the system coupled with building envelope. This is because BIPVT systems are active building envelopes since they replace a building component and at the same time they produce energy to cover building energy needs. Moreover, the proposed applications include façade-integrated as well as roof-integrated configurations. The performance of these two options is related with the incident solar radiation. A study (from energetic and economic point of view) about BIPVT systems for residential applications under different climates in Europe (Almeria, Milan, Naples, Freiburg) [11] showed that, for all the weather zones which were examined, the proposed roof BIPVT system is more economically convenient than the proposed façade/roof BIPVT configuration [11].

In terms of PVT systems appropriate for BI applications, Gaur et al. [60] presented numerical and experimental studies about BI semi-transparent PVT. Analytical expressions in terms of electrical and thermal parameters of a proposed system (with air duct and without air duct) were presented. Validation of the expressions was done by means of experiments on a prototype (New Delhi, India) [60]. Buker et al. [61] investigated a PVT/water system suitable for roof-integrated applications. In Fig. 2(a), the layers of the module studied by Buker et al. [61] are presented. Moreover, in Fig. 2(b) and Fig. 2(c) the plumping of the installation and the prototype of the study [61] are illustrated. The proposed system [61] includes a polyethylene heat exchanger loop underneath the PV modules to form a PVT roof collector. The roof structure consists of different layers: outer cover, layer of PV cells beneath the cover, EVA plastic layer at the back of the PV adjacent to the PV cells layer, polyethylene heat exchanger and roof support. It was noted [61] that the piping system is below the roof truss and joined utilizing flexible coupled connectors with valves in order to offer a leak free connection. Moreover, the supply pipe provides cold water to the polyethylene heat exchanger while the return pipe transports the hot water from the heat exchanger. It was also mentioned that the PV modules and the steel corrugated roof support are well clamped together and the polyethylene heat exchanger is placed in between [61].



c)

Figure 2. PVT/water system (appropriate for BI applications) studied by Buker et al. [61]: a) the heat exchanger loop underneath the PV modules, b) the thermal roof unit piping and c) the prototype of the proposed system (Source: [61]).

3.3. Concentrating PVT (CPVT) systems

In the literature there are few studies which examine environmental issues about CPVT systems. From Table 6 it can be observed that these investigations are about water-based systems (for buildings as well as for large-scale applications) and most of them adopt triple-junction PV cells. Regarding concentrating ratios, these range from low-concentration to high-concentration. The climatic conditions are for desert areas, Spain and Italy. In terms of the studied issues, most of the studies examine EPBT and CO_2 emissions.

With respect to the use of concentrating systems instead of using systems without concentration, in the work of Renno and Petito [64] it was noted that the high concentration is an interesting solution for domestic applications, from energetic and from economic point of view (especially for the case of southern Italy), during the life-cycle of the proposed CPVT system.

Table 6. Literature studies which include environmental issues about CPVT systems.

REFERENCE/YEAR OF THE STUDY	TYPE OF PV CELLS	WORKING FLUID	TYPE OF SYSTEM, APPLICATION, ETC.	REGION/ COUNTRY	ENVIRONMENTAL ISSUES STUDIED	LIFESPAN	RESULTS	ADDITIONAL INFORMATION/ FINDINGS
Burg et al. (2014) [62]	Triple-junction	Water	Low-cost PVT concentrator from innovative materials; large-scale applications; high-concentrating system	Desert areas	CO_2 emissions, EPBT, etc.	30 years	Albedo change influences CO_2 emissions	The system includes: 1) concrete tracking and supporting structure, inflatable mirrors with 10× lower cost than steel/glass technologies, 2) combination with absorption cooling and membrane distillation desalination
Cellura et al. (2011) [63]	Crystalline silicon	Water	BA; low-concentrating PVT system, installed on the roof of a building	Palermo, Italy	EPBT, GWP PBT, ozone layer depletion, acidification potential, etc.	20 years	EPBT and GWP PBT: 0.7 and 1 years, respectively	Mass and energy balance in the life-cycle of the reference system was conducted, including environmental impacts associated with energy source generation, water and raw materials production, end-of-life of the CPVT system
Renno and Petito (2015) [64]	Triple-junction	Water	BA; point-focus, high concentration PVT; domestic hot water	Three zones of Italy: north, center, south	CO_2 emissions, primary energy savings, etc.	20 years	3376 kg CO_2 avoided per year	The high concentration is an interesting solution for domestic applications, from energetic and from economic point of view (especially in southern Italy), during CPVT system life-cycle
Menoufi et al. (2013) [65]	Mono-crystalline	Water	BICPVT; concentration ratio (CR): 10×	Lleida, Spain	EI99, etc.		Considerable environmental impact reduction is achieved by replacing the conventional BIPV with BICPV	The phase of material manufacturing was studied

3.4. Other types of PVT systems/applications

In Table 7, studies (which include environmental issues) about several types of PVT configurations/applications are presented. It can be seen that except of PVT installations which are appropriate for buildings, there are also other types of PVT systems for applications such as crop drying [13] and water distillation [68]. Moreover, Table 7 shows that most of these investigations examine EPBT, CO_2 emissions and cost issues. In terms of the climatic conditions, different climatic conditions were examined.

Table 7. Literature studies which include environmental issues about several types of PVT systems/applications.

REFERENCE/YEAR OF THE STUDY	TYPE OF PV CELLS	WORKING FLUID	TYPE OF SYSTEM, APPLICATION, ETC.	REGION/ COUNTRY	ENVIRONMENTAL ISSUES STUDIED	LIFESPAN	RESULTS	ADDITIONAL INFORMATION/ FINDINGS
Barnwal and Tiwari (2008) [13]	Silicon cells	Air	PVT greenhouse dryer; crop drying	New Delhi, India	EPBT, CO_2 emissions, CO_2 mitigation, carbon credit, LCCE, etc.	30 years	EPBT: 3-5 years	It is a self-sustaining system with minimum operation/maintenance which can be utilized to dry high-water content fruits and vegetables
Kalogirou and Tripanagnostopoulos (2007) [66]	Polycrystalline and amorphous silicon	Water	PVT systems for industrial applications	Nicosia (Cyprus), Athens (Greece), Madison (Wisconsin)	Life-cycle cost, etc.	20 years	Positive life-cycle savings were obtained for the hybrid systems (the savings were higher for higher load temperature applications)	Although amorphous silicon modules are much less efficient than polycrystalline ones, better economic figures were found because of their lower initial cost (better cost/benefit ratio)
Kumar (2013) [67]		Water	PVT solar distillation system	New Delhi, India	CO_2 emissions, CO_2 mitigation, embodied energy, cost issues, LCCE, etc.	15 years; 30 years	Net CO_2 mitigation for the lifespan of 30 years: 32.5 t	Embodied energy (fabrication of the hybrid PVT active solar still): 3689 kWh and 5990 kWh for 15 and 30 years lifespan, respectively
Kumar and Tiwari (2009) [68]		Water	Passive vs. active hybrid PVT solar stills (for water distillation)	New Delhi, India	EPBT, embodied energy, life-cycle cost analysis, etc.	15 years; 30 years	EPBTs of the passive and active solar stills: 2.9 years and 4.7 years, respectively	The annual distillate yield of the active solar still is 3.5 times higher than the yield of the passive solar still
Nayak et al. (2014) [69]	Mono-crystalline silicon, multi-crystalline silicon, nano-crystalline silicon, amorphous silicon, CdTe, CIGS		PVT greenhouse dryer	New Delhi, India	CO_2 mitigation, embodied energy, EPBT, LCCE, carbon credits, EPF, etc.		EPF, LCCE, CO_2 mitigation and carbon credits earned were maximum for the mono-crystalline silicon PV; and thus, it was recommended for the system	The annual thermal and exergy performance of the proposed PVT dryer, considering various silicon and non-silicon-based PV modules was evaluated
Izquierdo and de Agustín-Camacho (2015) [70]	Multi-crystalline		PVT micro grid feeding a reversible air-water, 6 kW heating capacity heat pump	Madrid, Spain	Reduction of CO_2 emissions, energy balance, etc.		Savings in CO_2 emissions (replaced system: gasoil boiler): 836 kg CO_2 for December-April	If the replaced system is a natural-gas boiler, the savings are 574 kg CO_2 for December-April
Swissolar [71]			Several solar systems (for applications in industry, buildings, etc.), including PVT	Switzerland			Multiple advantages of the solar systems were presented, including reduction of CO_2 emissions	

4. FACTORS WHICH AFFECT PVT FROM ENVIRONMENTAL POINT OF VIEW

4.1. PV cell material

The profile (from environmental point of view) of a PVT system is influenced by the type of the PV cells. Thereby, before presenting PVT studies which have adopted different types of PV cells, it is necessary to present some information about PV cell materials.

4.1.1. General issues

PVs utilize semiconductor materials to generate electricity from solar energy and the most commonly used semiconductor element is silicon (Si). Solar cell is an electronic device which converts solar energy directly into electrical energy (through the photovoltaic effect). Solar cell design includes specifying the parameters of a solar cell structure in order to maximize the efficiency [31]. Multi-crystalline Si PVs have the greatest market share, followed by mono-crystalline Si, followed by CdTe (cadmium telluride) thin-film. Although CdTe thin-film has the lowest module production cost, multi-crystalline Si has higher efficiency, reducing the cost for the mounting structure and installation (since those are proportional to the area needed for the installation). The solar grade silicon production is known to be the most energy-intensive stage during the life-cycle of silicon PVs (when the typical Siemens process is utilized) [31].

Except of the above mentioned PV cells, there are also other types of PV cells such as amorphous and nanocrystalline Si, CIGS (copper indium gallium diselenide) and organic PV cells which are based on different materials and manufacturing processes [31].

In terms of some examples about EPBTs of rooftop mounted PV systems (for U.S- and European- production and installation under average U.S. irradiation of 1800 kWh/m^2/year and a performance ratio of 0.75), in the work of Fthenakis [31] EPBTs (including BOS, frame and module) of around 1.6 years (for mono-Si and multi-Si) and 0.7 years (for CdTe) were presented.

4.1.2. Hazardous materials used in PV cell production

In order to provide a more complete picture about PV cell materials, in the present subsection some information about hazardous materials utilized in PV cell production is presented.

The production of crystalline Si wafers begins with the mining of silica (SiO_2) which is found in the environment as sand or quartz. Then, silica is refined at high temperatures in order to remove O_2 and produce metallurgical grade silicon. In order to achieve very high purities there is a chemical process that exposes metallurgical grade silicon to hydrochloric acid and copper. The next step is to produce crystals of monocrystalline or multi-crystalline silicon [72]. The high temperature needed for crystalline-Si production makes it an extremely energy intensive and expensive process, and, in addition, there is production of large amounts of waste (80% of the initial metallurgical grade silicon is lost during the process). There are several chemicals which are utilized in the production of crystalline silicon and these need special handling and disposal (corrosive chemicals, etc.). In addition to the chemicals used by all crystalline silicon cell production, additional chemicals (which require special handling in order to prevent hazards) are adopted to manufacture mono-crystalline Si solar cells. Moreover, in order to make amorphous-Si cells, silane or chlorosilane gas is heated and mixed with hydrogen [72].

On the other hand, CdTe thin-film solar PV panels utilize layers of CdTe and cadmium sulfide (CdS). Cadmium (Cd) is by-product of zinc mining. The rare metal tellurium (Te) is by-product of copper, lead and gold mining, and its scarcity may be a bottleneck for the production of CdTe cells [72]. This will make the recovery of Te by means of recycling essential for the success of this rapidly growing technology. The major health and safety hazards related to the manufacture of CdTe cells are associated with the utilization of cadmium, cadmium sulfide, cadmium chloride and thiourea. Cadmium is carcinogen and extremely toxic [72].

With respect to CIS (copper indium diselenide) and CIGS, numerous chemicals are used in the production of these panels and many of them are very toxic. For example, these chemicals include hydrogen selenide (or selenium hydride) which is considered highly toxic [72]. On the other hand, depositing the CIS/CIGS layers onto a surface needs mixing of copper and indium (and gallium for the case of CIGS) with hydrogen selenide (and utilization of several industrial techniques). It should be noted that processes which use 100% of gallium and indium inputs are important due to the fact that these are globally rare metals [72].

4.1.3. Studies about PVT systems with different types of PV cell

Nayak et al. [69] evaluated the annual thermal and exergy performance of a hybrid PVT greenhouse dryer (New Delhi, India) by adopting several silicon and non-silicon-based PV modules: mono-crystalline silicon, multi-crystalline silicon, nano-crystalline silicon, amorphous silicon, CdTe and CIGS. Embodied energy and annual energy outputs were utilized e.g. for the calculation of EPBT, EPF (electricity production factor) and LCCE (life cycle conversion efficiency) of the system. The results demonstrated that EPF, LCCE, CO_2 mitigation and carbon credits earned were maximum for the mono-crystalline PV module, and thus, it was recommended for the proposed system.

Kamthania and Tiwari [52] analyzed the performance of semi-transparent hybrid PVT double pass façades, in terms of energy and exergy for four weather conditions of Srinagar, India. Several configurations were examined, including various silicon and non-silicon PV technologies: ribbon-, mono-, amorphous-, poly-, crystalline-, silicon; CdTe; CIS; HIT (heterojunction with intrinsic thin-layer); CIGS. The results revealed that:

1) The net annual electrical energy, overall annual thermal energy and overall annual exergy output of the HIT PV panel was found to be maximum (because of the high efficiency of the module amongst the other PV modules) and lowest for the amorphous-silicon PV panel (because of the lowest module efficiency) [52].

2) EPF and LCCE were maximum for the case of HIT PV module for high grades of energy (electrical) due to the highest module efficiency and the highest expected life in comparison to the other PV modules and minimum for the case of CIGS PV panel for low grades of energy (thermal) because of the low module efficiency and less expected life [52].

3) CO_2 mitigation and carbon credits earned were found to be maximum for the HIT PV module and minimum for the CIGS PV module [52].

Kamthania and Tiwari [52] concluded that HIT PV panel is recommended for the proposed system because of the low EPBT, high EPF and LCCE.

4.2. Heat transfer fluid

Results in terms of PVT/air vs. PVT/water applications have been presented by Tripanagnostopoulos et al. [35]. PVT/air systems were investigated, including scenarios for configurations which combine air and water heating. It was highlighted that the most interesting scenario for domestic applications (even if there is an increase in terms of the materials needed for the heat exchanger) is the combination of air and water heat recovery systems, which leads to reduction of the environmental PBTs for all the studied configurations. Moreover, it was noted that by comparing the results of PVT/air systems with those from their previous work about PVT/water systems [1] regarding similar system operating temperature (25°C), it was demonstrated that the values of the cost PBT, EPBT and CO_2 PBT for the PVT/air were higher because of the lower thermal efficiency of the air heat extraction in PVT/air systems [35].

Except of the above mentioned concepts of PV/water and PV/air, there are also bi-fluid PVT configurations. Assoa et al. [2] presented a PVT system which combines preheating of the air and production of hot water in addition to the classical electrical function of the PV cells. A mathematical model for the bi-fluid PVT was presented. Experiments were carried out in order to validate the values obtained from the simulation [2]. The solar-collector performance study showed that for the specific collector length and mass flow rate, the thermal efficiencies can reach around 80% and the estimation of the electrical efficiency revealed that the cooling of the PV cells is satisfactory but it can be improved. It was also noted that: 1) the simulation results demonstrated that this prototype seems to be adapted to moderate temperature level appropriate for domestic hot water production and for some solar cooling applications, 2) in the future, the photoelectric phenomena will be included in the proposed model [2].

4.3. Sunlight concentration

The PV modules can be combined with devices which concentrate solar radiation. This type of systems is known as concentrating photovoltaic (CPV). In CPVs, sunlight is focused onto the PV cell by means of optical devices. The CPV systems can adopt e.g. reflective or refractive optical devices and they are characterized by their concentration ratio (CR) [73]. The CR is the ratio between the aperture area of the primary concentrator and the active cell area [74]. For the specific case of BICPV applications, systems with CR less than 10× (one-axis tracking is sufficient for their operation) are of particular interest [74].

Based on the above mentioned concept of CPV, another group of solar generators has been created, known as CPVT systems. In the same way with CPV, CPVT devices can be combined e.g. with Fresnel lenses or reflectors and they can be adopted for building applications (depending on their CR) [74].

Some critical issues about CPVT systems, which can also influence their performance (from environmental point of view), are following presented:

- The combination of solar radiation concentration devices with PVs is considered as a viable method to reduce system cost, by replacing the expensive cells with a cheaper solar radiation concentrating device [73]. The use of less material for PV cells can be also considered as an advantage from environmental point of view [74].
- CPVs show higher efficiency than the simple PVs (without concentration); however, this can be achieved in an effective way by keeping PV temperature as low as possible [73]. Higher energy output over the life-cycle of a system is favorable for certain environmental indicators which take into account the lifetime energy production of the system.
- The distribution of the solar radiation on the surface of the absorber (PV module) and the temperature rise are two problems that influence the electrical output. The uniform distribution of the concentrated solar radiation on the surface of the PV and the suitable cooling are two critical issues which result in effective system operation and high electrical output [73].
- The effect of CR on the environmental impact of a BICPVT (building-integrated concentrating photovoltaic/thermal) device has been studied, by means of EI99 method [65]. A sensitivity analysis for different CRs was conducted and it was noted that increasing CR results in reducing CPV system environmental impact; however, this requires further analysis and confirmation by taking into account the efficiency of the

PV cells and the optical efficiencies under different CRs during operational phase. Moreover, it was highlighted that the increase of the CR is also associated with higher optical losses [65].

4.4. Other factors

4.4.1. Materials and components

Certainly, the materials of a PVT installation are related with its environmental performance. In terms of the solar thermal part of a PVT system, traditionally solar thermal systems have been dominated by metal and glass. However, in the literature there are studies which propose polymeric materials for solar thermal applications [75] as well as for PVT applications [76].

The position paper of Task 39 of IEA (year of the study: 2015) [75] describes the current state of the art for polymeric materials in solar thermal systems and encourages further research in this field. These materials present multiple advantages such as reduction of the cost, good energy performance for medium- and low-temperature applications, environmental benefits, multi-functional design of polymeric collectors (e.g. replacing conventional roofs and façades) [75]. However, there are some barriers: 1) monetary (investment for suitable production units, such as extruders or injecting molding systems is relatively high and only viable for high production rates; thus, there is a need for a corresponding big market), 2) non-monetary (polymer technology suffers from the image of not being durable, for example for certain collector designs there is a need for overheating protection, etc.) [75].

In addition, in the study of Cristofari et al. [76] about the thermal behavior of a copolymer PVT, it was noted that polymeric materials for solar thermal systems present advantages (reduction of the weight of the system, cost reduction, corrosion resistance, etc.) and disadvantages (low thermal conductivity, large thermal expansion, limits in terms of the service temperature, etc.) [76].

In the review study of Chow et al. [14] about hybrid PVT systems, the possible use of copolymer absorber in order to replace the commonly used metallic sheet-and-tube absorber was presented. It was mentioned that this replacement offers several benefits such as weight reduction and easier installation, simplification of the manufacturing phase (since fewer components are required) and reduction of the production cost. Nevertheless, it was highlighted that there are disadvantages such as low thermal conductivity, large thermal expansion and limited service temperature [14].

Moreover, Kroiß et al. [12] developed a sea waterproof hybrid PVT system with the aim of low cost and high electrical/thermal performance. The low-cost was achieved by the adoption of standard components combining a polypropylene thermal absorber with a commercial PV system. It was highlighted that polypropylene shows certain advantages in comparison to established absorber materials (e.g. copper or aluminum): it is sea waterproof, the material has low cost and the absorber is very light-weight. However, polymer absorbers present low thermal conductivity, increasing the heat transfer resistance from the PV cells to the cooling fluid. In order to eliminate this effect, the interface between the absorber and the PV panel should be optimized [12].

On the other hand, the adoption of additional components/materials for a PVT system can influence its performance from energetic as well as for environmental point of view. For example, the utilization of booster diffuse reflectors between the parallel rows of horizontal PVT systems installed e.g. on the roof of a building [1]. By taking into account that PVT systems installed on horizontal roofs need a minimum distance between the parallel rows (in order to avoid mutual shading of the PV panels), these areas can be utilized by adopting stationary flat diffuse reflectors (placed properly between the PV modules) [1]. By using this type of systems, there is an increase of the solar input on the PV modules (almost all the year) and in this way there is an increase of the electrical and thermal output. Certainly, there is an additional initial impact because of the additional materials for the reflectors; however, these systems show an increased energy production in comparison to the PVT configurations without reflectors [1]. In this way, on a long-term basis, this additional impact is compensated. More analytically, the findings of the LCA study [1] showed that the adoption of reflector for PVT/water systems for buildings (glazed and unglazed configurations; case for replacing electricity only) resulted in a reduction ranging from 0.1 to 0.5 years in EPBT and CO_2 PBT values, depending on the scenario.

Another investigation which includes small modifications of the reference PVT system in order to improve its performance has been conducted by Tonui and Tripanagnostopoulos [77]. Air cooling of a PVT air solar collector by means of natural flow was presented. The study included two low-cost modifications in order to enhance heat transfer to air stream in the air channel. The proposed technique consists of a thin metal sheet suspended at the middle or fins attached to the back wall of the air-channel (in order to improve the heat extraction from the panel). The results demonstrated that the modified systems show better performance than the usual type and they can improve the performance of integrated PV systems for natural ventilation applications in buildings (for space cooling and heating) [77]. Thus, a PVT system with small modifications (few additional components and small inputs in terms of additional materials) can show better energetic performance in comparison to the reference PVT configuration. Thereby, these small modifications are expected to improve the performance (from environmental point of view) of the reference system.

Moreover, in the study of Tripanagnostopoulos et al. [35] several configurations of PV and PVT systems for building roof applications (horizontal and titled; glazed and unglazed; with/without booster diffuse reflectors; with/without TFMS) were investigated, proving that small modifications (in terms of components and materials) of the reference PVT system can improve its performance from energetic and environmental point of view [35].

Concerning PVT systems with PCM (phase change material), a PVT/PCM configuration that produces electricity, stores heat and pre-heats water has been characterized under outdoor conditions (in Dublin, Ireland) [78]. The system includes a PV panel with a thermal collector (in which there is heat removal from a heat exchanger embedded in the PCM through a thermosyphon flow). The performance of the proposed system was compared with: 1) the same system without the component of PCM, 2) the same system without the component of heat exchanger or PCM, 3) the PV panel alone. The results of the investigation [78] demonstrated that the temperature achieved by the water was around $5.5^{o}C$ higher in comparison to a PVT configuration with no PCM component. It was also noted that PCMs are shown to be effective for storing heat for later heat removal in the frame of PVT applications [78].

4.4.2. Type of system in terms of its integration into the building

For some cases the specific type of the PVT can influence the performance (from environmental point of view) of a PVT installation. For example, building integration of a solar system (apart from the considerable advantages that offers) may reduce the energy output and in this way, the performance of the system (from environmental point of view) is affected [79, 80]. As it was discussed in 3.2., for some cases BA PVT systems show better behavior (based on certain environmental indicators) than BIPVT systems [33].

4.4.3. Type of application

The application of the PVT system is an additional aspect which is associated with the performance (from environmental point of view) of a PVT installation. Within the field of PVT there are different types of applications: small-scale vs. large-scale, applications for the building sector [1, 35] and for the industry [66], low-temperature vs. medium temperature heating, hot air vs. hot water heating [1, 35], drying of agricultural products [13], desalination [12], etc.

4.4.4. Recycling

Each of the materials (e.g. of a PVT system) has a resource footprint and a pollution footprint (especially during the phase of production) and a considerable part of this can be avoided by adopting recycling products (instead of manufacturing from new raw material) [81].

Material recycling includes melting or crushing the component and separating it (into its original constituent materials, which then re-enter manufacturing as raw material). Particularly for the metals, this is an efficient solution. In addition, the potential for material recycling is highly dependent upon the purity of the item [81].

4.4.5. Durability and lifespan of the materials/components

The durability of the materials/components of a PVT system should be taken into account. This is because this factor is related with the ability of the materials/components to resist wear and tear (e.g. on the building for the case of building applications). More durable components with longer lifespan require fewer replacements (or no replacement) over the use/operational phase of the PVT system and in this way the profile (from environmental point of view) of the studied system is affected. The durability of certain building materials can reach 50 years and for some cases the durability of certain materials is affected by the climatic conditions [81].

5. CONCLUSIONS

By taking into account that in the literature most of the reviews give emphasis on recent PVT developments/different types of PVT while few of these include LCA/environmental issues about PVT (Table 1), the present article presents a critical review which focuses on PVT from environmental point of view.

The literature review shows that:

- The studies with environmental aspects about PVT are more for BA PVT than for BIPVT, CPVT and BICPVT configurations. In terms of the studied environmental issues, the major part of the cases examines EPBT and CO_2 emissions.
- Most of the BA PVT investigations: 1) refer to domestic applications (including Mediterranean countries), 2) have water as working fluid, 3) use crystalline PV cells, 4) show EPBTs ranging from around 1 to 4 years, 5) adopt a lifespan of 20 years (Table 3). Specifically for the proposed applications, most of the systems are active PVT/water, producing water at temperatures suitable for domestic water heating. In this way, for most of the studied cases the PVT systems cover the domestic energy demand, contributing to the reduction of CO_2 emissions in the building sector.
- BIPVT studies refer to several types of PV cells, with air as working fluid (under variable climatic conditions). The EPBTs vary from around 2 to 14 years, depending on the configuration, and the adopted lifespans range from 5 to 30 years (Table 4).
- There are studies which examine both BA PVT and BIPVT systems (Table 5). Most of these investigations are about air-based systems. The results demonstrate that for some cases the BA systems show better performance (from environmental point of view) than the BI configurations.
- Specifically for BIPVT (Tables 4 and 5), the literature shows that these systems are a research topic with increasing interest and the proposed applications take into account the thermal/fluidic performance of the system coupled with building envelope.

Furthermore, the applications include façade-integrated as well as roof-integrated configurations and the performance of these two options is related with the incident solar radiation.

- There are few studies which evaluate environmental aspects of CPVT (high-concentration and low-concentration) systems (Table 6). These investigations are about water-based systems (for buildings and for large-scale applications) and most of them use triple-junction PV cells. The climatic conditions are for desert areas, Spain and Italy.

- There are some investigations about PVT for other types of applications (except of buildings) such as water distillation and drying of agricultural products (Table 7).

There are several factors which influence PVT performance from environmental point of view:

- PV cell material (some PV cell materials show lower impact (in comparison with other materials) during their manufacture but their efficiency during system life-cycle is low).
- Heat transfer fluid (for example a PVT/water system can present better performance from environmental point of view (in comparison to a PVT/air system) due to its better heat extraction).
- Sunlight concentration (the adoption of CPVT configurations means replacement of the PV cell material with concentrator material and in this way, there is reduction of the cost and the environmental impact).
- Utilization of alternative materials for the PVT device e.g. polymeric (taking into account that polymeric components show advantages (reduction of the weight of the system, etc.) and disadvantages (need of overheating protection, etc.)).
- Use of reflectors and small modifications (for example, TFMS) in order to improve PVT performance.

- The type of integration into the building.
- The type of application (e.g. for buildings, for industry).
- The adoption of recycling for certain materials/components.
- Durability and lifespan of the materials/components.

Given the fact that most of the cited references (which include environmental issues about different types of PVT systems) examine EPBT and CO_2 emissions, as a future prospect there is a need for more studies which are based on multiple LCIA methods (for example, ReCiPe midpoint and endpoint approaches can offer interesting information for several impact categories). Certainly, EPBT and CO_2 emissions give useful information about PVT profile but the adoption of additional methods and environmental indicators can provide a more complete picture about PVT performance from environmental point of view. In general, as a future prospect, more studies on LCA and environmental issues about PVT systems are needed, especially about BIPVT, CPVT, BICPVT and PVT systems for different applications (in the building sector, in the industry, etc.).

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