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# **Photovoltaic/thermal systems based on concentrating and non-concentrating technologies: Working fluids at low, medium and high temperatures**

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## **ABSTRACT**

The present article provides an overview about photovoltaic/thermal systems categorised by the temperature of the working fluid: Low-temperature (lower than 60 °C), medium-temperature (between 60 and 90 °C) and high-temperature (higher than 90 °C). Concerning photovoltaic/thermal-air systems for low-temperature use, the majority of studies involve building-integrated non-concentrating systems with phase change materials and working-fluid temperatures at around 30-55 °C. Concerning low-temperature photovoltaic/thermal-water systems, a large number of studies are about non-concentrating configurations appropriate for building-integrated and, in general, domestic applications with working fluids at approximately 50-60 °C. Regarding non-concentrating photovoltaic/thermal systems for medium-temperature use, a large number of references are appropriate for industrial and domestic applications (working fluids: air; water) with around 60-70 °C working-fluid temperatures. The literature review about medium-temperature concentrating photovoltaic/thermal systems shows that the majority of investigations concern photovoltaic/thermal-water systems with concentration ratios up to 190X and working fluids at approximately 62-90 °C, appropriate for domestic and water-desalination applications. As for high-temperature concentrating photovoltaic/thermal systems, most of them have concentration ratios up to 1000X, parabolic concentrators and use water (as the working fluid) at around 100-250 °C.

Moreover, in the field of high-temperature photovoltaic/thermal systems, most of the configurations are appropriate for building and industrial applications, and consist of triple-junction or silicon-based photovoltaic/thermal cells. In light of the issues mentioned above, a critical discussion and key challenges (in terms of materials, efficiencies, technologies, etc.) are presented.

*Keywords: Photovoltaic/Thermal (PVT) systems; Low-temperature applications; Medium-temperature applications; High-temperature applications; Technologies with/without solar concentration; Buildings, industry, power plants*

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## **ABBREVIATIONS**

BA	Building-Added
BA PVT	Building-Added Photovoltaic/Thermal
BI	Building-Integrated
BIPVT	Building-Integrated Photovoltaic/Thermal
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium (di)Selenide
CIS	Copper Indium Selenide
COP	Coefficient of Performance
CPC	Compound Parabolic Concentrator
CPV	Concentrating Photovoltaic
CPVT	Concentrating Photovoltaic/Thermal
CR	Concentration Ratio
E	Experimental
E-M	Experimental and Modelling (both)
G	Solar irradiance
HCE	Heat Collection Element

HIT	Heterojunction with Intrinsic Thin Layer
LCPVT-STC	Low-Concentrating Photovoltaic/Thermal - Solar Thermal Collector
M	Modelling
Mono-Si	Monocrystalline silicon
NIP	Normal Incidence Pyranometer
PCM	Phase change material
Poly-Si	Polycrystalline silicon
PV	Photovoltaic
PVT	Photovoltaic/Thermal
PVT/air	Photovoltaic/Thermal with air as working fluid
PVT/water	Photovoltaic/Thermal with water as working fluid
Re	Reynolds number
$T_b$	Temperature of the absorber plate
$T_{in}$	Inlet temperature
$T_{out}$	Outlet temperature

## 1. INTRODUCTION

Photovoltaic (PV) cells absorb and convert solar radiation into electricity [1]. However, the main part of the collected solar radiation is transformed into heat, increasing PV-cell temperature and, therefore, reducing PV-cell efficiency [2]. This undesirable phenomenon can be avoided by using a heat extraction device with fluid circulation. In this way, PV panels can work at a more satisfactory temperature. PV systems which combine PV modules with thermal units (involving the circulation of a fluid, e.g. air or water) are known as hybrid Photovoltaic/Thermal (PVT) systems and produce both electrical and thermal energy [1]. In other words, PVT installations provide higher total energy output (in comparison to PV modules which generate only electrical energy) and environmental advantages [3, 4].

PVT systems are appropriate for different kinds of applications (domestic, industrial, etc.). By placing emphasis on the working fluid, water-cooled PVT (PVT/water) and air-cooled PVT (PVT/air) systems are commonly used for water and indoor space heating, respectively [1].

The temperature of the working fluid plays a pivotal role and is associated with the type of application [5]. PVT systems appropriate for different temperatures/applications were developed: domestic hot water production, indoor space heating/cooling, desalination, pool heating, crop drying, industrial process heating and so on [6].

In the case of PVT applications in the building sector, it can be noted that there are two basic categories: 1) Building-Added Photovoltaic/Thermal (BA PVT) (for instance, these systems are mounted on the roof of a building), 2) Building-Integrated Photovoltaic/Thermal (BIPVT) (these systems form part of the building structure itself, e.g. façade- or roof-integrated configurations) [7].

There are articles that include reviews about PVT systems. In Table 1, the major references (with emphasis on review papers about PVT) are presented. It can be noticed that the majority of these studies focus on issues such as PVT design, performance, working fluids, applications, temperature effect and PV cooling.

**Table 1.** References about PVT systems with emphasis on review papers.

Study / year	Content
Tripanagnostopoulos (2007) [1]	PVT systems: Literature review PVT applications PVT design improvements Dual PVT: Experimental study
Charalambous et al. (2007) [8]	Different types of PVT modules PVT performance Evaluation of thermal/electrical output
Zondag (2008) [9]	PVT history PVT liquid- and air-collectors (issues about the modules) Ventilated BIPV with heat recovery (issues about the modules) PVT systems PVT market
Chow (2010) [10]	Groundwork and developments

	<p>Developments (during the last decade) in flat-plate PVT systems</p> <p>Developments (during the last decade) in Concentrating Photovoltaic/Thermal (CPVT) designs</p> <p>Developments (commercial, etc.) during the last decade</p>
Hasan and Sumathy (2010) [11]	<p>PVT development</p> <p>PVT devices</p> <p>PVT module concepts</p> <p>Performance analysis</p> <p>Techniques to improve PVT performance</p> <p>Future prospects of PVT systems</p>
Ibrahim et al. (2011) [12]	<p>PVT design and performance evaluation</p> <p>PVT future developments</p>
Avezov et al. (2011) [13]	<p>PVT/air modules</p> <p>PVT/water modules</p>
Zhang et al. (2012a) [14]	<p>Traditional Concentrating Photovoltaic (CPV) systems</p> <p>CPV cooling</p> <p>PVT systems</p> <p>Spectral-beam-splitting technology</p>
Zhang et al. (2012b) [15]	<p>PVT technology: Concept, theory, classification, performance, standards</p> <p>PVT research/development and practical applications</p> <p>Future studies</p>
Tyagi et al. (2012) [16]	<p>Solar thermal collectors</p> <p>PV technology</p> <p>PVT technology</p> <p>PVT novel applications</p>
Vivar et al. (2012) [17]	<p>Standards for CPV systems: The case of active cooling</p> <p>Standards for CPVT systems</p> <p>A proposal for evaluating CPVT systems</p>
Chow et al. (2012) [18]	<p>PVT developments in the twentieth century</p> <p>Flat-plate PVT systems: Recent developments</p> <p>CPVT systems: Recent developments</p> <p>Developments in recent years</p>
Shan et al. (2014) [19]	<p>PVT systems</p> <p>BIPVT systems</p> <p>CPVT systems</p> <p>PVT systems with heat pumps</p> <p>Case studies</p> <p>Limitations and solutions</p>
Sharaf and Orhan (2015a) [20]	<p>Foundations and overview</p> <p>Fundamentals and technological advances</p>
Sharaf and Orhan (2015b) [21]	<p>Literature about CPVT</p> <p>Performance assessment</p> <p>Overview – prospects</p>
Makki et al. (2015) [22]	<p>Temperature effect on PV-cell efficiency</p> <p>PV cell cooling</p> <p>PVT systems</p>
Lamnatou and Chemisana (2017) [7]	<p>Methods and indicators (from an environmental point of view)</p> <p>Studies which include environmental issues about PVT: Literature review</p> <p>Parameters which influence PVT environmental profile</p>
Ju et al. (2017a) [23]	<p>CPVT with waste-heat recovery: Literature review</p> <p>Research studies about CPVT with waste-heat recovery: Current status</p>
Ju et al. (2017b) [24]	<p>Spectral-beam-splitting CPVT:</p> <ul style="list-style-type: none"> <li>- General issues</li> <li>- Developments</li> <li>- Current status (in terms of research)</li> </ul>
Azarian et al. (2017) [25]	<p>CPVT concept</p> <p>CPVT from a thermodynamic point of view</p> <p>PV cells</p>

	PV cells and thermal collector: Materials Heat-transfer fluid PV-cell temperature Heat-extraction system
Joshi and Dhoble (2018) [6]	PVT concept PVT systems: Classification Non-concentrating PVT systems CPVT systems Spectral-beam-splitting PVT systems
Sultan and Ervina Efzan (2018) [26]	Types of PVT modules Solar greenhouses with PVT modules
Fudholi et al. (2019) [27]	Monofacial and bifacial PV cells Efficiency of bifacial PV modules PVT/air systems with monofacial PV cells PVT/air systems with bifacial PV cells
Vaishak and Bhale (2019) [28]	PVT systems PVT systems with heat pumps PVT systems with heat pumps: Details about the components Research and development Future prospects

The aforementioned issues indicate that in the literature about PVT there is a lack of review papers which place emphasis on working-fluid temperature. The present article provides an overview about different kinds of PVT systems, appropriate for buildings, industry, etc. Its main contribution is the classification of the PVT configurations according to the temperature of the working fluid. The classification criteria are as follows:

- Low-temperature systems: Working-fluid temperatures  $< 60\text{ }^{\circ}\text{C}$
- Medium-temperature systems:  $60\text{ }^{\circ}\text{C} \leq \text{working-fluid temperatures} \leq 90\text{ }^{\circ}\text{C}$
- High-temperature systems: Working-fluid temperatures  $> 90\text{ }^{\circ}\text{C}$

Furthermore, the PVT systems are categorised by taking into account additional criteria:

- Type of study (experimental, modelling, both experimental/modelling).
- Working fluid (air, water, nanofluids, etc.).
- Solar energy collection by means of concentrating or non-concentrating devices.
- Type of PV cells (mono-Si, poly-Si, etc.).
- Systems with or without thermoelectric elements.
- Efficiencies (electrical, thermal, etc.).

- Type of application (buildings, industry, drying, desalination, etc.).
- Location/country where a certain system was evaluated.

In light of the issues mentioned above, it can be noted that the proposed framework provides the basis for identifying key challenges (in terms of materials, technologies, efficiencies and so on) that PVT systems are facing.

## **2. LITERATURE REVIEW**

### **2.1. PVT SYSTEMS FOR LOW-TEMPERATURE APPLICATIONS**

The present section deals with PVT systems with working fluids at low temperatures (less than 60 °C). In the literature on PVT, there is a whole host of studies on this kind of systems and, therefore, three subcategories have been considered: 1) PVT/air, 2) PVT/water, 3) PVT with both air and water, PVT with nanofluids, etc.

In Table 2, selected references about PVT/air systems for low-temperature use are presented. The results show that:

- The majority of the references are about modelling or experimental/modelling studies on systems without solar concentration.
- Most of the systems do not have thermoelectric elements.
- A large number of investigations include mono-Si or poly-Si PV cells.
- In most cases, the maximum temperature of the working fluid (air) ranges from around 30 to 55 °C.
- Thermal efficiencies range from 10 to 90%. Moreover, many systems show PV conversion efficiencies around 6-16%. In certain cases, high overall efficiencies (80% or higher) were found.
- Regarding the type of application, a large number of investigations are about building-integrated configurations whereas there are a few studies on dryers.



- A large majority of the references are about systems with PCM appropriate for BI applications.
- In most cases, the systems were investigated for the climatic conditions of Europe and India.

In terms of the achievement of high efficiencies, it is worth mentioning the study by Nazri et al. [54] (PVT/air with a thermoelectric element) on the grounds that a maximum thermal efficiency of 84% was found. It was noted that mass flow rate considerably influences thermal-efficiency results. It is also worth mentioning the study by Kamthania and Tiwari [35]. Multiple silicon-based and non-silicon-based BIPVT/air modules were investigated and the findings show that the Heterojunction with Intrinsic Thin Layer (HIT) system has the highest: i) module efficiency, ii) net annual electrical energy, iii) overall annual thermal energy, iv) exergy output.

Regarding BIPVT, Assoa and Ménézo [34] investigated a roof-integrated PVT/air system. A model was developed and validated with data of an experimental setup near Lyon, in France. It was found that forced ventilation offers advantages from a thermal-production point of view. However, natural ventilation provides adequate cooling of the PV panels. In Figure 1, the experimental building with the prototype roof-integrated PVT/air system is illustrated.



**Figure 1.** The roof-integrated PVT/air system studied by Assoa and Ménézo [34]. An experimental building at TENESOL company site. Source: Assoa and Ménézo [34].

**Table 2.** PVT/air systems: working fluid at low-temperatures.

Study / year	Type of study	Solar concentration	Type of PV cells	Thermoelectric element	Temperature of the working fluid: Low	Efficiencies	Type of application: - Buildings - Etc.	Location of the study
Candanedo and Athienitis (2009) [29]	E-M	No	Not directly stated	No	Higher than 30 °C	Not directly stated	BIPVT (roof-integrated); Net-zero energy solar house	Canada
Vats and Tiwari (2012) [30]	M	No	Mono-Si; poly-Si; amorphous silicon; CdTe; CIGS; HIT	No	22 °C (maximum)	16% for HIT, 6% for amorphous silicon	BIPVT (roof-integrated, semi-transparent)	India
Sopian et al. (2013) [31]	M	Yes (there is a reflector below the PV cells)	Bifacial	No	Air-flow temperature along the length of the panel: around 29.5 °C (maximum)	Total: around 78% (maximum) for the double-path mode	BI with bifacial PV cells and reflectors	Not directly stated
Rajoria et al. (2013) [32]	M	No	Not directly stated	No	Outlet air temperature: around 59 °C (maximum); Case 2: Delhi, January	PV cell: around 11.8% (maximum); Case 1: Delhi, January	BIPVT (tiles)	India
Aelenei and Pereira (2013) [33]	M	No	Not directly stated	No	Air inside the cavity: 43 °C and 54 °C, with and without PCM, respectively	Systems at 9.00 a.m.: around 22% (maximum); ventilated BIPVT without PCM	BIPVT (façade-integrated) with/without PCM	Portugal
Assoa and Ménéz (2014) [34]	E-M	No	Poly-Si	No	Air temperature (outlet of the air gap): around 35 °C (maximum)	Reference, PV cell: 12%	BIPVT (roof-integrated)	France
Kamthania and Tiwari (2014) [35]	E-M	No	Mono-Si, poly-Si, ribbon, amorphous silicon, CdTe, CIGS, CIS, HIT	No	Outlet air temperature: 20.5 °C (maximum) at 12 pm	Hourly variation of electrical efficiency: from around 6% to 18%, depending on the PV module	BIPVT (façade-integrated)	India
Aelenei et al. (2014a) [36]	E-M	No	Poly-Si	No	Air-gap maximum temperature: around 50 °C	For $(T_{in}-T_{out})/G = 0.01$ : thermal around 10%, overall around 20%	BIPVT (façade-integrated) with PCM	Portugal
Aelenei et al. (2014b) [37]	E-M	No	Poly-Si	No	Air-cavity maximum temperature: around 47 °C	Not directly stated	BIPVT (façade-integrated) with PCM	Portugal
Sohel et al. (2014) [38]	E-M	No	Not directly stated	No	Air outlet temperature: around 58 °C (maximum)	Electrical: around 9-10% (maximum); Thermal: around 90% (maximum)	Net-zero energy buildings; Solar Decathlon house	Australia; China

Machni et al. (2015) [39]	M	No	Thin-film CIS	No	The most effective performance: PCM transition temperatures of 18 and 25 °C	The incorporation of PCM into the back surface of the PV module has little effect on the power production efficiency	BIPVT (façade-integrated) with PCM	Central Europe
Xiang and Gan (2015) [40]	E-M	No	Mono-Si	No	Maximum temperature at the top side of the model: around 37 °C	Not directly stated	BIPVT (wall) with PCM	UK
Li et al. (2015a) [41]	M	No	Not directly stated	No	Scenario: a cloudy day after two consecutive sunny days, maximum tank-temperature around 41 °C	Not directly stated	BIPVT with air-to-water heat pump	USA
Slimani et al. (2016) [42]	M	No	Mono-Si	No	Outlet air temperature: a maximum value of 50 °C at 12:00 was found	Electrical: around 10.5% (maximum); Thermal: around 70% (maximum)	Drying of agricultural products	India
Delisle and Kummer (2016) [43]	M	No	Mono-Si	No	The heat-pump-water-heater temperature was set at 55 °C	Electrical: 15.2% (at reference conditions)	BIPVT (roof-integrated) with air-to-water heat pump	Canada
Lin et al. (2016) [44]	M	No	Not directly stated	No	Maximum enclosure temperature: around 29 °C	Not directly stated	BIPVT combined with PCM wall	Australia
Favoino et al. (2016) [45]	E	No	Amorphous silicon	No	Up to 45 and 50 °C: indoor glass surface of the aerogel-filled configuration in winter and summer, respectively	PV cell: 6% (nominal efficiency); peak efficiency of the latent-heat-thermal-energy-storage system: 60-70%	BIPVT (façade-integrated) with PCM	Italy
Haddad et al. (2016) [46]	E	Yes	Mono-Si	No	Hourly temperature (PVT/air collector without reflector): around 40 °C (maximum)	Not directly stated	PVT applications with reflectors	Algeria
Tiwari et al. (2016a) [47]	E-M	No	Semi-transparent	No	Maximum drying-chamber temperature: around 45 °C	PV cell: around 13.5% (maximum)	PVT integrated into a greenhouse dryer (crop drying)	India
Oliveira (2016) [48]	M	No	Mono-Si	Yes (thermoelectric heat pumps)	Not directly stated	Goals for 1000 W/m <sup>2</sup> incident solar radiation: PV-module efficiency $\geq$	BIPVT (façade-integrated) with natural or forced air	Europe, Portugal

						15%; System heating efficiency $\geq$ 40%; System cooling efficiency $\geq$ 15%	circulation and heat pumps	
Tripathy et al. (2017) [49]	M	No	Mono-Si (semi-transparent)	No	Solar-cell temperature: around 44 °C (maximum)	Electrical: around 11.7% (maximum)	BIPVT (roof-integrated)	India
Liu et al. (2017) [50]	E-M	No	Not directly stated	Yes (thermoelectric ventilator)	Fresh air temperature: between 18.3 and 31 °C	Electrical (for the system): around 12.6% (maximum); Coefficient of Performance (COP): 3.35 (maximum)	Buildings	China
Dimri et al. (2017) [51]	M	No	Semi-transparent	Yes (thermoelectric cooler)	Fluid outlet temperature: around 57 °C (maximum)	Overall electrical (in fraction): around 13.5% (maximum)	Indoor space heating or drying of agricultural products	India
Liu et al. (2018a) [52]	E-M	No	Mono-Si	Yes (thermoelectric ventilator)	Fresh air outlet temperature of the PVT-thermoelectric ventilator system: around 34 °C (maximum)	Electrical: around 16% (maximum); Thermal: around 55% (maximum)	Buildings: power production, waste heat recovery, air supply, etc.	China
Agathokleous et al. (2018) [53]	E-M	No	Poly-Si	No	Maximum temperature: around 35 °C (air outlet: the duct between the PV module and the brick wall)	Overall energy efficiency of the system: 25.5-33.5%; Electrical efficiency of the system: 24-28.5% (PV-module temperature: 30-57°C)	BIPVT (façade-integrated) applications: Naturally ventilated	Cyprus
Nazri et al. (2018a) [54]	M	No	Mono-Si	Yes	Back plate and air temperatures in the channels: 20 and 10 °C higher than the ambient temperature, respectively	Thermal: 84% (maximum); Electrical: 12% (maximum)	Drying of agricultural products	Not directly stated
Liu et al. (2018b) [55]	E	No	Not directly stated	Yes (thermoelectric ventilator)	Maximum outlet air temperature: 28.5 °C	PVT average electrical efficiency: 10% (sunny day); average thermal efficiency of the PVT/thermoelectric: 26.7%	Buildings	China
Nazri et al. (2018b) [56]	E	No	Mono-Si	Yes (thermoelectric generators)	Outlet air temperature: 40 °C (maximum); mass flow rate: 0.02 kg/s;	For mass flow rate 0.09 kg/s: thermal around 60% (maximum), electrical	Temperature control	Malaysia

					maximum radiation intensity	around 12% (maximum)		
Irshad et al. (2019) [57]	E-M	No	Not directly stated	Yes (thermoelectric air cooling)	Working temperature of the thermoelectric air-cooling system: 24-38 °C	PV panel: 14.6%	BIPVT applications with air conditioners	Malaysia
Pereira and Aelenei (2019) [58]	E-M	No	Poly-Si	No	Air-cavity temperature: around 43 °C (maximum)	Optimised scenario: 10% electrical and 54% thermal	BIPVT (façade-integrated) with PCM	Portugal
Pal Singh et al. (2019) [59]	M	No	Not directly stated	No	Maximum output temperature: around 27.5 °C	Thermal: around 45% (maximum)	PVT applications with curved grooved absorber plates	Not directly stated
Kalkan et al. (2019) [60]	M	No	Crystalline silicon	No	For air velocity 1 m/s, 400, 800 and 1000 W/m <sup>2</sup> , maximum outlet air temperatures: 33, 47 and 54 °C, respectively	For the optimal design, overall: 53.4%	Buildings	Turkey

In Table 3, selected references about PVT/water systems for low-temperature applications are presented. The results demonstrate that:

- A large number of investigations include both modelling and experiments on systems without solar concentration.
- In most cases, the systems do not include thermoelectric components.
- The majority of the studies about concentrating systems refer to CRs less than 10X and include a whole host of configurations (with Compound Parabolic Concentrators (CPCs), Fresnel lenses, micro-concentrators, parabolic-trough concentrators, etc.).
- In most cases, mono-Si and poly-Si PV cells were used.
- The majority of thermal efficiencies are around 50-85% and electrical/PV efficiencies are approximately 12-15%.

- Many references are about BI configurations and, in general, about systems for buildings and domestic use whereas there are a few studies about agricultural applications (e.g. greenhouses, dryers of agricultural products).
- There are a few investigations about PVT systems with PCMs, integrated-collector-storage, heat pipes, chillers, desiccants and polymer PVT collectors.
- Most of the systems were evaluated for the climatic conditions of Europe and China, operating at around 50-60 °C working-fluid temperatures.

Regarding the achievement of high efficiencies, Alves et al. [102] investigated a PVT/water with a Solarus reflector (CR: 1.7X) and mono-Si PV cells. The system is appropriate for domestic water heating and, in the case of Sweden, showed an electrical efficiency of 19.1%. Alves et al. [102] noted that by increasing the water flow rate, more heat (from the receiver) is removed. This means that there is a reduction in PV-cell temperature and increase in PV efficiency. Moreover, Khelifa et al. [84] studied a PVT/water system (without solar concentration). In certain cases, high thermal efficiencies (around 94%: maximum) were found and, in relation to these high efficiencies, it was highlighted that the collector is perfectly insulated and covered by a flat glass [84].

**Table 3.** PVT/water systems: working fluid at low-temperatures.

Study / year	Type of study	Solar concentration	Type of PV cells	Thermoelectric element	Temperature of the working fluid: Low	Efficiencies	Type of application: - Buildings - Etc.	Location of the study
Ibrahim et al. (2009) [61]	M	No	Poly-Si	No	Water temperature (outlet): around 31 °C (maximum)	Thermal: around 50% (maximum); PV cell: around 12% (maximum)	Domestic applications	Not directly stated
da Silva and Fernandes (2010) [62]	M	No	Mono-Si	No	Maximum tank temperature: around 50 °C	Global annual energy: 24% (15% thermal; 9% electrical)	Domestic hot water production	Portugal
Chemisana et al. (2011) [63]	E-M	Yes (CRs: 7-10X)	Crystalline silicon	No	Maximum water temperature: around 33 °C ( $Re = 125$ ; channel height/width = 2.43; module length = 1 m)	Thermal: around 65% (maximum)	BIPVT applications with Fresnel linear concentrators	Spain
Sonneveld et al. (2011) [64]	E	Yes (CR: 25X)	Mono-Si	No	Incoming water temperature: 22.4 °C; outgoing water temperature: 25.8 °C; flow: 18.6 kg/s; module length: 1.55 m	Thermal: 56%; Electrical: 11%	Greenhouses with Fresnel lenses (cultivation of ornamental plants)	Netherlands
Cristofari et al. (2012) [65]	M	No	Poly-Si	No	PV-cell temperature for the PVT: 30.6 °C (maximum)	Average efficiencies (PVT without air layer): 29% for the thermal and 14% for the PV	Domestic hot water production by using polymer PVT collectors	Mediterranean
Redpath et al. (2012) [66]	E	Yes (CR: 1.8X; a configuration without concentration was also studied)	Poly-Si	No	Outlet temperature: around 57 °C (maximum) for the PVT with CPC	Thermal: around 50-60%, depending on the system; Electrical: around 8-10%, depending on the system	PVT with/without CPCs for domestic and industrial applications	UK
Gang et al. (2012) [67]	M	No	Mono-Si	No	Water temperature: 45 °C (or higher)	Standard electrical efficiency (PV module): 15%	Domestic applications: PVT with heat pipes	China
Chávez Urbiola and Vorobiev (2013) [68]	E-M	Yes (CR: around 52X)	Not directly stated	Yes (thermoelectric generators)	Thermal energy stored in water at a temperature of 50 °C (approximately)	Electrical efficiency of the system: 5%; Thermal: 50%	Domestic applications	Mexico

Yin et al. (2013) [69]	E-M	No	Mono-Si	No (but it is noted that a case with thermoelectric element could be examined (future prospect))	Equilibrium temperature with water flow: around 40 °C	At 25°C, PV cell efficiencies: 15.1% and 11.9%, for 850 and 1100 W/m <sup>2</sup> , respectively; Thermal efficiency: 53.9% (1100 W/m <sup>2</sup> , 66 ml/min water flow)	BIPVT (roof-integrated) with PCM	USA
Amriza I et al. (2013) [70]	E-M	Yes (PVT: 2 lines of 26 series connected PV cells optimised for concentrating systems)	Crystalline silicon	No	Maximum outlet temperature: around 53 °C	PV cell: 14.3% (standard conditions)	Buildings	Spain
He et al. (2013) [71]	E-M	No	Not directly stated	Yes (cooling and heating system)	Maximum water temperature in the storage tank: around 32-34 °C	System COP: higher than 0.45; Thermal (experimental): 12.06%; Electrical (experimental): 10.27%	Domestic applications	China
Shan et al. (2013) [72]	M	No	Not directly stated	No	Maximum outlet temperature: 56.3 °C	PV: around 12.5% (maximum)	Appropriate for BIPVT applications	China
Vivar et al. (2013) [73]	E	Yes (CR: 38X)	Mono-Si	No	Fluid temperature: not exceeding 60 °C	The combined efficiency of the system can exceed 70%; Average electrical: 8%; Average thermal: 50%	Domestic applications with PVT with micro-concentrators (Fresnel mirrors)	Australia
El-Seesy and Khalil (2014) [74]	E	Yes (geometric CR: 4X)	Mono-Si	No	Hot water average temperature: 53 °C	Not directly stated	PVT applications with low-cost mirrors	Egypt
Ibrahim et al. (2014) [75]	E	No	Poly-Si	No	Outlet temperature: around 50 °C (maximum)	PV: 10.4-11.3%; Thermal: 44-51%	BIPVT	Malaysia
Buker et al. (2014) [76]	E-M	No	Mono-Si	No	Water temperature: around 35 °C (maximum)	System thermal: around 20% (maximum); PV: around 15% (maximum)	BIPVT (roof-integrated)	UK
Buker et al. (2015) [77]	E-M	No	Mono-Si	No	One of the case studies: roof with an average water temperature of 30.25 °C (mass flow rate: 6 l/min)	PV: around 15% (maximum); Overall thermal efficiency (PVT system): around 20% (maximum)	BIPVT (roof-integrated) with desiccant	UK
Evola and Marlett	M	No	Poly-Si	No	Outlet temperature: 40 °C (inlet)	Electrical: around 13.5%; Thermal	Industrial	Italy



a (2014) [78]					temperature = 35 °C)	(maximum): around 59% (for inlet temperature = 20 °C)	premises: Integration on concrete roofs	
Kroiß et al. (2014) [79]	E	No	Poly-Si	No	Fluid outlet temperature: around 22 °C (maximum)	Electrical (PVT system): 14% (standard test conditions); Mean thermal (PVT system): 69%	Desalination by using polymer PVT collectors	Germany
He et al. (2014) [80]	E-M	No	Not directly stated	Yes (cooling and heating systems)	Water temperature: 21 °C (average)	Electrical (of the heat-pipe PVT): approximately 16.7%; Thermal (of the system): around 23.5%	Building applications with heat-pipe PVT systems	China
Kim et al. (2014) [81]	E	No	Mono-Si	No	Outlet temperature: around 44 °C	Thermal and electrical efficiencies (average) of the BIPVT collector: 30% and 17%, respectively	BIPVT (roof- integrated)	Korea
Ziapou r et al. (2014) [82]	M	No	Poly-Si	No	For 120 kg of water in the tank and collector area 1.5 m <sup>2</sup> ; tank water temperature 45.9 °C	For 120 kg of water in the tank and collector area 1.5 m <sup>2</sup> : electrical (overall) 12.5%, thermal (overall) 36.1%	Domestic applications with integrated- collector- storage solar water heater	Different cases were examined
Brown e et al. (2016) [83]	E	No	Mono-Si	No	Temperature at the outlet pipes: around 24 °C (maximum)	Not directly stated	Buildings: PVT applications with PCM	Ireland
Khelifa et al. (2016) [84]	E-M	No	Not directly stated	No	Outlet temperature: 39 °C (maximum)	Thermal: around 94% (maximum)	Water heating, drying, air conditioning, etc.	Algeria
Adeilla et al. (2016) [85]	E	Yes	Not directly stated	No	Output temperature: around 36 °C (maximum)	Electrical: 17%; Thermal: 83%	BIPVT	Indoor testing by means of a solar- simulator
He et al. (2016) [86]	E-M	Yes (CR less than 2X)	Silicon- based	No	Maximum hot- water temperature for the PVT with concentrator: 58 °C	Not directly stated	PVT applications with diffuse- reflection concentrators	China
Rosa- Clot et al. (2016) [87]	E	No	Poly-Si	No	Maximum daily water temperatures: 47 and 55 °C, depending on the case	Average electrical efficiencies of systems A and B: 8.8% and 13.2%, respectively	Buildings and industrial applications	Italy
Finoc- hiaro et al.	E-M	No	Not directly stated	No	Maximum temperature: around 58 °C	Under cooling conditions an energy-	BA PVT combined with desiccant	Italy

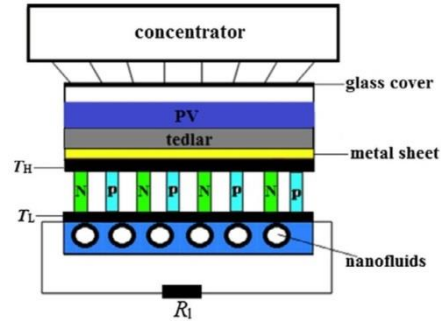
(2016) [88]					(psychrometric chart)	efficiency-ratio of 12.8 was found (this ratio is 50.7 if PV generation is taken into account)		
Jouhara et al. (2016) [89]	E	No	Not directly stated	No	PVT module temperature: between 28 and 33 °C	Energy conversion efficiency: 50% for the PVT configuration	BIPVT (roof-integrated)	UK
Wang et al. (2016a) [90]	E	No	Poly-Si	No	Tank water temperature maximum: 47.2 °C (simulated:900 W/m <sup>2</sup> ; water flow rate 600 L/h)	Daily average thermal, electrical and total efficiencies of the system: 61.1%, 7.8% and 68.9%, respectively (simulated:900 W/m <sup>2</sup> ; water flow rate 600 L/h)	Heat-pipe BIPVT	China
Wang et al. (2016b) [91]	E	No	Poly-Si	No	Maximum tank-water temperature: 53.83 °C (simulated:900 W/m <sup>2</sup> ; water flow rate 200 L/h)	Maximum thermal: 44% (simulated:300 W/m <sup>2</sup> ; water flow rate 200 L/h); Maximum electrical: 7.9%	Heat-pipe BIPVT; potential of building integration: walls, roofs, balconies	China
Chemisana et al. (2016) [92]	E	Yes (geometric CR: 10.32X)	Crystalline silicon	No	Outlet water temperature: 52 °C	Mean optical efficiency: 51%	BIPVT (façade-integrated) with Fresnel reflectors	Spain
Karimi et al. (2017) [93]	E	Yes (CR: 5.85X)	Mono-Si	No	Water-temperature in the tank (for the CPVT system): 33.1 °C (final), 15 °C (initial)	For the CPVT system (one of the cases): Thermal 40.8% and electrical 14.7%	Buildings: PVT with Fresnel lenses	China
Jaaz et al. (2017) [94]	E	Yes	Poly-Si	No	Maximum PV-cell temperature (PVT with CPC): 67 °C	Electrical: 14.5% (maximum)	PVT with CPCs	Malaysia
Asaee et al. (2017) [95]	M	No	Crystalline silicon	No	Maximum water temperature: 55 °C	User-defined efficiency of the PV panels: 11.7%	BIPVT (roof-integrated)	Canada
Gautam and Andresen (2017) [96]	M	No	Not directly stated	No	At the top of the tank: 55 °C to prevent the growth of <i>Legionella pneumophila</i>	Electrical: around 11.4% (maximum, for the BIPVT in Spain)	BIPVT (façade-integrated) with direct flow (boxed) absorber	Denmark; Spain
Buonomano et al. (2017) [97]	M	No	Poly-Si	No	Domestic-hot-water set point temperature: 45 °C	PV (reference): 12%; PVT winter: around 9%	BIPVT (roof-integrated) with chiller	Italy

Li et al. (2017) [98]	E-M	Yes (CR: 3.6X)	Si-based	No	Maximum temperature: around 41 °C at the inlet of the first heat exchanger of the CPVT; rooftop (case: Spain)	In one of the cases: optical efficiency of the CPCs 84%	PVT for buildings: CPCs vs. flat modules	Spain; Scotland; UK
Soltani et al. (2018) [99]	M	Yes (CR: 8X)	Crystalline silicon	Yes	Maximum temperatures of the two sides of the thermoelectric generator: 89.97 and 45 °C	Thermal: around 57% (maximum); electrical (thermoelectric generator): about 0.5% (maximum)	PVT with parabolic-trough collectors	Not directly stated
Yang et al. (2018) [100]	E-M	Yes (CR: 8X)	Mono-Si	No	Glass-cover-plate temperature: around 60 °C (maximum)	Overall (CPVT system): 55.6-59%; Electrical efficiencies (system): 16.6-20% (experimental); Optical efficiency and mirror utilisation (concentrator): 94.4%	PVT with quasi-parabolic concentrators	China
Fayaz et al. (2019) [101]	E-M	No	Poly-Si	No	Maximum output temperature (PVT): 57.4 °C and 56 °C (numerical and experimental results, respectively)	Maximum thermal (PVT system): 81% and 77.36% (numerical and experimental results, respectively); Electrical: 12.75% improved experimentally for the PVT-PCM	PVT with PCMs	Malaysia
Maadi et al. (2019) [102]	M	No	Poly-Si	No	Output temperature: around 43 °C (considering the greenhouse effect)	If the greenhouse effect is considered, there is an increase of 12% in thermal efficiency (case: 300 W/m <sup>2</sup> )	Buildings	Not directly stated
Alves et al. (2019) [103]	E-M	Yes (CR: 1.7X)	Mono-Si	No	Test 2: water outlet temperature (average): 49 °C (experimental), 48.7 °C (modelled)	For Sweden, electrical: 19.1%; For Portugal, electrical: 18.9%; Thermal: around 63% (maximum)	PVT with reflector/concentrator; Domestic water heating	Sweden; Portugal

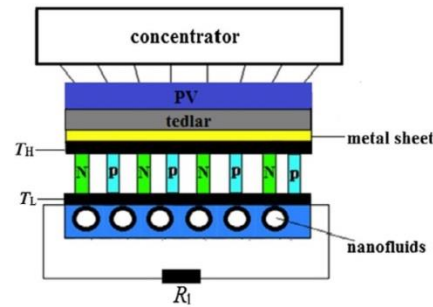
With respect to PVT based on nanofluids, Wu et al. [104] investigated a CPVT system with thermoelectric elements (figure 2). Glazed and unglazed configurations were

examined. In order to improve heat removal, nanofluid was used as a heat sink. It was noted that nanofluid shows better performance in comparison to water (for instance, from a heat-transfer point of view).

a)



b)



**Figure 2.** The low-temperature CPVT system studied by Wu et al. [104]: a) system with a thermoelectric component, b) nanofluid cooling tubes. Source: Wu et al. [104].

In Table 4, studies about different kinds of low-temperature PVT systems (bifluid configurations or systems with fluids different to those included in Tables 2 and 3), are presented. The results show that:

- The majority of the references are experimental/modelling investigations without involving solar concentration and thermoelectric devices.
- In many cases, silicon-based PV cells were used.
- Most of the investigations about concentrating systems refer to CRs up to 20X, involving configurations such as CPCs and parabolic-trough concentrators.
- The majority of the PV efficiencies are 13-15% (approximately). Moreover, in many cases, thermal efficiencies reach up to around 70%.

- Different types of applications were presented: by way of illustration, BI systems and configurations with PCM as storage material.
- A large majority of the studies are based on systems with working fluid temperatures around 40-55 °C.
- The systems were investigated for different climatic conditions.

**Table 4.** PVT systems: working fluids (nanofluids, air/water, etc.) at low-temperatures.

Study / year	Type of study	Working fluid	Solar concentration	Type of PV cells	Thermoelectric element	Temperature of the working fluid: Low	Efficiencies	Type of application: - Buildings - Etc.	Location of the study
Wu et al. (2015) [104]	M	Nanofluid	Yes (CRs up to 5X)	Not directly stated	Yes	PV cell: around 53 °C (maximum)	Thermal: 54.3% (maximum; theoretical)	Engineering applications	Not directly stated
Oruc et al. (2016) [105]	M	Water electrolyzer	No	Silicon-based	No	Average temperature of the electrolyte in the chamber: 53 °C	Energetic efficiencies of the PVT system: 56-59%; Electrical: around 15% (maximum)	Water and/or room heating; Powering fuel cell-based cars	USA
Su et al. (2016) [106]	M	Bifluid (water-water or air-water or water-air or air-air)	No	Not directly stated	No	Water–water PVT: hot water at 39.4 °C (0.1 kg/s); air–air PVT: hot air at 45.6 °C (0.1 kg/s)	Water–water PVT: electrical and overall efficiencies: 7.8% and 84.2%, respectively (0.15 kg/s)	PVT with dual channels for different fluids	China; India
Jarimi et al. (2016) [107]	E-M	Bifluid (air; water)	No	Not directly stated	No	With both fluids operating (at the same time), mean PV-cell temperature: 51.4 °C (air flow rate: 0.0074 kg/s)	Electrical: around 4-4.5%, depending on the case	PVT-bifluid applications	Malaysia
Othman et al. (2016) [108]	E	Air; Water	No	Transparent	No	Outlet temperature 44.6 °C (0.01 kg/s air mass flow rate; 350 W/m <sup>2</sup> ); Outlet temperature 32.2 °C (0.02 kg/s water mass flow rate; 350 W/m <sup>2</sup> )	Optimum results: 0.05 kg/s air mass flow rate; 0.02 kg/s water mass flow rate; total thermal efficiency (combi system): 76%; average outlet temperature: 27.4 °C; electrical efficiency: 17% (800 W/m <sup>2</sup> )	PVT with air and water heating systems	Malaysia
Yazdanifard et al.	M	Water; TiO <sub>2</sub> /water nanofluid	Yes (CRs: 4X, 6X, 8X, 10X, 12X,	GaAs	No	Outlet water temperature: 37.4 °C (0.008	Total energy efficiency 62% (in the case	PVT with parabolic-	Not directly stated

(2017) [109]			14X, 16X, 18X, 20X)			kg/s; 894.2 W/m <sup>2</sup> )	«laminar, glazed, CR = 20X»)	trough collectors	
Sardara badi et al. (2017) [110]	E	ZnO/water nanofluid	No	Mono-Si	No	PV-surface temperature, PVT with PCM and nanofluid: around 46 °C (maximum)	Overall exergy (PVT with PCM and nanofluid): 13.42%	PVT with nanofluid and PCM	Iran
Riverol a et al. (2018) [111]	E-M	PV cells immersed in deionised water or isopropyl alcohol	Yes (geometric CR: 10X)	Mono-Si	No	Maximum temperature: around 50 °C	Isopropyl- alcohol case shows the highest optical efficiencies 80-81% (maximum)	BIPVT (façade- integrated) with PV cells immersed in liquid	Spain
Moren o et al. (2018) [112]	E-M	Deionised water (PV cells immersed in deionised water)	Yes (geometric CR: 12X)	Silicon- based passivated emitter rear cells	No	Maximum temperature: around 50 °C	Optical: 76.14%	BIPVT (façade- integrated) with PV cells immersed in liquid	Spain; Italy; Portugal
Abdelr azik et al. (2019) [113]	M	Water/grap hene nanofluid; Water/ silver	No	Poly-Si	No	All the fluids remain liquids (phase of usage) and the temperature is lower than 60 °C	Electrical: 9.6- 11.4% (depending on the model); Thermal: around 79% (maximum; based on the models studied)	PVT with nanofluids and nano-PCM	Not directly stated
Dimri et al. (2019) [114]	M	Two versions: 1) air- based, 2) water- based	No	Not directly stated	Yes (thermoelectri c cooler)	Opaque PVT- thermoelectric air collector: around 38 °C (maximum fluid temperature)	Opaque PVT- thermoelectric air collector: overall electrical 14.2% (maximum)	Buildings	India

## 2.2. PVT SYSTEMS FOR MEDIUM-TEMPERATURE APPLICATIONS

In the literature about PVT systems with working-fluid temperatures between 60 and 90 °C, there is a more balanced number of cases with/without solar concentration in comparison to the literature about PVT systems with low-temperature working fluids.

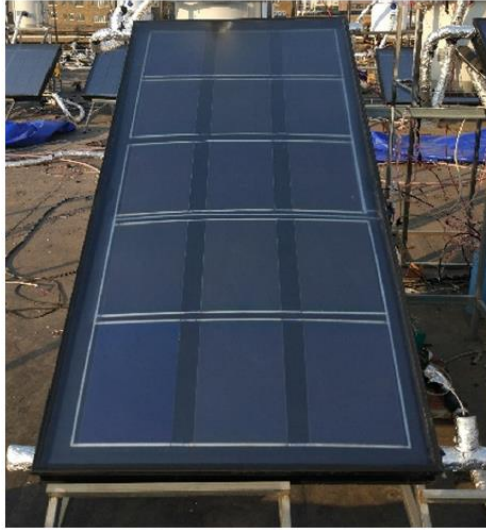
Table 5 presents studies about PVT systems without involving solar concentration and with using working fluids at medium temperatures. The results indicate that:

- A large number of references include experimental/modelling and modelling studies about systems without thermoelectric components.
- In most cases, silicon-based PV cells were utilised.

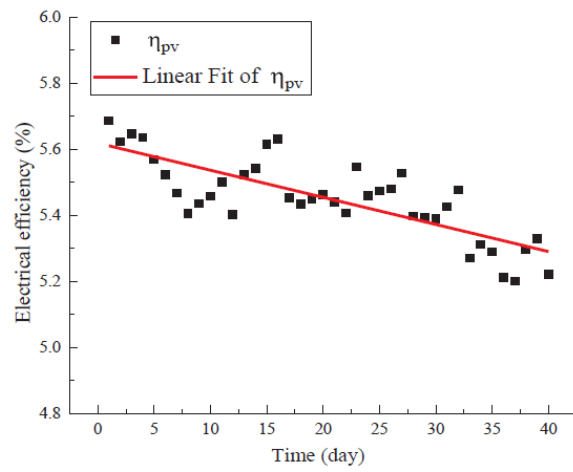
- The majority of the thermal efficiencies are around 55-60% and electrical/PV efficiencies are approximately 13-15%.
- A large majority of the investigations are about PVT/water and PVT/air configurations, for industrial and domestic applications (including BI systems).
- There are a few references about configurations with PCMs, heat pumps, ethylene-tetrafluoroethylene cushions and polymeric PVT collectors.
- In the vast majority of cases, the working-fluid temperatures are approximately 60-70 °C.
- The systems were evaluated for different climatic conditions.

Ren et al. [133] investigated an amorphous silicon PVT/water configuration appropriate for medium-temperature applications, verifying that this kind of PV technology is feasible from a technical/thermodynamic point of view (for medium-temperature applications). The experiments were conducted in Hefei, in China. In Figure 3, the PVT system and experimental/numerical results are illustrated.

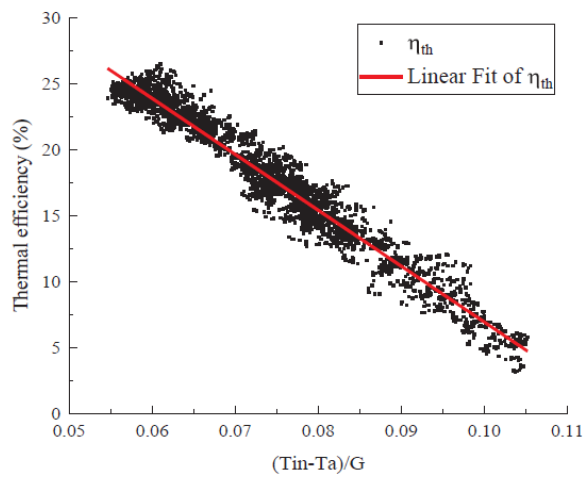
a)



b)

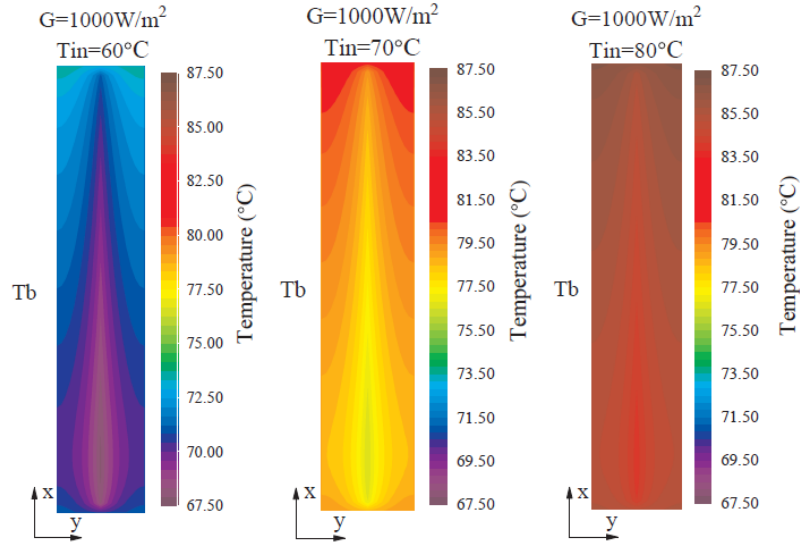


c)





d)



**Figure 3.** The amorphous silicon PVT/water system studied by Ren et al. [133]: a) experimental setup, b) electrical efficiency (experimental results), c) thermal efficiency (experimental results), d) temperature distribution of the absorber plate ( $T_b$ ) (numerical results; different inlet temperatures ( $T_{in}$ )). Source: Ren et al. [133].

**Table 5.** PVT systems without involving solar concentration: working fluids at medium temperatures.

Study / year	Type of study	Working fluid	Type of PV cells	Thermoelectric element	Temperature of the working fluid: Medium	Efficiencies	Type of application: - Buildings - Etc.	Location of the study
Cristofari et al. (2009) [115]	E-M	Water	Poly-Si	No	Solar-collector output: 62 °C (maximum)	Average: 55.5% (thermal), 12.7% (PV)	Polymeric PVT for domestic applications	France
Rajoria et al. (2012) [116]	M	Air	Not directly stated	No	Outlet air temperature: around 70 °C (maximum; case III)	Electrical (average): 11.3%	System appropriate for BI applications	India
Kalogirou et al. (2014) [117]	M	Air	Poly-Si	No	Air-gap temperature around 77 °C (maximum): for an air gap of 0.02 m and a steady flow velocity of 0.05 m/s	PV cell: 15%	BIPVT	Cyprus
Herrando et al. (2014) [118]	M	Water	Mono-Si	No	Constant hot water supply temperature: 60 °C	PV module: 15.4% (maximum)	Domestic applications	UK
Canelli et al. (2015) [119]	M	Water	Not directly stated	No	Temperature of the fluid for the end user: set at 60 °C	For the PVT system: Not directly stated	Buildings: PVT with chiller	Italy; Canada

Shyam et al. (2016) [120]	E-M	Water	Crystalline silicon	No	Outlet water temperature: around 80 °C (maximum; clear sky)	Module: around 6% (maximum)	Domestic and industrial applications	India
Khanjari et al. (2016) [121]	M	Pure water; Ag-water nanofluid; Alumina-water nanofluid	Not directly stated	No	Maximum outlet temperature: around 65 °C in one of the cases (Ag-nanoparticle)	Thermal around 84% (maximum) and electrical around 11% (maximum) in the case of Ag-water nanofluid	PVT with nanofluids	Not directly stated
Sotehi et al. (2016) [122]	E-M	Water	Not directly stated	No	Temperature of the water in the storage tank: 60 °C in order to reduce the risk of <i>Legionella</i> growth	Air conditioning system with reverse cycle (COP = 2.8; compressor electrical efficiency: 80%)	Desalination with solar stills; Net zero energy buildings	Algeria
Tiwari et al. (2016b) [123]	E-M	Air	Not directly stated	No	Temperature ranges from around 18 °C to 63 °C (Room 1, Room 2)	PV cell: 15%	BIPVT (roof-integrated)	India
Hu et al. (2016) [124]	E	Air	Amorphous silicon	No	Maximum temperature of the air inside the cushion: 67.8 °C (summer)	Virtual system efficiency (electricity and thermal energy): 25.5% (average experimental results, approximate method)	Ethylene tetrafluoroethylene cushion roof-integrated PVT	China
Hasan et al. (2017) [125]	E-M	Nanoparticles (SiC, TiO <sub>2</sub> and SiO <sub>2</sub> ) with water	Poly-Si	No	Maximum PVT plate temperature: 87 °C	Electrical and thermal efficiencies: 12.75% and 85%, respectively (1000 W/m <sup>2</sup> ; flow rate: 0.167 kg/s, ambient temperature: about 30 °C)	PVT with nanofluids	Malaysia
Chialasiri and Isaacson (2017) [126]	E-M	Air	Silicon	No	Average output temperature (after the optimisation): 64.7 °C	Thermal: 25-40%; electrical: around 6-8%	BIPVT (fenestration)	USA
Bigaila and Athienitis (2017) [127]	M	Air	Silicon-based	No	Maximum supply-water temperature: 100 °C	PV (standard test conditions): 15%	BIPVT (façade-integrated) with air-to-water heat pump and PCM	Canada
Gaur et al. (2017) [128]	M	Water	Mono-Si	No	Maximum outlet temperature: around 70 °C (PVT without PCM; summer)	PV efficiency with PCM: around 17-19% (maximum); Thermal efficiencies without PCM:	PVT with PCM: Industrial and domestic applications	France

						52.34% (winter) and 43.73% (summer)		
Bellos and Tzivani dis (2017) [129]	M	Water with nanoparticles	Not directly stated	No	Mean storage-tank temperature: around 64 °C (maximum; at the end of the day; nanofluid case)	Mean yearly efficiencies (nanofluid): thermal: 43.8%; electrical: 12.6%	Domestic applications; PVT with nanofluid	Greece
Herrando et al. (2018) [130]	M	Water	Poly-Si	No	Water is extracted when the temperature at the top of the tank is higher than 80 °C	Thermal: around 70-73% (maximum); PV module (nominal): 14.7%	Domestic applications; PVT with polymeric components	Spain; UK; Greece
Zulakmal et al. (2019) [131]	M	Air	Not directly stated	Yes (thermoelectric generators)	PV-panel initial temperature: around 72 °C	Efficiency (maximum): 4.6% (thermoelectric generator)	PVT with thermoelectric generators	Not directly stated
Xiao et al. (2019) [132]	M	Water	Not directly stated	No	For depth of the bottom channel = 0.01 m, the maximum temperature was found to be 83.5 °C at 13:30	Total thermal efficiency of the stepped PVT solar still with a bottom channel: 50.6%; Electrical: around 10% (maximum)	PVT with solar stills for water desalination	Not directly stated
Ren et al. (2019) [133]	E-M	Water	Amorphous silicon	No	The performance of the system was examined at 60, 70 and 80 °C (operating temperatures)	Efficiencies at 60, 70 and 80°C (daily): thermal 32.3%, 24.9% and 17.2%, respectively; Electrical: 5.3%, 5.1% and 4.9%, respectively	Buildings	China
Nazri et al. (2019) [134]	E-M	Air	Mono-Si	Yes	Maximum outlet-air temperature: 64.4°C (mass flow rate: 0.001 kg/s)	Optimum exergy efficiency of the PVT/thermoelectric: around 38%	Domestic and industrial applications	Malaysia
Boumaraf et al. (2020) [135]	E-M	Water	Poly-Si	No	Maximum fluid temperature: around 68-78 °C, depending on the configuration	For the water glazed PVT collector: electrical 6.3%, thermal 57.7%	Domestic and industrial applications	Algeria

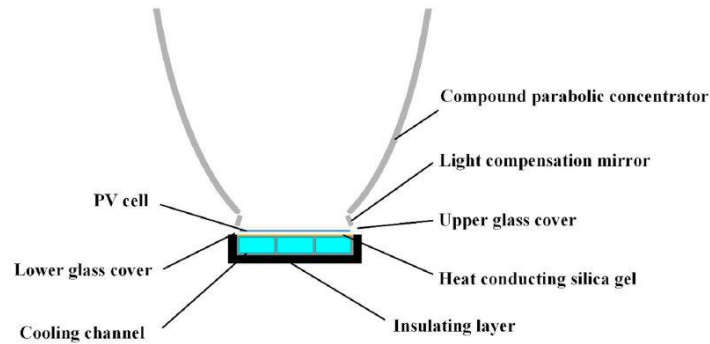
In terms of CPVT, Haiping et al. [136] developed and tested a flash tank integrated with a low-concentrating PVT system with CPCs (geometric CR: 4X; Figure 4), demonstrating the feasibility of this system for cogeneration of fresh water and electricity. The PVT panel is based on mono-Si PV cells, produces electricity and preheats saline

water. A solar thermal collector is connected with the PVT module in order to enhance the heating of the saline water. The experimental findings revealed a vaporisation coefficient of 5% and an average electrical efficiency of 13.3%.

a)



b)



**Figure 4.** The medium-temperature CPVT studied by Haiping et al: a) The Low-Concentrating Photovoltaic/Thermal - Solar Thermal Collector (LCPVT-STC) experimental set-up, b) details about the CPVT module. Source: Haiping et al. [136].

In Table 6, references about PVT systems involving solar concentration and using working fluids at medium temperatures are presented. The results suggest that:

- The majority of the references are about modelling and experimental/modelling investigations on PVT/water systems without thermoelectric elements.

- In most cases, the CRs are up to 190X and the working-fluid temperatures are around 62-90 °C.
- In most of the investigations, mono-Si and multi-/triple-junction PV cells were used.
- The majority of thermal efficiencies are approximately 50-68%. In most cases, PV efficiencies are around 10-19% and 35-38%, depending on the PV cells (single-junction vs. multi-junction, etc.).
- A large number of investigations are about domestic applications and desalination whereas there are a few studies on greenhouses.
- The systems were examined for different climatic conditions.

**Table 6.** PVT systems involving solar concentration: working fluids at medium temperatures.

Study / year	Type of study	Working fluid	Concentration ratio (CR)	Type of PV cells	Thermoelectric element	Temperature of the working fluid: Medium	Efficiencies	Type of application: - Buildings - Etc.	Location of the study
Sun and Shi (2009) [137]	M	Air	2X	Not directly stated	No	Temperature of the PVT system: around 92 °C (maximum)	Combined efficiency (system with CPC): around 75% (maximum)	PVT with CPCs	Not directly stated
Cui et al. (2010) [138]	E	Water	Theoretical maximum CR: 5.1X	Mono-Si	No	PV cell: 87.7 °C (907 W/m <sup>2</sup> )	PV cell: 5.7% (907 W/m <sup>2</sup> ); total efficiency of the CPVT system: higher than 70%	PVT with CPCs	China
Bernardo et al. (2011) [139]	E-M	Water	Geometric CR: 7.8X	Mono-Si	No	Water outlet temperature: around 77 °C (maximum)	Measured electrical: 6.4% at 25°C water outlet temperature	Domestic hot water production; pool heating	Sweden; Portugal; Zambia
Kerzmann and Schaefer (2012) [140]	M	Water	80X	Multi-junction	No	Bulk fluid temperature: around 62 °C (maximum; July)	Multi-junction cell (average): 34.7%	PVT with Fresnel lenses	USA
Ong et al. (2012) [141]	E-M	Water	CR up to 5000X	Low-thermal resistance multi PV chip receiver package	No	Deionised water, pre-heated to around 80 °C: evaporator	Optical: around 85%	Desalination	Switzerland ; Egypt

Jiang et al. (2012) [142]	M	Water	CRs: 1.1X, 2X	Thin film	No	Working-fluid temperature: around 85 °C (maximum)	Optical: 94% (average)	PVT with natural convection; PVT with CPCs	USA
Calise et al. (2012) [143]	M	Water	Future prospect: combination of solar heating/cooling with CPVT	Crystalline silicon (future prospect: III-V PV cells)	No	PVT modules operate up to 80°C	PVT average electrical: slightly lower than 10%	Trigeneration PVT system; Domestic applications	Italy
Petrucci et al. (2013) [144]	M	Water	Not directly stated	Not directly stated	No	Coolant exit temperature: 90 °C	Electrical: 18%; Thermal: 62%	Buildings	Portugal
Xu and Kleinstreuer (2014) [145]	M	Water-based nanofluids	100X	Silicon-based; Triple-junction	No	Nanofluid outlet temperature: set at 62 °C	For nanofluid outlet temperature 62°C: electrical 11%, thermal 59%	Domestic	USA
Jaffré et al. (2014) [146]	E	Water	20X (approximately)	Mono-Si	No	Mean temperature: around 62 °C (maximum)	Lens optical (measured): 77%; PV cell: 11% (measured, at 50°C); Thermal: 50% (measured, at 50°C)	Domestic water heating; PVT with Fresnel lenses	France
Tan et al. (2014) [147]	E	Water	Not directly stated	Crystalline silicon	No	In a specific case: 62.8 °C working-fluid temperature in the tank	PV cell (maximum): 5.21% (with concentration); Mirror optical: 70% ; Maximum instantaneous thermal (metal cavity heating): 68.2%	PVT with parabolic-trough mirrors	China
Garcia-Heller et al. (2014) [148]	M	Water	2000X	Triple-junction	No	90 °C hot water outflow	The system converts 25% of the direct normal irradiance into electrical energy and 62.5% to low-grade heat; Combined efficiency: 87.5%	Indoor space heating and cooling; Desalination	Algeria
Hughes et al. (2014) [149]	E-M	Water	Around 500X	III-V multi-junction	No	Final temperature of the cooling fluid: around 81 °C (maximum; June)	Evacuated-tube collectors: 65%; PV cells: 36%	Desalination with CPVT with parabolic dish and evacuated-tube collectors	UK
Kiflemariam et al. (2014) [150]	M	Air	One of the cases: CRs 2-5X	Not directly stated	Yes (thermoelectric generator)	Temperature distribution for CR = 3X and wind velocity 1-3 m/s: 40-82 °C (approximately)	Not directly stated	PVT with thermoelectric generators	Not directly stated

Renno and De Giacomo (2014) [151]	M	Water	500X, 1000X	Triple-junction InGaP/InGaAs/Ge	No	One of the cases: 75.4 °C fluid outlet temperature (average)	PV cell: 39.15% (maximum)	Domestic	Italy
Del Col et al. (2014) [152]	E-M	Water	120X	Triple-junction GaInP/GaAs/Ge	No	It is possible to produce heat at 80-90 °C	One specific case: average electrical and thermal efficiencies, 23.1 % and 41.6%, respectively	Domestic hot water production; swimming pools	Italy
Atheya et al. (2015) [153]	M	Water	Not directly stated	Not directly stated	No	Working-fluid output temperature: around 88 °C (maximum; for mass flow rate 0.002 kg/s)	Electrical: around 12.5% (maximum); Thermal: around 42% (maximum; case: partially covered PVT-CPC water collector)	PVT with CPCs	India
Intiaz Hussain and Lee (2015) [154]	E-M	Water	Not directly stated	Triple-junction	No	For 0.5 L/min, 30 °C ambient temperature, 900 W/m <sup>2</sup> : predicted temperature 75 °C	Efficiency of the U-shaped collector: 76% (maximum) at zero temperature difference between the ambient and working fluid	PVT with Fresnel lenses	Korea
Gholami et al. (2015) [155]	M	Water	0-1000X	Triple-junction	No	One specific case: maximum fluid temperature around 87 °C	Electrical: 38% (maximum; under working conditions); thermal: 48% (maximum; under working conditions)	Domestic applications; CPVT with dish concentrators	Iran
Li et al. (2015b) [156]	E-M	Water	Geometric CR: 2.4X	Not directly stated	No	Final water temperature: 70 °C	Electrical and thermal efficiencies of the system during the test: 6% and 35%, respectively (for final water temperature: 70 °C)	BIPVT with air-gap-lens-walled CPC	China
Wiesenfarth et al. (2016) [157]	E-M	Water	5000X	Multi-junction	No	Outlet temperature (receiver): fixed at 90 °C	Theoretical maximum: 79.2% (for the system)	Desalination with CPVT with mirror dish	Germany
Intiaz Hussain et al. (2016) [158]	E-M	A mixture of antifreeze liquid and water	Not directly stated	Multi-junction	No	Temperature of the fluid in the pipe (with enclosure): 62.3 °C	Global efficiencies (CPVT system; average; steady state): 76% with enclosure, 70% without enclosure	Greenhouses; PVT with Fresnel lenses	Korea

Ziapour et al. (2016) [159]	M	Water	Not directly stated	Not directly stated	No	Water storage-tank temperature: around 70 °C (maximum) in the case with reflectors	Solar cell: around 13% (maximum value in certain cases)	Domestic applications; PVT with mirrors or aluminium reflectors	Not directly stated
Al Imam et al. (2016) [160]	E-M	Water	Maximum CR: 1.82X	Not directly stated	No	Average plate temperature: around 87 °C (clear days)	Thermal: around 50% (maximum); Total: around 63% (maximum)	PVT with CPC and PCM	Bangladesh
Mohsenzadeh et al. (2017) [161]	E-M	Water	Geometric CR: 8.34X	Mono-Si	Yes	Daily average temperature of the PV cells for the mode CPVT/thermoelectric with cover (hybrid system): 93.8 °C	CPVT/thermoelectric with cover (hybrid system): thermal 46.2%, electrical (total): 4.8%	PVT applications with parabolic-trough concentrators and triangular cooling ducts	Iran
Calise et al. (2017) [162]	M	Water	10X	Triple-junction InGaP/InGaAs/Ge	No	CPVT set-point temperatures: 50 °C (winter), 90 °C (summer)	Thermal (CPVT): 63.4%; electrical (CPVT): 18.9%	Polygeneration system: CPVT, chiller, fuel cells, etc.	Italy
Elsafi (2017) [163]	M	Air	2X	Not directly stated	No	Maximum air temperature (humidification-dehumidification-humidification/CPVT): around 64 °C (summer)	Not directly stated	Desalination based on PVT with CPCs	Saudi Arabia
Akrami et al. (2018) [164]	M	Water	10X	Not directly stated	No	PV-cell temperature: around 100 °C	Whole system: overall exergy efficiency 11.3%; CPVT exergy efficiency: less than 30%	Domestic applications; PVT with reflectors, chiller and proton exchange membrane electrolyser	Not directly stated
Guo et al. (2018) [165]	E	Water	Not directly stated	Not directly stated	No	Maximum temperature of the inlet saline water (vacuum still): around 70 °C	Electrical: 12.5% (maximum)	Desalination	China
Shadmehri et al. (2018) [166]	M	Water	Local concentration factor: 0-190	Mono-Si	Yes	Medium	PV cell: 15.75%; Thermal: around 47% (maximum; numerical simulation with cover)	Buildings, industry; PVT with triangular cooling duct and parabolic reflector	Not directly stated
Kandil et al. (2019) [167]	M	Water	Up to 1500X	Triple-junction InGaP/InGaAs/Ge	No	For CRs higher than 400X, cooling-water temperatures higher than 75 °C	For CRs higher than 400X, thermal efficiency higher than 65%; electrical: 34-42% (approximately), depending on the CR (cell	PVT with Fresnel lenses for hot climates	Kuwait

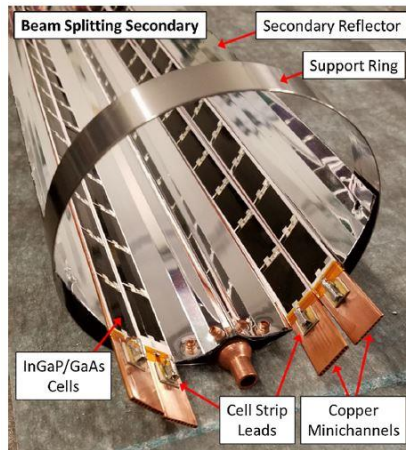


							temperatures: 25 and 80 °C)			
Gomaa et al. (2019) [168]	E	Water	6X, 10X	Mono-Si	No	Hot water temperature at the receiver exit (maximum): 74 °C (0.025 L/min flow rate, ambient temperature: 37.6 °C)	Thermal 61.3% (0.025 L/min flow rate, outlet maximum temperature 57 °C); for geometric CR 6X and 460 W/m <sup>2</sup> , electrical efficiency 11%	Domestic and industrial applications; PVT with linear Fresnel mirrors	Jordan	
Haipin g et al. (2019) [136]	E	Water	Geometric CR: 4X	Mono-Si	No	Flash-tank design: 90 °C by regulating the flow rate	Electrical: about 13.3% (average)	Desalination by means of PVT with CPCs	China	

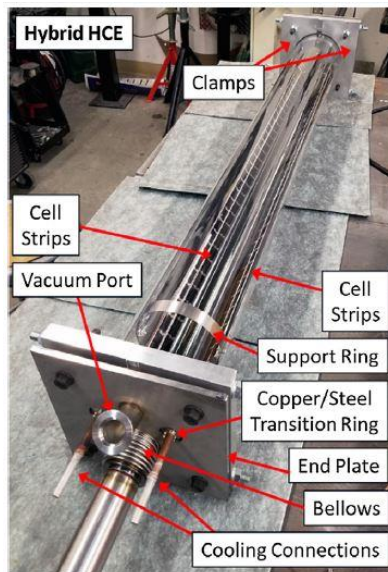
### 2.3. PVT SYSTEMS FOR HIGH-TEMPERATURE APPLICATIONS

In the field of PVT systems with the working fluids at high temperatures (higher than 90 °C), one challenge is to cope with the reduction in PV-cell efficiency at high temperatures. Crisostomo et al. [169] noted that spectral beam splitting is a solution that allows PV cells to work at low temperatures whereas thermal receiver operates at high temperatures. However, in this case, the fraction of solar irradiation that without beam splitting would be converted into heat by the PV cell is lost. SiN<sub>x</sub>/SiO<sub>2</sub> multilayer thin-film filters were used as beam splitting devices in a linear Fresnel mirror-based CPVT system with CR 10X. Indoor testing was conducted (involving filters, silicon-based PV cells, thermal sensor and solid-state plasma light source). The experiments revealed that the PV cells, illuminated by the light reflected by the filters, show 9.2% (absolute) higher efficiency in comparison to the same PV cells without the filters [169]. Widyolar et al. [170] investigated a spectrum splitting hybrid concentrating solar power/CPV collector (design, simulations, testing; geometric CR: 50X; Figure 5). Double-junction InGaP/GaAs solar cells were used. Experiments using a fluid with suspended solid (alumina based) particles heated up to 600 °C were conducted.

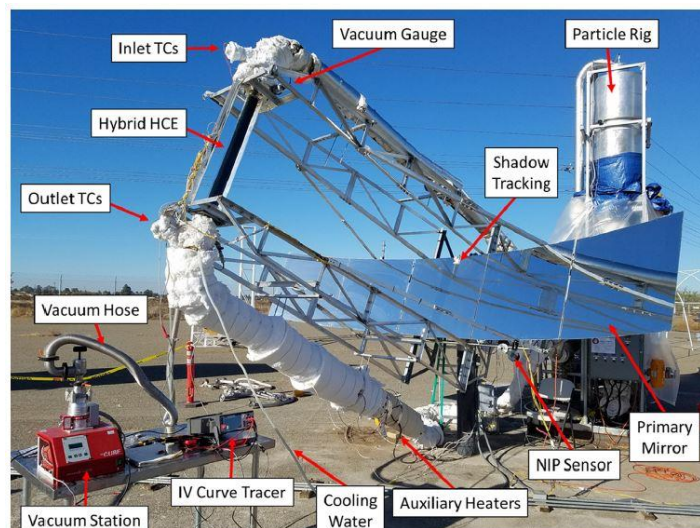
a)



b)



c)



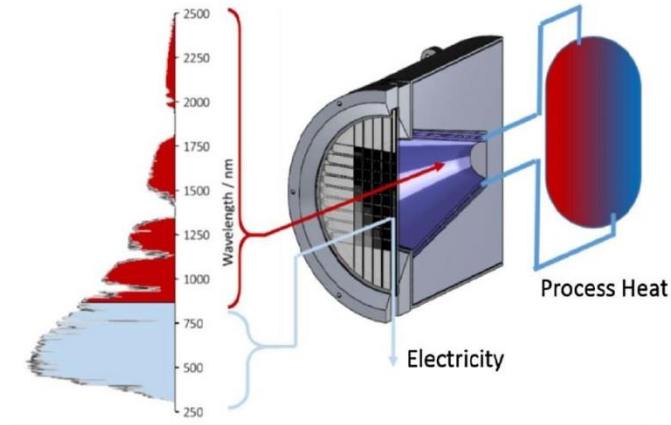
**Figure 5.** The high-temperature CPVT system studied by Widyolar et al. [170]: a) details about the secondary reflector, b) hybrid Heat Collection Element (HCE), c) primary mirror, Normal Incidence Pyranometer (NIP) sensor, shadow tracking, etc. Source: Widyolar et al. [170].

In Table 7, references about PVT systems with solar concentration for high-temperature use are presented. The analysis indicates that:

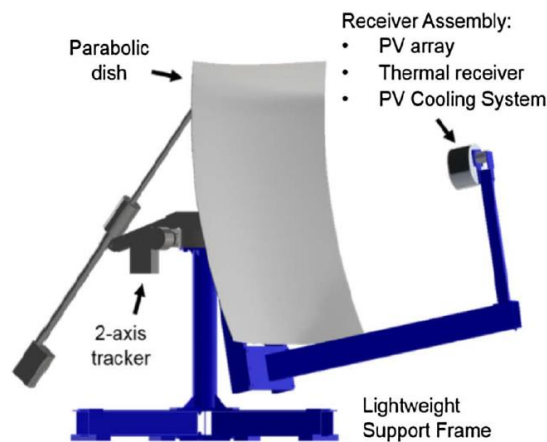
- The majority of the references are about modelling studies, suggesting that experimental developments are still in their early stages.
- In most cases: i) the systems do not include thermoelectric elements, ii) CRs are up to 1000X, iii) the working fluid is water, iv) temperature spans are from around 100 to 250 °C.
- There are a few investigations with working fluids such as oils, salts and nanofluids.
- Most of the systems have triple-junction or silicon-based PV cells.
- The majority of thermal efficiencies are around 50-60% and electrical/PV efficiencies are approximately 20-30%.
- Regarding applications, a large majority of the investigations refer to domestic installations, desalination, polygeneration and large-scale systems.
- A vast majority of the references are about configurations with parabolic concentrators.
- The systems were examined for different climatic conditions.

Riggs et al. [205] presented a study about high-temperature PVT systems (Figure 6: schematics), highlighting the fact that concentrating solar systems offer multiple applications such as industrial and commercial. Moreover, it was found that the energy produced offers cost savings, verifying that solar systems are competitive in comparison to conventional fuels such as propane and coal.

a)



b)



**Figure 6.** Schematics related to the study by Riggs et al. [205] about CPVT systems for high-temperature applications: a) energy conversion (hybrid receiver), b) CAD model of a dish-based CPVT system with 2-axis tracker. Source: Riggs et al. [205].

**Table 7.** PVT systems appropriate for high-temperature applications.

Study / year	Type of study	Working fluid	Solar concentration	Type of PV cells	Thermoelectric element	Temperature of the working fluid: High	Efficiencies	Type of application: - Buildings - etc.	Location of the study
Mittelman et al. (2009) [171]	M	Water	200X	Triple-junction	No	Coolant outlet temperature: around 210 °C (maximum) for CR 200X	For coolant outlet temperature: around 210 °C and CR 200X: thermal around 59%, electrical around 19%	Desalination	Not directly stated
Otanicar et al. (2010) [172]	M	Heat-transfer fluid	Up to 200X	GaAs; Silicon-based	No	Peak fluid temperature: around 250 °C	Maximum combined efficiency: around 32.3% for solar concentrations 10–50 and a band-gap 1.5–2.0 eV (approximately)	CPVT coupled electrothermal model	Not directly stated

Zhao et al. (2010) [173]	M	Water	Not directly stated	Crystalline silicon	No	Working-fluid temperature at the outlet of the thermal unit: 108 °C (maximum)	Electrical: 10.4% (maximum); Thermal: 66%	PVTs with direct absorption	Not directly stated
Jiang et al. (2010) [174]	M	Heat-transfer fluid	Geometric CRs up to around 9X (evaluation parameter: 7X)	Silicon-based	No	Heat energy of about 250-300 °C can be achieved	Overall optical: 76.4% (maximum) with the optimised splitting coating	Parabolic-trough PVT with beam-splitting filter and evacuated-tube collectors	Not directly stated
Al-Alili et al. (2012) [175]	M	Water	Not directly stated	Not directly stated	No	Tank temperature (average): around 99 °C (maximum)	The COP of the hybrid solar air conditioner is higher than that of a vapour-compressor-cycle (with PVs; solar absorption cycle)	PVT with desiccant; domestic-hot-water production	United Arab Emirates
Chávez - Urbiola et al. (2012) [176]	E	Water	55X, 95X	Crystalline silicon; amorphous silicon	Yes (Bi <sub>2</sub> Te <sub>3</sub> )	Hot-plate temperature: 200 °C	Efficiencies of the thermoelectric-generator concentrator systems (maximum irradiance): 4-17%, depending on the case	Domestic (or other) applications; CPVT with parabolic mirrors	Mexico
Buonomano et al. (2013a) [177]	M	Heat-transfer fluid	Not directly stated	Triple-junction	No	Assumption: the system operates up to 180 °C	Electrical (in one of the cases): 19-25%; optical: slightly lower than 60%	PVT with parabolic dish for indoor space heating/cooling, domestic hot water, electricity	Not directly stated
Buonomano et al. (2013b) [178]	M	Water	Geometric CR 500X	Triple-junction	No	Maximum operating temperature: 100 °C	PV cell: around 35%	PVT with parabolic dish for indoor space heating/cooling, domestic hot water, electricity	Italy
Wu et al. (2013) [179]	E	Distilled water; Propylene glycol; Silicone oil; Mineral oil	Geometric CRs: 10-30X	Not directly stated	No	Aim of the project: working fluid up to 150 °C	Not directly stated	High-temperature applications	Australia
Calise et al. (2013) [180]	M	Water	Not directly stated	Triple-junction	No	Maximum output temperature: around 175 °C (summer); set point: 170 °C	Based on the beam radiation: thermal 50%, electrical 20.8%	PVT with parabolic dish for indoor space heating/cooling, domestic hot water, electricity	Italy
Polonsky et al. (2013) [181]	E	Water	Around 400-450X	Triple-junction GaInP/GaInAs/Ge	No	PV cell: around 120 °C (maximum)	Maximum efficiency (for the module): around	PVT with parabolic dish concentrators	Israel; Germany

							22% at CR about 400X; Optical (measured): 86.5%		
Helmers et al. (2014) [182]	M	Water	Geometric CRs: 10-2000X	Multi-junction	No	At CRs higher than 300X, thermal losses are almost negligible at mean fluid temperatures up to 160 °C	For CRs higher than 300X, system overall efficiency: 75%; Maximum electrical: around 29%	Industrial	Not directly stated
Calise et al. (2014a) [183]	M	Water	Not directly stated	Triple-junction	No	CPVT outlet temperature: 100 °C (or higher)	CPVT thermal: up to 60%; electrical: around 20%	Desalination; polygeneration	Italy
Crisostomo et al. (2014) [169]	E	Water	10X	Front junction n-type silicon	No	Maximum temperature (thermal output): it is expected to reach 150 °C	Thermal: 75%; Maximum PV-cell (hybrid system with filter): 29.1%	PVT with Fresnel mirrors for commercial and industrial buildings	Australia
Gomes et al. (2014) [184]	E-M	Water	1.5X	Mono-Si	No	Collector stagnation temperature: about 120 °C	PV panel: 15%	Asymmetric CPVT collectors	Sweden
DeJarnette et al. (2014) [185]	M	Fluid with plasmonic nanoparticles	Not directly stated	GaAs	No	Goal: to achieve an operating temperature of 300 °C	Exergetic: higher than 40% (at 300 °C)	PVT with spectral fluid filters and plasmonic nanoparticles	Not directly stated
Liu et al. (2014) [186]	E-M	Not directly stated	Geometric CRs from around 3X to 30X (approximately)	Crystalline silicon	No	Operating temperature of the thermal receiver: 300 °C	Efficiency of the system: 26.5% (for solar cell operating at 25°C)	Heat engine; CPVT system with beam splitter and linear Fresnel reflector	China
Mojiri et al. (2014) [187]	M	Water; Propylene glycol; Ethylene glycol	CRs: from 10X to 20X	Crystalline silicon	No	Heat-transfer liquids for temperatures higher than 100 °C	Not directly stated	PVT rooftop applications with micro-concentrators	Not directly stated
Calise et al. (2014b) [188]	M	Water	Not directly stated	Triple-junction	No	The PVT can operate at 100 °C (maximum)	One specific case: electrical 20%, thermal 50% (based on beam radiation)	Desalination; trigeneration system; PVT with parabolic-trough collectors	Italy
Looser et al. (2014) [189]	E-M	Various commercial heat-transfer fluids	Not directly stated	Silicon-based	No	Goal: heat production at 135 °C (approximately)	Goal: enhancement of system efficiency and reduction in lifetime energy costs	Beam-splitting applications; PVT with micro-concentrators	Australia
Calise et al. (2015) [190]	M	Water	Not directly stated	Triple-junction	No	The system includes one-axis tracking and can operate at 100 °C (maximum)	Exergy efficiency (summer day): around 20%	Desalination; polygeneration; PVT with parabolic-trough collectors	Italy
Mojiri et al.	M	Water; Propylene	20X	Crystalline silicon	No	The hybrid receiver has a	PV cell (baseline):	Rooftop applications	Not directly stated

(2015) [191]		glycol; Ethylene glycol				high- temperature (higher than 150 °C) liquid channel	around 20.6% (CR: 1X; 25 °C)	with micro- concentrators	
Otanic ar et al. (2015) [192]	M	Working fluid	Ranging from 40X to 240X or from 50X to 600X, depending on the case	The values selected for the bandgap refer to: Si, GaAs, CdTe, InGaP	No	Maximum heat- transfer-fluid outlet temperature: 600 °C	For outlet fluid temperature 300°C: thermal around 75% (maximum), electrical around 28% (maximum)	Applications with spectral filtering and high- temperature PV	Not directly stated
Renno and Petito (2015) [193]	M	Water - glycol	100-900X	Triple- junction InGaP/InG aAs/Ge	No	Maximum fluid outlet temperature (summer): around 118 °C	PVT system: electrical around 25% (maximum),ther mal around 70% (maximum)	Domestic applications with point-focus parabolic- concentrator PVT	Italy
Crisost omo et al. (2015) [194]	M	Water	10X	Si, GaAs, GaInP/Ga As	No	Hybrid- collector goal: pressurised water at around 140 °C	Optical: 71% (maximum); Thermal: 80% (maximum)	Domestic or industrial applications; PVT with spectral beam splitting and Fresnel mirrors	Not directly stated
Abdelk ader et al. (2015) [195]	M	Water	100X, 300X, 500X, 700X, 900X	Triple- junction InGaP/InG aAs/Ge	No	Maximum output fluid temperature: around 94 °C (CR: 900X)	Thermal: around 59% (maximum); Electrical: around 22% (maximum)	PVT with parabolic mirror concentrators	Libya
Atheay a et al. (2016) [196]	M	Water	Not directly stated	Not directly stated	No	Outlet fluid temperature: around 130 °C (maximum; case: glazed inverted absorber partially covered PVT- CPC)	Electrical: around 13.2% (maximum; case: partially covered horizontal PVT- CPC); instantaneous thermal: around 59% (maximum; case: glazed inverted absorber partially covered PVT- CPC)	PVT with CPCs	India
Sharaf and Orhan (2016) [197]	M	Pure water; Al <sub>2</sub> O <sub>3</sub> /water nanofluid; Al <sub>2</sub> O <sub>3</sub> /synt hetic oil nanofluid	Up to 2000X	Multi- junction InGaP/ InGaAs/Ge	Yes	One of the cases: heat- transfer-fluid outlet temperature: around 120-125 °C	Multi-junction PV cells eliminate the negative impact of high temperature on conversion efficiency (for high CRs)	PVT systems with densely- packed receivers	Not directly stated
Stanley et al. (2016) [198]	E	Water	Geometric CR 42X	Silicon- based	No	Receiver: primary thermal absorber inlet temperature up to 200 °C	Total (for the system; at 120 °C receiver temperature): 50%; Electrical: about 3.8% (relative to the total incident power)	Spectral beam splitting PVT with linear concentrators; industrial applications	Australia

Tripathi and Tiwari (2016) [199]	M	Water; Molten salt	Not directly stated	Not directly stated	No	Outlet fluid temperature: 190 °C (maximum)	PV module: around 12.5% (maximum)	PVT with CPCs	India
Tripathi et al. (2016) [200]	M	Water	Not directly stated	Not directly stated	No	Outlet water temperature: around 195 °C (maximum; mass flow rate 0.002 kg/s; January)	Electrical: around 13% (maximum)	PVT with CPCs	India
Hassan (2016) [201]	M	Water; Ag/water nanofluids	1X, 2X, 3X, 4X, 5X, 6X, 7X, 8X, 9X, 10X	Mono-Si	No	Maximum working-fluid temperatures: around 100 °C	One of the cases: electrical 12.25%, thermal exergetic 1.72%	Domestic	Not directly stated
Abdelhamid et al. (2016) [202]	E-M	Oil	60X	Thin-film single-junction GaAs	No	Maximum outlet temperature: 365 °C	At the maximum outlet temperature (365 °C): experimental thermal efficiency (average) about 37%, maximum electrical around 8%	Power plants	USA
Radwan et al. (2016) [203]	M	Water	Up to 40X	Poly-Si	No	For CR 40X and $Re = 5$ , outlet water temperature 90.2 °C	Electrical 16-19.5%, thermal 60.5-63%, depending on the case (CR, $Re$ )	PVT with point-focus Fresnel-lens concentrators	Egypt
Singh and Tiwari (2017) [204]	M	Water	Not directly stated	Not directly stated	No	Outlet water temperature: around 110 °C (maximum)	Electrical: around 12% (maximum); annual cogeneration: 22.55%	PVT with CPCs for water distillation	India
Riggs et al. (2017) [205]	M	Water	Up to 1800X	Multi-junction GaAs	No	Temperatures up to 650 °C at the surface of the thermal receiver	PV cell: 27-33%	Domestic hot water heating; desalination; food processing, etc.	USA
Widyolar et al. (2017) [206]	E-M	Heat-transfer fluid (Therminol VP-1)	Geometric CR around 60X	Single-junction GaAs	No	Maximum outlet temperature: 365 °C	Thermal (experimental): approximately 37%; Maximum electrical: about 8%	PVT with CPCs	USA
Lamnati et al. (2018) [207]	M	Water	Geometric CR around 13X	Poly-Si	No	Heat production: at about 140 °C: Lecoeuvre et al. (2018) [208]	Annual production: 996 kWh electricity, 2190 kWh thermal	Buildings, etc.; PV modules with concentrating solar thermal unit	France
Gomaa et al. (2018) [209]	M	Water	From around 5X to 46X (approximately)	Silicon-based	No	Operation at 150 °C is appropriate for double-effect absorption refrigeration and organic Rankine cycle	One specific case: 18% electrical, 62% thermal	Buildings; industry	Not directly stated



Moaleman et al. (2018) [210]	M	Water-ammonia absorption refrigeration cycle	15X	Mono-Si	No	Output fluid from the panels around 130-140 °C (maximum; June, July)	Electrical: 12.8% (average annual); Thermal: 58% (average annual)	Buildings; industry	Iran
Ben Youssef et al. (2018) [211]	M	Water	10X, 20X	Triple-junction InGaP/InGaAs/Ge	No	Maximum outlet hot water temperature: 220 °C (midday)	Electrical: 21% (maximum); Thermal: 62% (maximum)	Textile-industry applications; PVT with parabolic-trough concentrators	Tunisia
Vossier et al. (2018) [212]	M	Oil	For line-focus: 25-50X; for point-focus: 1000-2000X	Single-junction	No	Maximum temperatures: 393 °C, 550 °C	Maximum efficiency for the high-temperature PV cell (for normal global solar radiation): 42.3%	Power plants	USA
Alayi et al. (2019) [213]	M	Heat-transfer fluid	Not directly stated	Not directly stated	No	Maximum output temperature of the CPVT collector: 150 °C	For the simulations: heat exchanger with 60% efficiency; Collector fin efficiency factor: 0.7	CPVT with parabolic-trough concentrators for buildings	Iran
Widyolar et al. (2019) [170]	E-M	Water; Heat-transfer fluid with particles	Geometric CR 50X	Double-junction InGaP/GaAs	No	The system was tested at 600 °C (maximum)	Simulations: Optical 64%; Thermal 52% (at 600°C); Efficiency of the back-reflecting CPV subsystem: 6%	Power plants; domestic or commercial hot-water production	USA
Al Nimr and Al Ammari (2019) [214]	M	Organic fluid (solar cells immersed in the fluid)	Not directly stated	Not directly stated	No	Outlet temperature at the exit of the absorber tube: 130 °C (maximum)	Based on the designed configuration: PV-module efficiency around 12%; absorber efficiency 64-75%	PVT based on organic Rankine cycle; PVT with parabolic-trough concentrators	Jordan
Valizadeh et al. (2019) [215]	M	Water	Not directly stated	Not directly stated	No	Outlet fluid temperature (maximum): around 95 °C (0.1 m/s)	By increasing the length of the collector from 3 to 90 m: thermal efficiency 62.5% and 60%; Electrical: around 20-22% (maximum)	Domestic and industrial applications with linear parabolic-trough concentrators	Not directly stated

### 3. CHALLENGES AND FUTURE PROSPECTS

In light of the issues discussed in section 2, PVT systems for low- and medium-temperature applications pose the following challenges:

- Development of PVT systems which are based on multiple kinds of PV cells (apart from the typical configurations with Si-based PV cells) and different types of working fluids (nanofluids, bi-fluid systems and so on).
- Design of innovative systems with concentrators and/or thermoelectric components, aiming at the achievement of high electrical and thermal efficiencies for a wide range of applications (residential, agricultural, industrial, etc.).
- Development of burgeoning systems which form part of the building structure itself (BI solar systems).

On the other hand, high-temperature PVT systems pose challenges such as:

- Utilisation of PV-cell materials and concentrators suitable for high CRs.
- Design of PVT configurations with CRs higher than 1000X and working-fluid temperatures higher than 300 °C, offering a whole host of applications (industrial, large-scale power generation and so on).
- Testing (under real and experimental conditions).

In the literature on PVT systems, there are studies which place emphasis on CPVT technologies, highlighting the fact that systems with solar concentration offer a raft of solutions ranging from domestic hot water production to organic-Rankine configurations. In this case, an additional challenge is related to heat-transfer components/medium. Elements such as fins, micro-channels, storage devices, heat exchangers and PCMs were evaluated with a view to examining issues such as heat-transfer performance and thermal/electrical efficiencies. Moreover, the performance of the heat-transfer fluid depends on multiple factors, namely viscosity, density, temperature, thermal mass, time

and mass flow rate. Furthermore, the systems should be feasible from an economic point of view. To this end, parameters such as feed-in tariff and carbon credit should be considered [216].

Additional CPVT challenges are associated with the evaluation of the systems from different angles (experimental, numerical and so on), investigation of the impact of the concentrators (CR, temperature, etc.) and the role of the COP. The results of the literature on CPVT show that these systems are promising and, in the short run, are expected to be competitive with conventional energy systems [217].

#### **4. CONCLUSION**

The present article provides a thorough review of PVT systems from a specific viewpoint. In particular, the PVT configurations have been categorised by the temperature of the working fluid. In each case, useful information has been extracted: namely working fluid, PV-cell types, solar concentration ratio, fluid temperature, electrical and thermal efficiencies, type of application and location of the study.

Analyses of the main features of the PVT systems (on the basis of three working-fluid temperature ranges: low, medium and high) have revealed the major trends of the research that has hitherto been conducted. Accordingly, gaps remaining to be filled have been identified (simultaneous improvement of electrical and thermal efficiencies and so on).

By way of illustration, more diverse PV technologies need to be used and developed, especially in the case of systems operating at high temperatures. To this end, thermal systems should be optimised, in line with different levels of solar concentration and resulting temperatures. On the other hand, hybridisation with thermoelectric elements is a hitherto-immature technology and, therefore, further development is needed. The remaining challenges are more numerous for the high-temperature applications, in terms

of working fluid, heat transfer components and heat storage. Much as modelling and simulations provide solid design tools, tests under real operating conditions are absolutely required. Additional factors such as costs, payback times, materials and environmental impacts (in comparison to conventional energy systems) should also be taken into account.

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