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Review

A Review of Photovoltaic Thermal (PVT) Technology for Residential Applications: Performance Indicators, Progress, and Opportunities

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Abstract: Solar energy has been one of the accessible and affordable renewable energy technologies for the last few decades. Photovoltaics and solar thermal collectors are mature technologies to harness solar energy. However, the efficiency of photovoltaics decays at increased operating temperatures, and solar thermal collectors suffer from low exergy. Furthermore, along with several financial, structural, technical and socio-cultural barriers, the limited shadow-free space on building rooftops has significantly affected the adoption of solar energy. Thus, Photovoltaic Thermal (PVT) collectors that combine the advantages of photovoltaic cells and solar thermal collector into a single system have been developed. This study gives an extensive review of different PVT systems for residential applications, their performance indicators, progress, limitations and research opportunities. The literature review indicated that PVT systems used air, water, bi-fluids, nanofluids, refrigerants and phase-change material as the cooling medium and are sometimes integrated with heat pumps and seasonal energy storage. The overall efficiency of a PVT system reached up to 81% depending upon the system design and environmental conditions, and there is generally a trade-off between thermal and electrical efficiency. The review also highlights future research prospects in areas such as materials for PVT collector design, long-term reliability experiments, multi-objective design optimisation, techno-exergo-economics and photovoltaic recycling.

Keywords: solar energy; photovoltaic thermal systems; PVT system classification; combined heat and power

1. Introduction

Sustainable development has been the mantra of the modern world, and accordingly, the United Nations had adopted 17 sustainable development goals (SDGs) [1] with emphasis on gender and social inclusion to eradicate poverty, protect the globe and promote peace and prosperity. It is understood that processes involved in energy generation are one of the key contributors to climate change, and the energy sector generates nearly 60% of greenhouse emissions. One of the SDGs, i.e., SDG-7, is focused on providing affordable and clean energy to the civic society by fostering innovations and investments at different stages of energy production and generation. There was a 6.2% [2] increase in the percentage of the population with access to electricity across the world from 2010 levels, and this value is 13.2% in the case of the rural community. As per the International Renewable

Energy Agency's (IREA) 2020 energy progress report [3], 0.8 billion people were still without access to electricity in 2018. Grid-based energy systems have been subjected to economic and governance barriers for decades. Therefore, there is a push towards decentralized [4] or distributed and smart systems due to their ability to transform energy access by covering all the three elements of energy trilemma, i.e., costs, emissions and security. However, the increased penetration of distributed energy sources may cause unusual effects on the electricity distribution network, including reverse power flow, leading to the need for changes in the conventional power system structure, and this is where smart electricity systems will be crucial to manage the entire network. There are almost 400 individual technology designs and components currently at different technology readiness levels (TRL) [5] to reduce CO_2 emissions. Solar technology is among them with the scope of both on grid and off grid connections to produce electricity and heat. Photovoltaics (PV) and solar thermal are well-established technologies to produce solar energy [6]. However, it can be inferred from Figure 1 that the share of solar PV and solar thermal in different regions is relatively low compared to other renewable energy sources like biomass, hydropower and modern bioenergy.

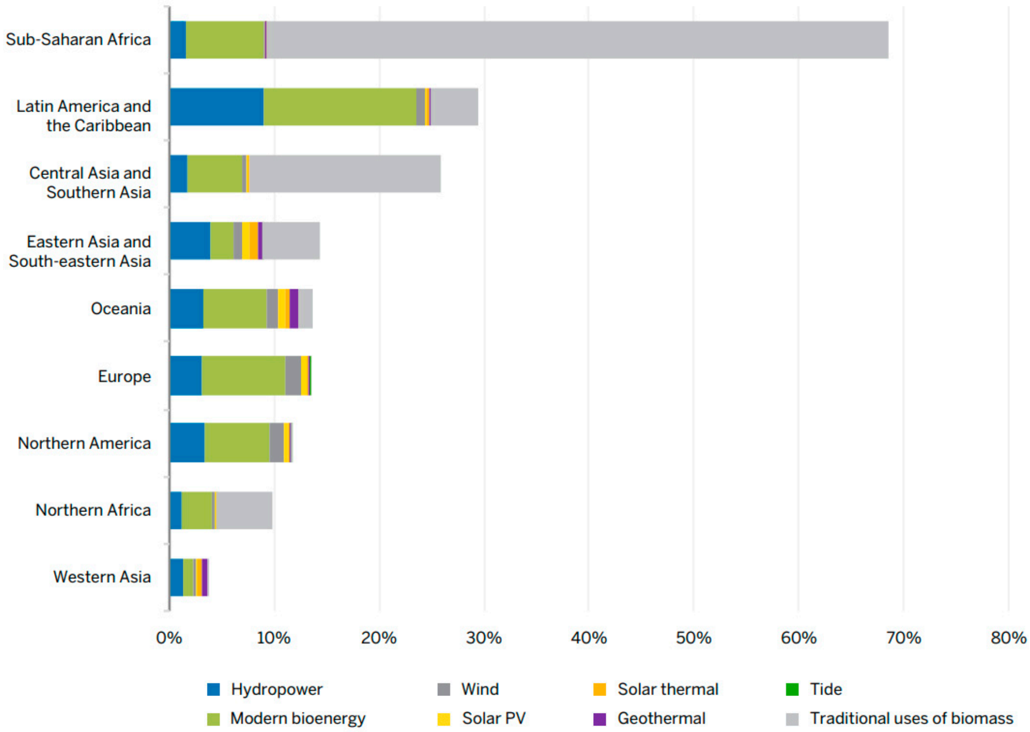


Figure 1. Renewable share in total final energy consumption different regions, 2017 [3].

1.1. Energy Transition, Transformation and Access Perspectives

The main drivers of the global energy transformation from fossil fuels are a fall in renewable energy costs, reduced carbon emissions, enhanced energy security, complete energy access, job creation and economic gain. According to the energy transition report [5], the share of renewable energy in the primary energy supply has to be 65% by 2050 from 15% in 2015. This enormous increase would need investments amounting to USD 29 trillion through to 2050. In the recent IREA report [7], the share of renewable energy in electric power generation by 2050 was reported to be 86%, while annual solar PV deployment was set to 360 GW/yr. China, the United States and the European Union are the top three residential PV growth markets [8]. Solar PV power would be supplying 13% and 25% of total electricity demand by 2030 and 2050, respectively; that is, a final tenfold increase in share compared to 2016 levels to meet the Paris climate change agreement [4].

Out of this 25% projection, 40% would be coming from distributed solar energy and the rest from the utility-scale installations.

Heat has been the largest energy end-use, accounting for 50% of global final energy consumption and of which 7% was supplied by solar thermal [8]. China and Europe account for 82% of total solar thermal capacity in operation [9]. The global solar thermal market is projected to grow at a rate of higher than 3% [10] during 2020–2025, and space heating applications are expected to dominate the installations. In the world, space and water heating consume nearly 56% of the total energy use in residential buildings, while the rest of the energy demand is for lighting, cooling, appliances, cooking and other equipment [11]. So, to meet the world's heating, cooling and power demands, the emphasis is on accelerating the adoption of clean energy technologies through technological, policy and market interventions.

As an example, the European Union (EU) is on track to meet the 20% emissions reduction target by 2020. The European Council (EC) [12] had adopted the climate and energy framework in 2014 and set the targets for 2030 to achieve 27% improvement in energy efficiency, 27% renewable energy share and, 15% electricity interconnection and cut down greenhouse gas emissions by 40% from 1990 levels. The target for energy share and energy efficiency was revised in 2018 upwards to 32% and 32.5%, respectively. To explore the renewable and waste energy potential, innovative solutions such as solar thermal, geothermal and heat pumps can be used for integration into the district heating and cooling networks. The above directive [13] is in line with the benefits of PVT technology, which can be coupled to heat pumps and storage heaters for enhanced efficiency and diverse applications. A review [14] of 14,000 completed, European-funded, renewable energy projects between 2005 and 2021 observed that only 0.1% of the projects were targeted at the real implementation on an urban scale and the rest of them are mostly theoretical aimed at creating awareness, publishing and collaboration. However, the trend is changing from 2013 especially in projects funded by Horizon 2020 and Seventh Framework Programme (FP7) programs. Photovoltaics and solar thermal account for most projects, followed by biomass and geothermal. The study also reported that projects did not show importance to the aesthetic impact and social acceptance of technologies in the cities. The solar energy technologies face significant barriers [15] from the aesthetic and conservative point of views, especially during integration to heritage sites and buildings. So, it is important to encourage actual demonstration projects of innovative solutions considering the techno-economic, legal and social factors. For example, the Interreg 2 Seas SOLARISE project [16] is one of such projects involving diverse entities collectively aiming to demonstrate future technologies, study the impact of energy storage capacity and boost the adoption of solar energy in historical and public buildings and low-income households.

Heating and cooling account for 50% of the European Union's final energy consumption, out of which 80% is demand from buildings [17]. According to the reference [18], space heating and water heating accounts for 40% and 17% of final energy consumption in buildings. In the European Union, 75% of heating and cooling demands are met using fossil fuels, and 22% is supplied from renewable energy sources [19]. Therefore, the EU's agenda to digitalise the building sector is parallel to the digitalization of energy systems and can tap the unexplored building sectors. Figure 2 illustrates the percentage of residential and commercial PV capacity in some EU countries until 2018. The utility-scale solar segment is dominant in member states like Romania, Spain and Bulgaria, where very attractive feed-in-tariff schemes were offered. The exclusion of utility scale from incentive programmes in Belgium has resulted in very few large-scale PV installations. The development of smart-grids and smart-ready buildings leads to well-connected communities and allows for the penetration of high-capacity renewables and distributed energy technologies. The EC is also vigilant in terms of the energy security challenges caused by the high penetration of renewables and is open to the energy mix decided by member states. It is reported [20] that some member states have decided to use nuclear energy, a base load and clean energy source as a part of their national energy mix. In the latest report

[21], it was presented that the EU has been advancing with its energy union strategy and will become a leader in renewables by escalating its objective towards energy efficiency. In addition, it is expected that the share of electricity in the final energy demand in Europe will reach 53% by 2050 [21], and that electricity production from renewables will tremendously increase to achieve net zero greenhouse gas emissions. Figure 3 shows a pathway where renewables account for 86% of the power generation mix, and solar PV would have the largest installed power capacity by 2050.

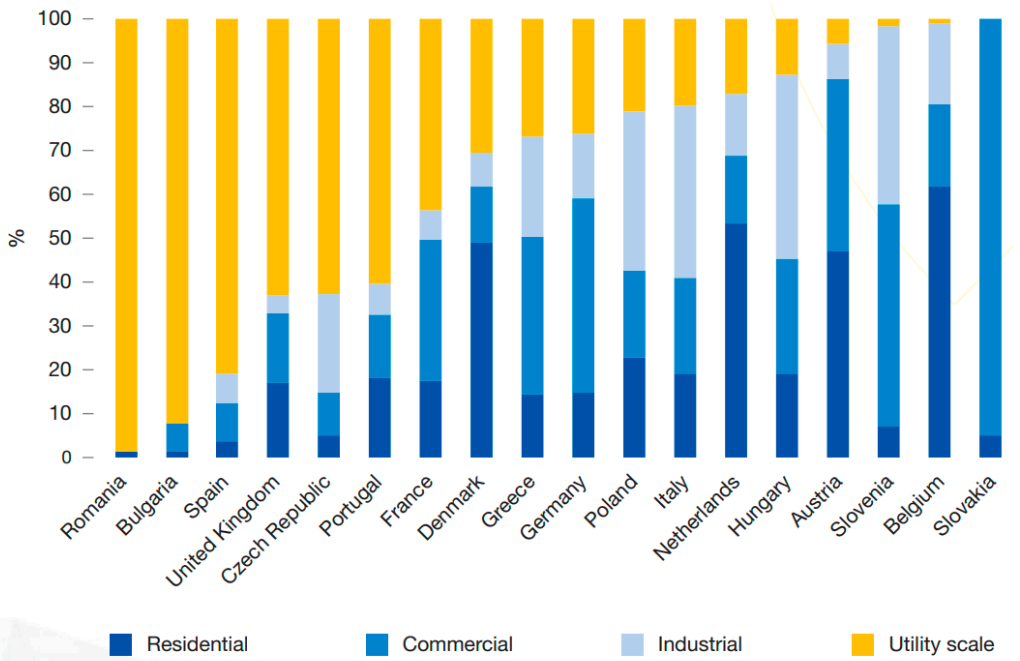


Figure 2. Share of different segments in Solar PV total capacity of EU selected countries until 2018 [22].

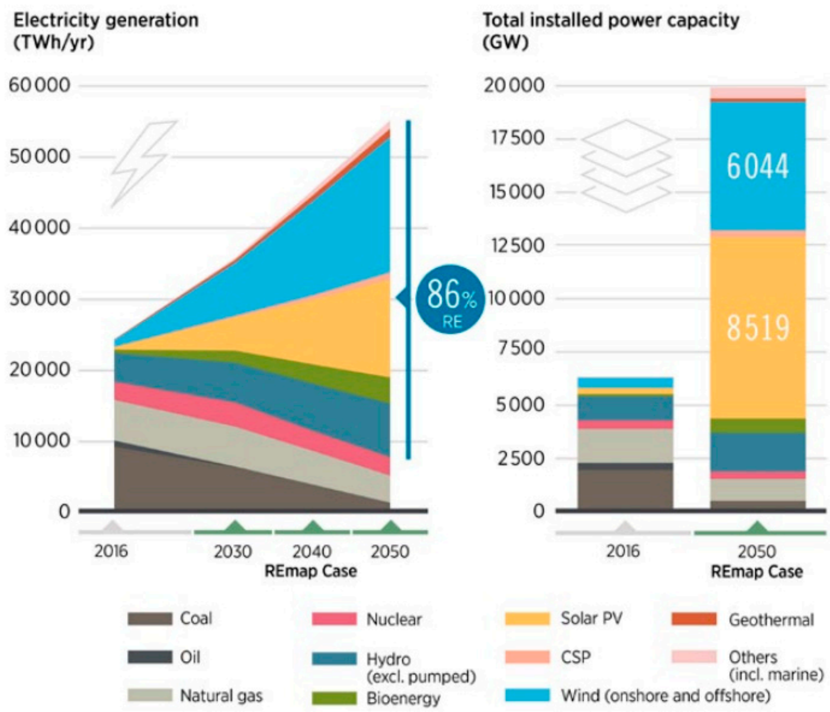


Figure 3. Share of different energy technologies in electricity generation and capacity [4].

To summarise, most of the projection and roadmap studies have simulated scenarios that lead to a shift in the energy system from high fuel and operational costs to a system with higher capital and lower fuel costs. The higher capital costs are due to the investments required to build and renovate the infrastructure to support the high renewable penetration for combined power, heating and cooling needs. The share of electricity in the final energy demand is expected to rise due to the decarbonisation targets of the transport sector using electrical vehicles [23]. The solar PV market witnessed record global growth in 2019 when PV generation increased by 22% [24] despite decelerating growth in China, the world's largest PV market. The decision to discontinue feed-in-tariffs for focussing on controlling costs and addressing grid integration challenges has temporarily affected the PV expansion in China. Meanwhile, the United States observed stable solar PV growth driven by federal tax incentives and state-level policies. The year 2019 was very good for solar technology in the EU since it witnessed a solar boom with a 104% rise in the installed capacity compared to the previous year. The increase was attributed to the competitive solar energy price, closing deadline for the member states to the binding 2020 emission targets, tender's/auctions tools, self-consumption, digitalization, storage and corporate power sourcing. Figure 4 illustrates the top 10 EU solar PV markets for the period 2018–2019. Spain observed a significant solar boost due to grid connection deadlines in 2019 for the auctions in 2017 and the introduction of power purchase agreement/wholesale-based solar power plants. Germany witnessed decent growth, thanks to its continuing self-consumption and feed-in-tariff premiums for medium- and large-scale commercial systems. The main driver for Netherland's growth is the technology-neutral tender programme and its unique net metering scheme [22].

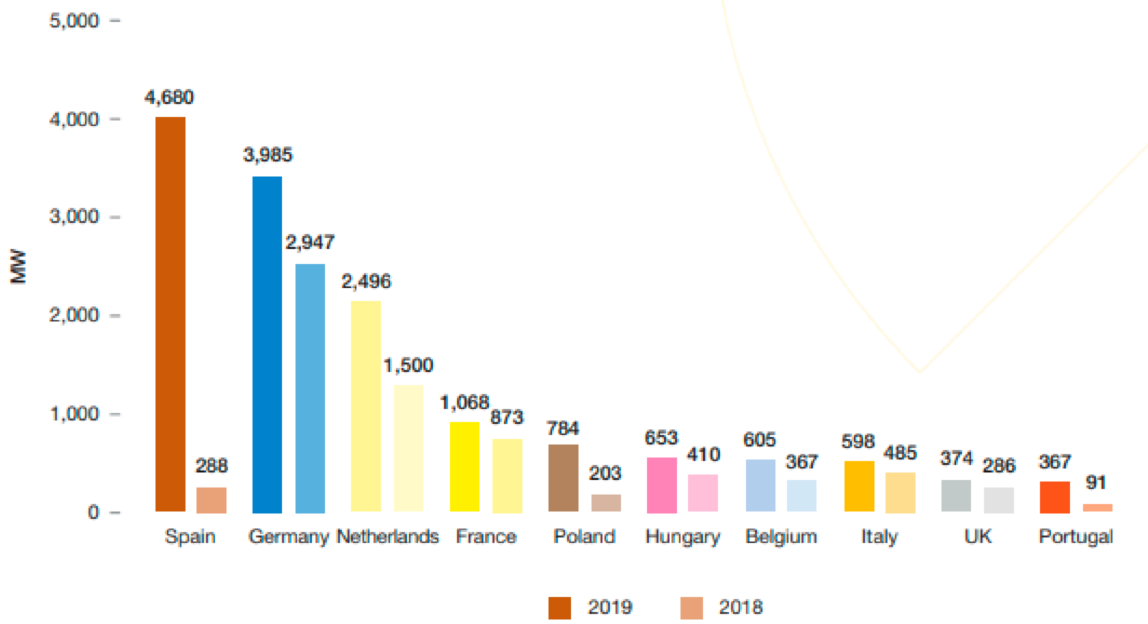


Figure 4. Top EU countries along with the UK Solar PV markets, 2018-19 [22].

The solar PV market has the potential and necessary support again to penetrate the energy market. Meanwhile, the solar thermal market shrunk by 6% in 2019 compared to 2018 while experiencing significant market pressure from PV and heat pumps for small-scale solar water heating systems. Since heating accounts for a significant amount of energy demand, the potential of hybrid photovoltaic/thermal (PVT) systems in combined power, heating and cooling should be utilised to escalate the share of renewables in district heating and cooling. PVT is attractive for applications with limited space [25] since it produces thermal and electrical energy [26] at a reduced cost compared to a separate PV and thermal collector system [27]. PVTs can be considered for several applications such as district heating, drying, desalination and energy generation for residential and public buildings [25].

1.2. Summary of Recent PVT Review Articles

During 2015–2020, several researchers have tried to analyse the PVT technology by categorising the components through systematic reviews. The authors [28] investigated the effects of working fluid on the performance of flat plate PVT collectors by categorizing operating media, designs and climatic conditions. The review showed the electrical and thermal efficiencies of collectors for different physical locations and stressed the importance of nanofluid, bi-fluid, advanced materials to construct PVT collectors as part of future research. A similar updated review based on operating media was carried out by Hemmat et al. [29], where the use of both fluids and nanofluids in single, dual and nanofluid flows along with PCM was thoroughly presented. Moreover, the review suggested that there is still scope for studies on optimising geometry and key performance parameters of PVT.

The application of nano-fluids was summarized by Abbas et al. [30] and identified the necessity to study the effect of nanofluid usage on the lifetime enhancement of PVT systems. Yazdanifard et al. [31] reviewed the parameters affecting nanofluid-based PVT's performance and suggested a comprehensive investigation of nanofluids based on economics and emission reduction. Huang et al. [32] presented a comprehensive review of spectral splitting technologies used in PVT systems and outlined the challenges and opportunities for design considerations. In addition, the authors proposed a generalized technique to find an optimal nano filter for PVT and highlighted that the stability of the nano materials is still a great challenge for practical applications. A similar conclusion about the instability of hybrid nanofluids was reported by Shah et al. [33], and it was reported that there is scope for testing hybrid nanofluids in PVT systems due to their ability to escalate electrical efficiency. Said et al. [34] reviewed the environmental effects of conventional and nanofluid-based PVT systems and highlighted different challenges and benefits of nanofluids and recommended a comprehensive evaluation of the economics of nanofluids usage in PVT systems.

Another study [35] presented performance evaluation studies of water- and air-type PVT collectors. In addition, the application of PVT for various applications such as building integrated photovoltaic thermal systems, concentrated PVT systems and PVT coupled with a heat pump was discussed. Similarly, Kasaeian et al. [36] conducted a critical review on the application of PVT for combined heat and power systems and highlighted that the majority of studies were focused on thermal aspects, and economic analysis work was limited. The performance and economic feasibility of PVT system studies were summarized by Brahim et al. [37] who suggested that there is scope for research in techno-economic analysis of PVT system, PVT demonstration applications and feasibility studies. Wu et al. [38] studied the integration methods of PV to the thermal absorbers and suggested carrying out practical research on the long-term reliability of PVT modules during operation.

Many review papers are focused on the concentrated PVT systems due to their higher efficiencies. Sharaf et al. conducted an in-depth review of concentrated PVT systems in two different studies [39,40] covering fundamentals, design and performance assessments. Similarly, the authors of [41] classified the concentrated PVT systems into thermally coupled and decoupled and presented a thorough review of different heat transfer components and their economics. Jaaz et al. [42] focused on the design of compound parabolic concentrated PVT systems to outline research opportunities for better design and materials used for reflectance and absorbance. A waste heat recovery and spectral beam splitting-based concentrated PVT systems were reviewed by Ju et al. [43,44], covering studies based on research and development, theoretical and experimental analysis, feasibility analysis and conceptual designs. The authors noticed a gap in decision-making models to aid in identifying the areas where the above-mentioned system could have high potential to accelerate towards market success. A few review studies [45–47] have focused on the PVT-thermo electric generators and highlighted that there is still a gap in the research based on feasibility analysis, 3-dimensional numerical analysis and long-term field tests under real environmental conditions. In addition, the scope for the development of grid interconnection of PVT for multistage power conversion and microgrid integration was highlighted.

High temperatures lead to a drop in electrical efficiency of photovoltaics (PV) [48], and hence there is substantial research in the field of PV cooling technologies, as seen in the review papers discussed so far. A phase-change material (PCM) is a kind of cooling substance used in the PV and PVT systems, and articles [49–51] presented recent advances in the PV and PVT -PCM systems and found that numerical models of the PVT-PCM system and its life cycle analysis (both numerical and experimental) are very limited. In addition, the authors suggested that PCMs relevant for PVT applications must be developed for the enhancement of heat transfer. Thermal absorbers and their fixing methods to PVT are significant for facilitating maximum heat transfer, and Wu et al. [38] presented a detailed review and described that the EVA-based lamination method was found to be the best for integration. Lamnatou et al. [52,53] reviewed a PVT based on environmental challenges and concluded that many studies are based on standard PVT focused on energy payback time and CO_2 emissions. Moreover, these are mostly limited to domestic water heating with very few applications in the industry. As a part of future research, it was recommended to focus on life cycle analysis and environmental analysis, including other important environmental indicators, to achieve a holistic picture of PVT and concentrated PVT integrated into buildings in residences and industrial settings. Several review studies have acknowledged the impact of climatic conditions on the PVT collector performance, which is critically reviewed by Elbreki et al. [54], where the authors summarised the influence of each parameter on the electrical, thermal and overall efficiency of the PVT system based on the available results from the literature. Debbarma et al. [55] reviewed building-integrated PV and PVT studies and reported that PVT is preferable to PV, and indicated that it is essential to utilize its thermal energy to avail the economic benefit. Figure 5 summarises the key areas discussed in reviews so far.

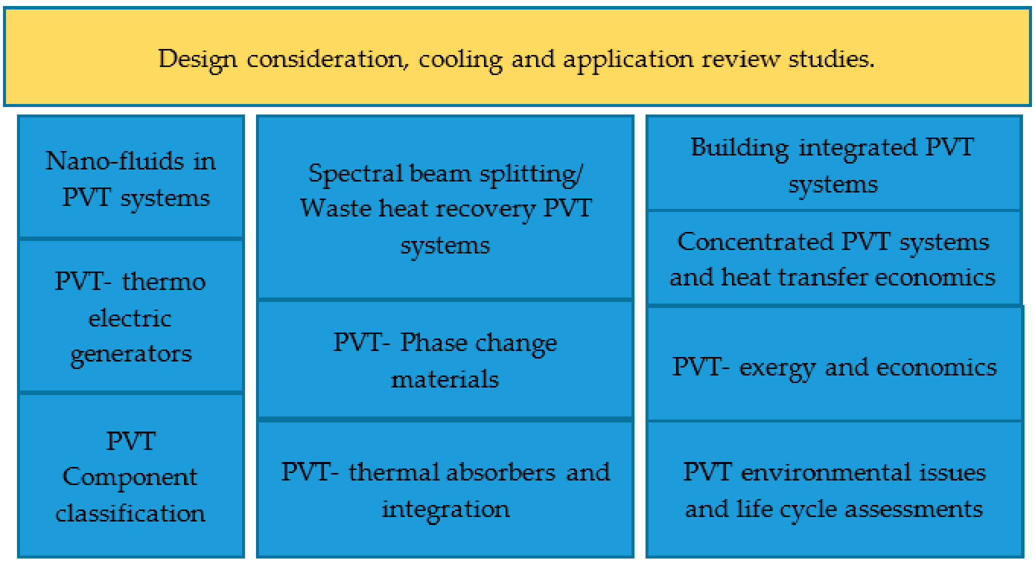


Figure 5. Summary of the topics covered in previous review studies.

2. Aims of the Paper and Literature Review Methodology

This article gives an extensive review of the progress of PVT systems in the residential sector and discusses factors affecting the performance of different PVT systems. The study also lists the performance indicators necessary for studying the feasibility and market potential of PVT technology using multi-criteria decision analysis. Finally, the research gaps in PVT technology for solar energy adoption in residential segments are discussed. This review article will add to the existing literature on PVT technology reviews and be useful for development and improvement of PVT technology suitable for extensive applications and thus contributing to sustainable development.

A systematic literature review (SLR) [56] approach was chosen to identify and select the relevant literature to address the objectives. The goal is to review the progress and identify the research gaps in the PVT technology for residential applications and find the key performance criteria for feasibility studies. The first step in the process was to generate a strong Boolean expression covering a range of articles without significant bias. Web of Science and Scopus were used to fetch articles from extensive multiple databases. The stepwise methodology that was followed is explained in Table 1. After applying certain inclusions and exclusions, the number of articles to be used in this review was finalized.

Table 1. Stepwise methodology for literature review.

	Steps	Limit
Step 1	Boolean expression: TITLE ((“photovoltaic/thermal*” OR “PV/T”) AND TITLE-ABS-KEY (residential OR domestic))	Abstract, Title, keywords
Step 2	Boolean expression applied to title only	Title
Step 3	Search results selected from steps 2 and 3 refined to articles only excluding review papers and conference papers	Articles
Step 4	Search results refined to year range 2000–2020	Years: >2000& <2021
Step 5	Search results limited to few specific journals	22 Journals
Step 6	List of significant studies marked for review	Studies aimed at the objectives of this review
Step 7	Addition of significant studies excluded in step 2, 3 and 5	
Step 8	Match and remove duplicates from both web of science and Scopus search	
Step 9	Studies shortlisted for review	

The asterisk (*) represents any group of characters, including no character.

The paper is organised as follows: Section 3 discusses the different types of PVT systems that have been developed and their economics. Section 4 presents the discussion and summary of selective studies, lists the PVT system’s performance indicators and Section 5 details the progress, limitations and future research opportunities.

3. Review of PVT Studies

The idea of PVT collectors for residences was first introduced in the 1970s by Martin Wolf [49] to increase the performance of PV and utilize the electricity and heating from the hybrid system. Many studies [57–63] on the PVT system were carried out after that. However, extensive studies of a complete hybrid PVT system to houses matching the heating and cooling demands were not adequate until the 2000s. Figure 6 shows the general classification of the PVT collector, and Figure 7 shows parts of a typical PVT collector. The discussion of PVT systems based on the cooling medium, concentrators and economics are presented in subsequent sub-sections.

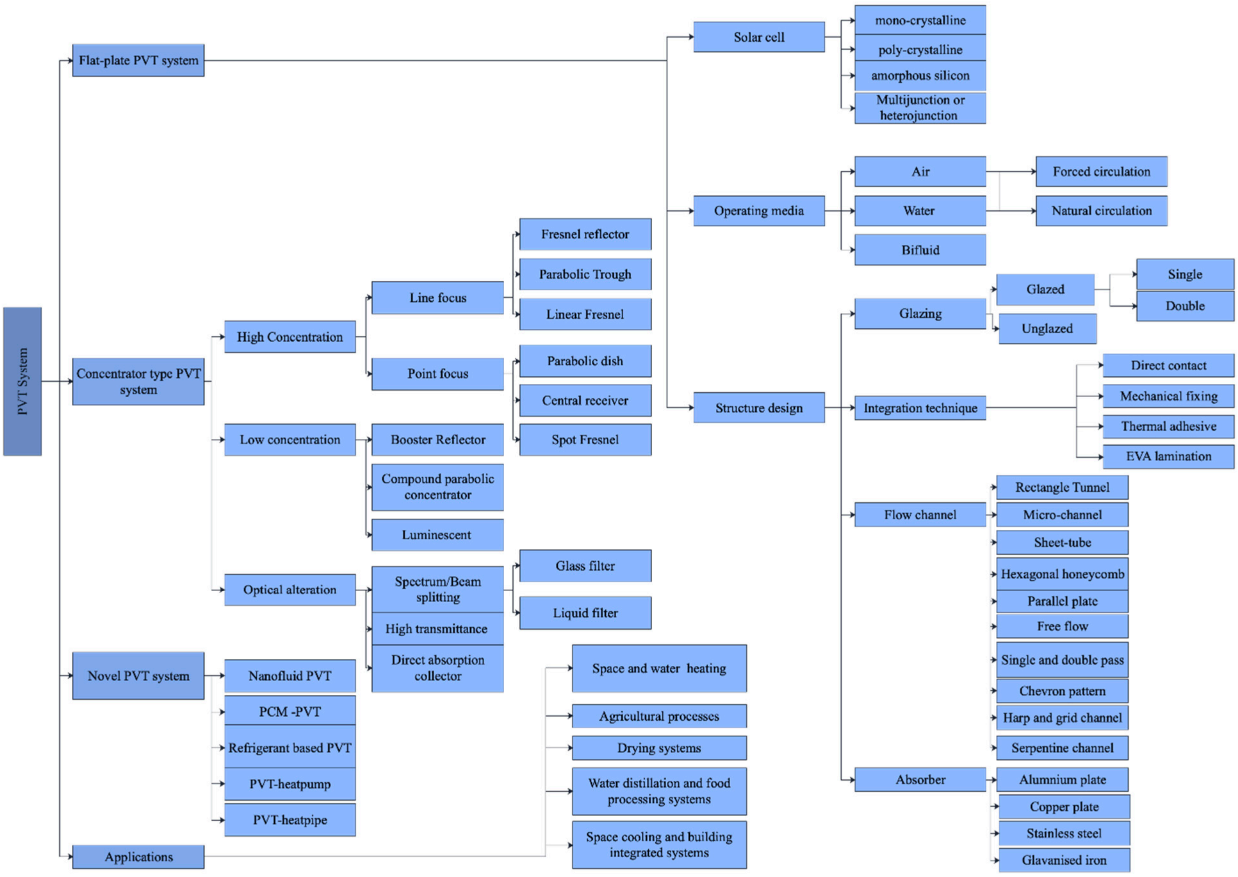


Figure 6. General classification of the PVT system (Information taken from [28,38,40,64]).

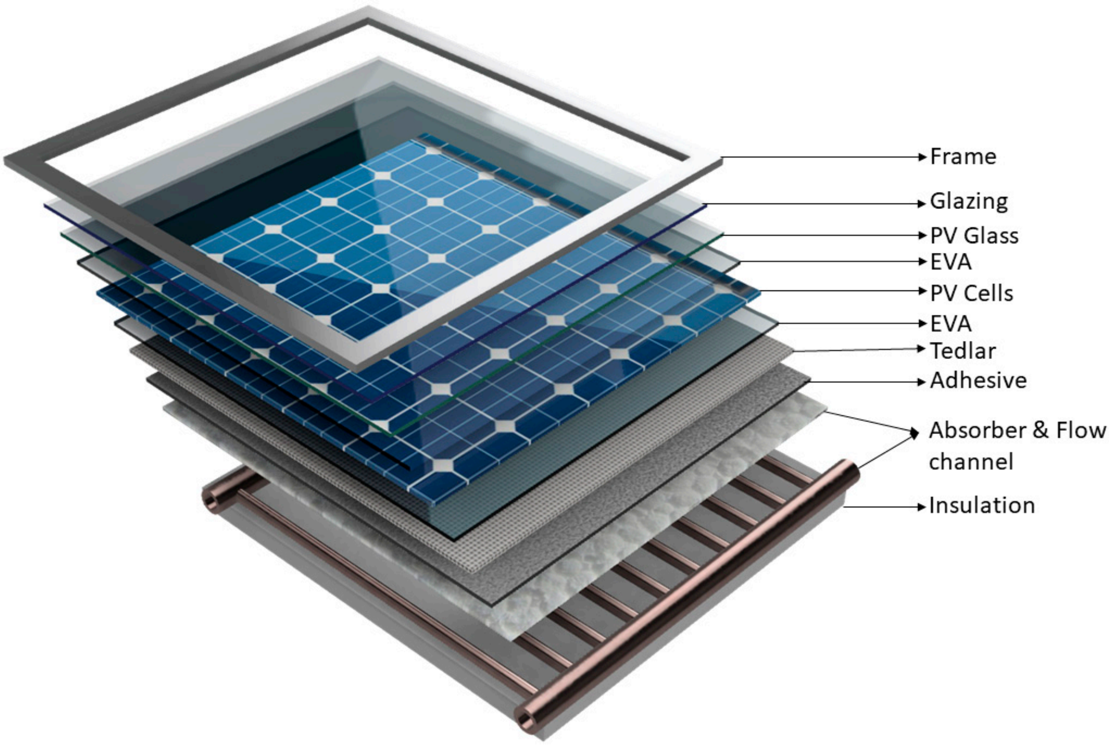


Figure 7. Detailed parts of typical water-based PVT collector.

3.1. Water-Based PVT Systems

Vokas et al. [65] conducted a theoretical study on hybrid PVT systems in two geographical locations and confirmed the strong influence of climate and solar radiation on the system's output. The system was able to cover 47.79% and 25.03% of heating and cooling demand for a house with a total surface area of 30 m^2 of PVT modules in the region of Athens. Gurlich et al. [66] analysed the PVT for direct trigeneration (heating, cooling and electricity) in European residential buildings and observed that the performance of the PVT system depends on the boundary conditions of the demand profile, climate and energy price levels in the location. Similarly, Calise et al. [67] have initially presented a trigeneration system including PVT, single-stage LiBr-water absorption chiller, storage tanks and auxiliary heaters. It was observed that the appropriate demand for hot water is crucial for utilizing the peak thermal energy of PVT since it is not possible to store all that energy in a storage tank. Furthermore, the replenishment profile of water [68] can significantly influence the sizing of the PVT system. Thus, the authors of [67] modified the system later in the study [69] by including the reversible heat pump and zeolite adsorption chiller. It was presented that the PVT system should always be supported with an auxiliary system to satisfy the hot water and space cooling demands. In addition, dynamic simulation results indicated that the PVT system performance is scarcely dependent on the setpoint temperatures of the collector and storage tank.

The software package TRNSYS is often used for analysing the PVT systems in residential settings since the readily available components can be used to design a model that can generate results consistent with the experimental data as shown in [70]. Barbu et al. [71] looked at the potential of a simple PVT system using TRNSYS for a small residential setup at two different locations with similar climates in France and Romania, respectively. The proposed system was able to meet the household demands of 58% in Romania and 48% in France with the help of a battery. Another study by Kalogirou et al. [72] presented TRNSYS numerical simulation results for a PVT in three locations, i.e., Nicosia, Athens and Madison. The research compared polycrystalline silicon (pc-Si) cell PVT and an amorphous silicon (a-Si) cell PVT performance. It was observed that the electrical production of pc-Si cells is better than a-Si but with slightly lower thermal energy. In addition, the authors concluded that the hybrid PVT system is viable in the areas of low-temperature water applications such as domestic hot water use. The discussed system met between 60% and 87% of the hot water demand depending upon the location. Similarly, Nualboonrueng et al. [73] investigated the performance of a-Si, crystalline-Si (c-Si) and pc-Si PVT systems in Bangkok using TRNSYS simulation and reported that the optimal flow rate for all variants was 20 kg/h, which makes the system work in the thermo-syphon mode and, as a result, reduces the overall system costs. The solar thermal contributions of a-Si, pc-Si and c-Si-based PVT systems are 43.3%, 44.8% and 46.8%, respectively.

Chow et al. [74] identified the collector fin efficiency and tube bonding quality as the critical design factors impacting the overall thermal efficiency of PVT and designed a flat-box thermal absorber from an aluminium alloy, as shown in Figure 8. The authors conducted a numerical analysis using ESP-R building simulation software using typical weather year data followed by an 8-h long experiment under realistic conditions. It was concluded that the PVT system is suitable for tropical/sub-tropical climate applications, and the thermal efficiency reported was within the ranges of 45–48% and 49–52% for closed-circuit and open-circuit operations, respectively, while electrical efficiency varied within the range 9–11%.

Figure 8. Assembly of aluminium finned flow channels (reprinted from [75], with permission from publisher).

A direct solar-roof-based hybrid PVT system was studied numerically using TRNSYS by Fraisse et al. [76]. In this research, the following four configurations, as shown in Figure 9a, were studied: PV and solar thermal collector separately, unglazed PVT, glazed PVT and low emissivity (LE) ($\epsilon = 0.4$) glazed PVT. The annual energy performance can be seen in Figure 9b, where the glazed LE PVT had better performance than other configurations. In addition, the glazed LE PVT system emitted less CO_2 emissions both from heating and electricity. However, it was observed that the unglazed PVT performed 1.47 times and 2.1 times better in terms of electricity production when compared to the glazed LE PVT and the conventional PV + T separated configuration.

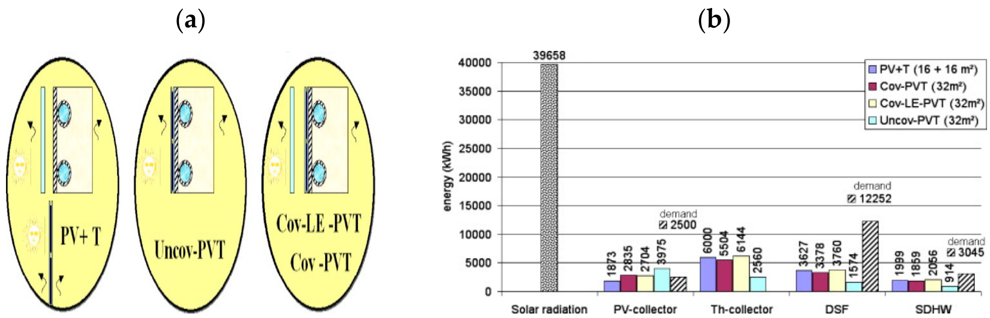
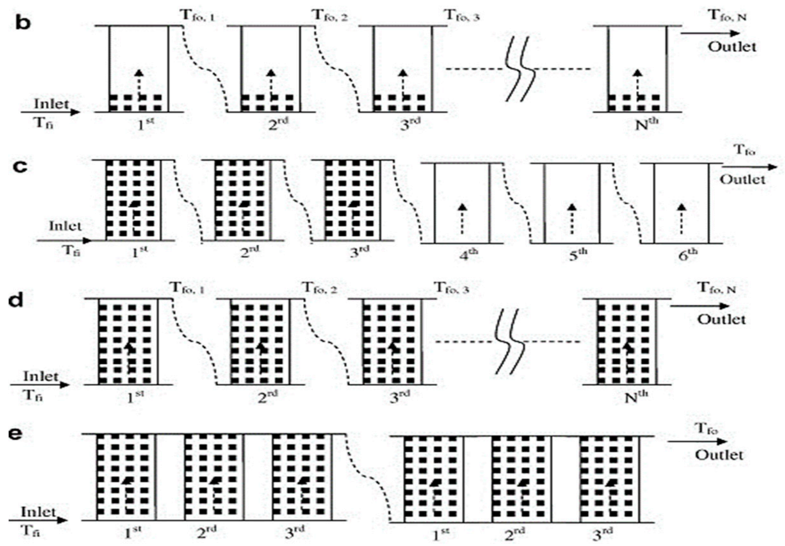


Figure 9. (**a**) Four different configurations; (**b**) annual energy performance for four configurations (reprinted from [76], with permission from publisher).

Theoretical modelling of partially covered flat plat collectors was done by Dubey et al. [77] where four different configurations (Figure 10a) in five different cities were considered. The cities had different climatic conditions with differences in sunshine hours and global to diffuse solar radiation ratio. The results of exergy, thermal and electrical energy were shown in Figure 10b. The authors confirmed that a fully covered collector is beneficial if the primary requirement is electrical energy, and in the case of a thermal energy yield, a partially covered collector had better performance.

(**a**)



(b)

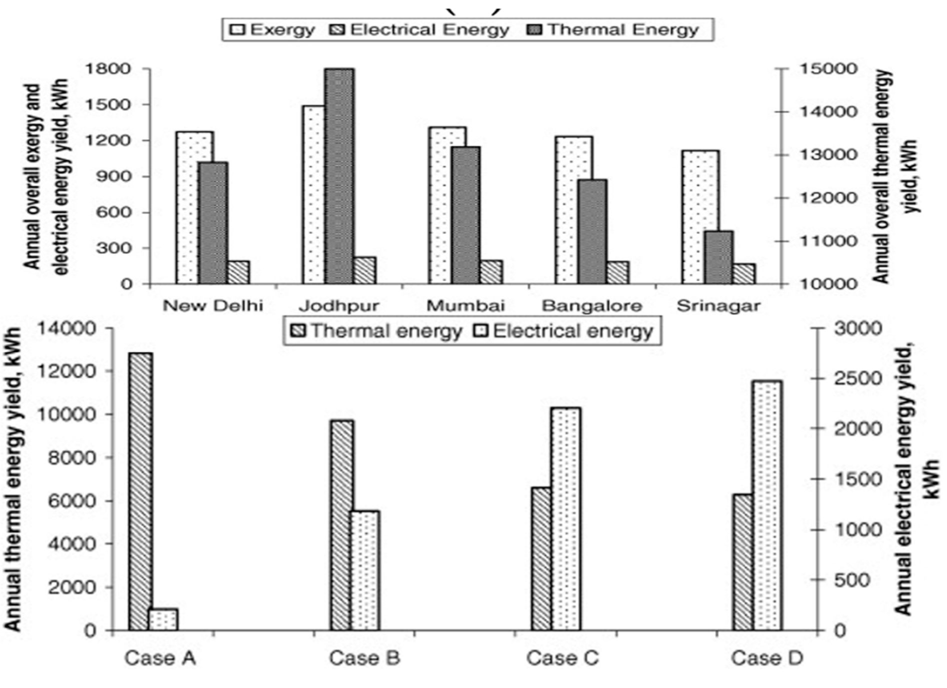


Figure 10. (**a**) Four different configurations (collectors partially covered by PV connected in series, glazed PV-collectors in series, PV-collectors in series, series and parallel combination of PV-collectors); (**b**) annual exergy, thermal and electrical energy values for five cities and four different configurations (reprinted from [77], with permission from publisher).

A BIPVT system cooled under natural convection and forced circulation was studied numerically using computational fluid dynamics and then experimentally by Corbin et al. [78]. It was observed that forced circulation could lower both the maximum and average PV cell temperature. Natural ventilation lowered the temperature of cells only when the inlet temperature is high, and insolation was significant. The amount of heat recovery using the pumped water was adequate, and the outlet temperatures reached 50 °C. The amount of useful thermal flux from the collector has a linear relation to insolation and inlet water temperature. The water-cooled BIPVT witnessed a 5.3% increase in electrical efficiency compared to the naturally cooled BIPVT.

An active opaque PVT façade system using refrigerant as fluid can produce electricity and thermal energy and acts as a barrier to reduce heat gain by 40% and heat the cavity air for preheating the building's fresh air [79]. The system's electrical efficiency was 9%, and the COP reached up to 3.1 while providing hot water up to 40 °C. The energy performance of four system configurations shown in Figure 11 for space heating and domestic hot water in a single-family house is compared in [80] using results from TRNSYS and reported that the simpler configuration involving PVT and heat pump is a good solution for heating-dominated buildings. Yao et al. [81] have proposed a hybrid residential heating system using a direct expansion solar PVT assisted heat pump with a borehole heat exchanger (BHE). The authors compared the performance of the hybrid system with a single BHE and reported that the former had better thermal energy performance. The parametric analysis confirmed that mass flow rate and inlet temperature played a key role in heat extraction from BHE. The maximum outlet temperature of the water was 40.8 °C at a solar fraction of 67.5% and irradiation of 600 Wm^{-2}. Dannemand et al. [82] studied the performance of PVT coupled with a heat pump and two storage tanks by conducting transient analysis in TRNSYS, as shown in Figure 12. The setup was expected to be low cost compared to the liquid–liquid heat pump systems with a ground source heat exchanger. The system's performance was assessed based on the International Energy Agency solar heating and cooling programme [83] key performance indicators, which include solar thermal fraction, solar electrical fraction, net renewable energy fraction and inverse system seasonal performance factor. The idea is a buffer storage tank that can be charged using an unglazed PVT collector to the temperature levels of the ambient air even without sufficient solar irradiation. However, it was reported that the system was not economical for the loads considered in the study and recommended testing it for multifamily buildings.

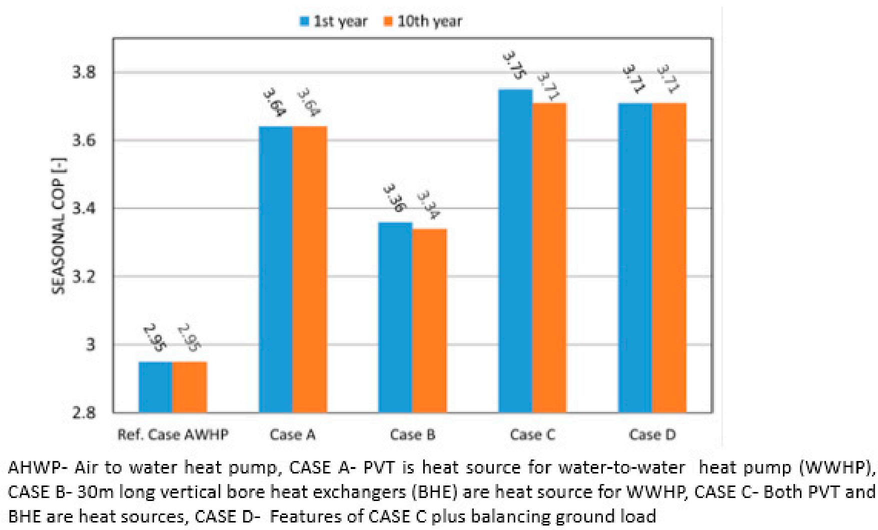


Figure 11. Seasonal coefficient of performance of different system configurations (reprinted from [84], with permission from publisher and information is added).

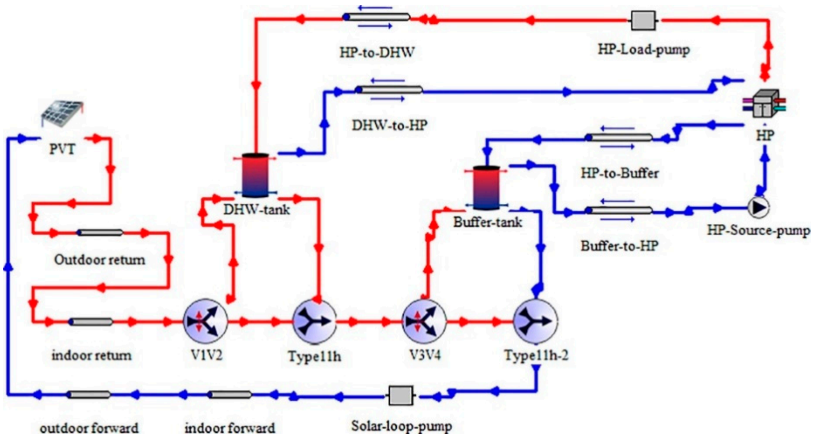


Figure 12. TRNSYS model of the proposed system (reprinted from [82], with permission from publisher).

Jeong et al. [85] have conducted a feasibility study of combined heating, cooling and domestic water system coupled to PVT and ground source heat pump using TRNSYS. The authors reported that the seasonal performance factor of the hybrid system increased by 55.3% compared to the conventional GSHP for a building in Seoul, Korea. It was observed that the SPF is dependent on the set supply temperature and the use case of produced solar heat. Yao et al. [86] studied a direct expansion PVT heat pump coupled with phase-change material (PCM) to overcome the intermittency of solar energy due to weather changes. The coefficient of performance for heating was 6.6, a significant 94% higher than the conventional air conditioning system. The overall efficiency was 73.87%, and the temperature of underfloor heating with build-in PCM heat storage reached 22–31 °C. Possible refrigerant leaks characterize the direct expansion PVT heat pump systems due to their design features. Hence, the indirect expansion PVT heat pump systems, where a fluid is used to absorb the solar thermal energy and transfer it to the heat pump cycle, can be a simple solution. So, Obalanlege et al. [87] investigated a solar combined heat and power system by conducting short-term analysis to understand the ability of the system to respond to intermittency by understanding transient effects and contribute to the development of control systems for running the energy system with optimized parameters. The coefficient of performance of the heat pump was not affected by the increase in solar irradiation, while overall systems' COP increased by 1.2. The system's thermal and electrical efficiencies were increased with larger tank size and higher flow rate, while panel temperature is decreased. The enhancement of thermal efficiency was significant compared to electrical efficiency. Chen et al. [88] experimentally studied a PVT and dual-source heat pump water heating system. An air-cooled evaporator mode was selected when there was inadequate solar energy, while a water-cooled mode was adopted when there was sufficient solar irradiation. It was reported that the electrical efficiency could be increased up to 13.44% in a water-cooled way.

Integrating the heat pump into the PVT system is a widely employed design concept to increase the overall energy efficiency. However, the refrigerants used in the system are not eco-friendly and may lead to environmental damage, thus potentially reducing the ecological benefits of a solar energy system. The inclusion of a battery or a heat pump increases the cost of the solar energy system [89], and sometimes using excess battery energy can impact [90] the sizing of the actual PVT system. Thus, Behzadi et al. [91] proposed a novel PVT system (excluding battery and pump) with a thermal storage unit with the potential to zero energy bills for buildings via two-way trade of low-temperature heat and electricity by the local grids. The modelling of the system is done using Matlab-TRNSYS and was employed for a real case study house located in Denmark. The proposed system's yearly utilisation factor was calculated as 61% and could easily match the building's hot water demand. The system was feasible without auxiliary systems due to selling excess energy to the local grids.

Zarei et al. [92] worked on increasing the performance of a solar CCHP for residential consumption by using a hybrid ejector-VCR refrigeration cycle driven by the PVT (Figure 13a) and used environmentally friendly refrigerants such as R290 and R600a. The authors specifically studied the effect of panel cooling on the performance of the ejector-VCR refrigeration cycle while using the coolant water from the outlet into the condenser. R290 has shown the better performance of the refrigeration cycle by 7.5% compared to R134a. Cooling the PV panels enhanced the COP by 5.25%, increased the outlet water temperature by 9.16 °C and reduced the refrigerant mass flow rate by 25.24%. It was reported that the mass flow rate affects the outlet water temperature and then the overall efficiency of the PVT system. Figure 13b illustrates the energy distribution incident on the PVT.

Erixno et al. [93] conducted an experimental investigation for the real-time performance of a single-home PVT-based system for combined heat and power (CHP). The experiment was carried out for 31 days with real supply and load conditions. The authors reported that the PVT panel electrical and thermal efficiencies decrease, respectively, by about 1.2% and 1.89% per year. The proposed 1.25 kW_P system contributed to 14.95% and 27.48% of electrical and thermal energy generation, respectively, as shown in Figure 14.

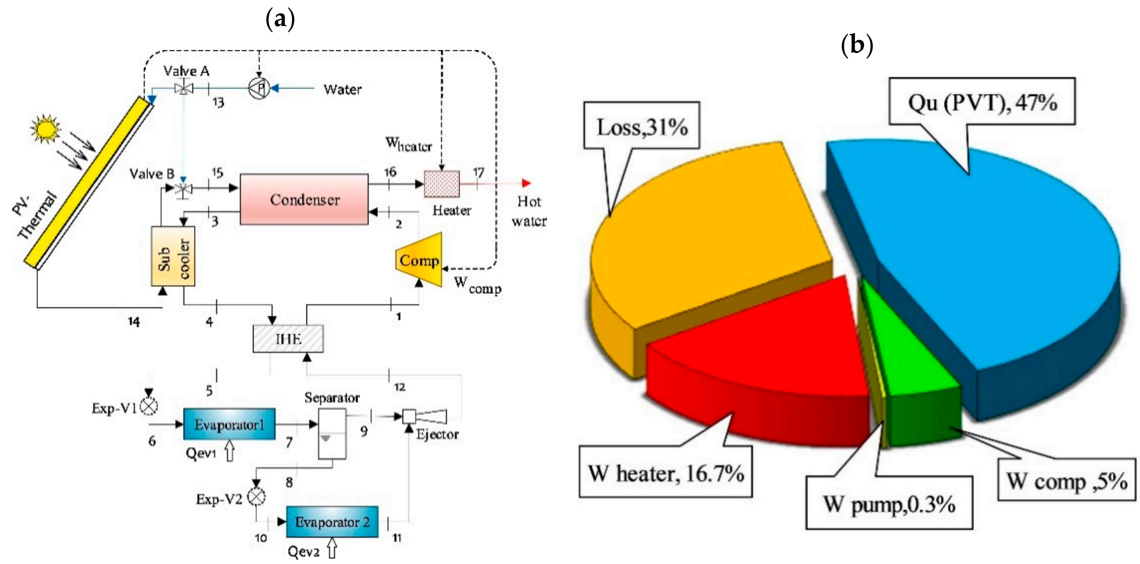


Figure 13. (**a**) Schematic of the system; (**b**) distribution of energy incident on PVT from the Sun at irradiation = 945 Wm^{-2} and water mass flow rate = 0.013 kg/s (reprinted from [92], with permission from publisher).

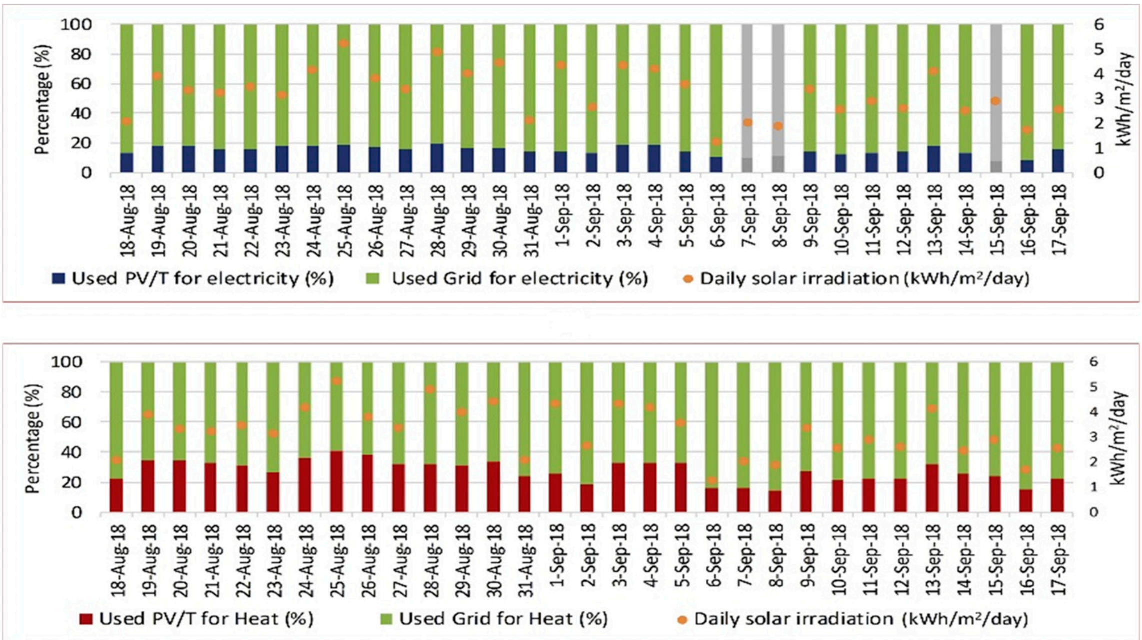


Figure 14. Percentage of PVT contribution to supply the electrical and heat demands for 31 days (reprinted from [93], with permission from publisher).

Pokorny et al. [94] conducted an experimental and analytical investigation of a new concept of glazed PVT collector (encapsulation was done using polysiloxane gel) for a multifamily building with 45 flats and 100 occupants in three locations. Two different configurations were tested involving rooftop installation and façade integration, and the simulation study results are shown in Figure 15. It was reported that the specific thermal and electrical yield of façade PVT installation was lower compared to the rooftop PVT.

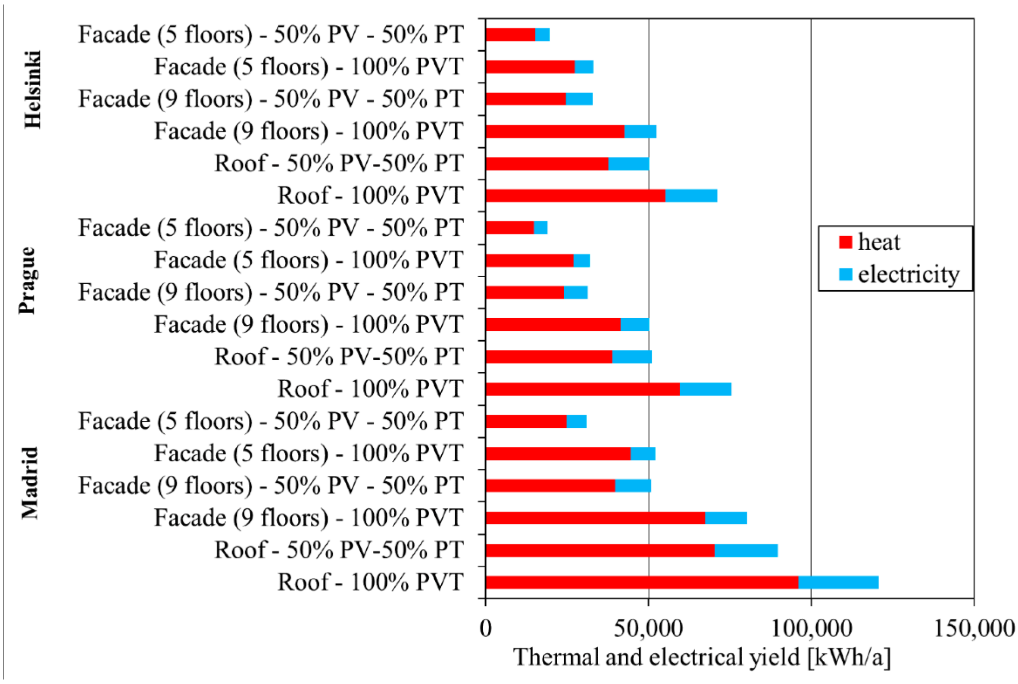


Figure 15. Thermal and electric yield for all the alternatives in three locations (reprinted from [94], with permission from publisher).

The combination of solar thermal collectors and PVT has been studied recently in different domestic energy demands. One of the studies [95] based on organic Rankine cycle used the amorphous silicon (a-Si) cells integrated with evacuated flat plate collector (EFC) (a-Si-PVT) and studied its performance by comparing it with conventional EFC, polycrystalline silicon (poly-Si) PVT and PV. It was observed that the poly-Si PVT collector operating temperature was higher than the a-Si-PVT, and correspondingly, the electrical efficiency of poly-Si-PVT was lower than the a-Si-PVT. In another study [96], the authors compared a ground source heat pump driven by PVT and conventional solar thermal collectors for energy performance to supply the cooling, heating and hot water demands of a two-storey building. The energy system was coupled to a low-temperature terminal unit, like radiant systems, leading to the improved energy performance of heat pumps. Ma et al. [97] have studied a serial connection PVT and solar thermal collector (STC) in a steady-state. It is evident from Figure 16 that the primary energy savings of the proposed coupled system were higher than the PV and other types of collectors. As a part of Solar Decathlon Europe, Kazanci et al. [98] have designed a custom-made PVT for integrating it to an HVAC system of a plus energy house. The complete system was analysed for two locations, i.e., Copenhagen and Madrid, using TRNSYS, and the annual results estimated that the PVT system generated 2.6% and 3.3% more energy than the PV + solar thermal collector combination.

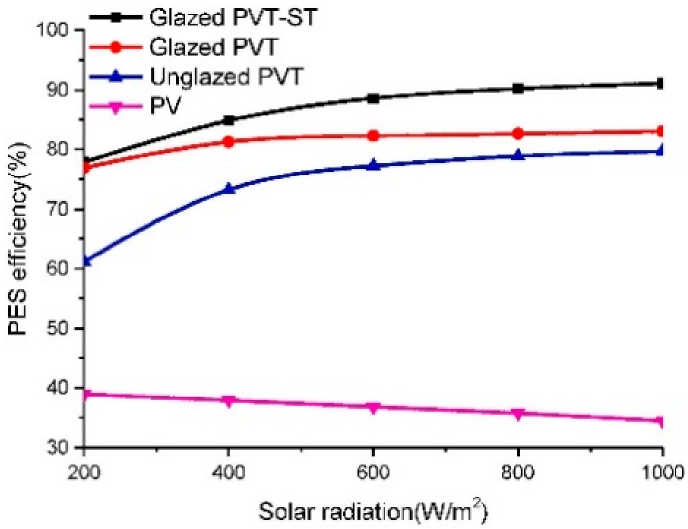


Figure 16. Primary energy savings of different systems (reprinted from [97], with permission from publisher).

Bigorajski et al. [99] analysed the single glazed micro PVT for operation in a moderate climate for a single-family in Poland. A correction factor was introduced to calculate the PV cell temperature based on the construction of the module, and it was observed that the results fairly approximate the temperature values obtained during the experiments. It was recommended that the system should be sized to the heating demands in the summer to avoid overheating during summer due to the rise in temperature of water in storage, which was caused due to less demand. Thus, it was advised to connect the system to additional heat consumer-like seasonal heat storage. Thinsurat et al. [100] have numerically evaluated the feasibility of the PVT integrated into thermochemical sorption using the working pair of $SrCl_2$-NH_3 seasonal energy storage via ANSYS. A detailed model of the one-diode model was presented to predict the electricity and thermal energy under different weather conditions using MATLAB. At lower outlet fluid temperatures, the electrical and thermal efficiencies were increased due to the reduced heat loss between the PVT and ambient, including low PV temperatures. The airgap between the glass and the PV played a significant role in the cold climates preventing the heat loss to ambient. The seasonal storage integrated with a 7.76 m^2 PVT system was able to store and shift the heat load to cover the demand from November to February. The combined system was able to store thermal energy between March–October, demonstrating the ability to satisfy a single household’s complete hot water demand all year long.

The influence of channel configuration on the performance of PVT collector was studied by Yu et al. [101] by considering two different roll bond absorber plates as shown in Figure 17a,b. The grid-channel PVT (PVT-2) had better electrical and thermal efficiency than the harp-channel PVT (PVT-1). PVT-1 had less pressure drop and thermal inertia in the pipes and was able to work under natural circulation or with less electricity. The harp-channel plate was evaluated using the conventional F′ efficiency factor used in the sheet and tube absorber, while the grid-channel plate required a performance test. PVT-2 was recommended in the case of forced circulation. The performance of a copper-sheet-laminated PVT using copper oxide/water and nanofluid was studied by Michael et al. [102] and reported that the nanofluid-based system significantly improved the thermal efficiency compared to water-based PVT. However, the electrical efficiency saw a reduction due to the higher temperature of the PVT collector obtained because of the higher thermal conductivity of nanofluid and fixed effectiveness of the heat exchanger. It was suggested that the electrical efficiency could be improved with a better design of heat exchanger with high effectiveness accounting for nanofluid volume concentration. Lari et al. [103] have conducted a techno-economic performance analysis of a hybrid parallel-serpentine heat exchanger-based PVT system. The authors compared an uncooled PV system with a water-cooled and nanofluid PV system for the climate of Dhahran, Saudi Arabia, and reported an increase of 8.5% and 13% electrical output, respectively. This proposed PVT system was modified by retrofitting a PCM thermal battery [104], and the performance was compared with the system without PCM retrofit. The low operating temperatures of PVT adversely affected the discharging of PCM battery and reduced electrical and thermal efficiencies by 2.2% and 7.7%, respectively, compared to the system in [103]. Haurant et al. [105] evaluated a 3D dynamic numerical model of a custom-made bionic channel heat exchanger-based PVT. The dynamic model was based on energy conservation and was well-adapted to the fractal geometry of the heat exchanger and can be used as a function in simulation tools like TRNSYS.

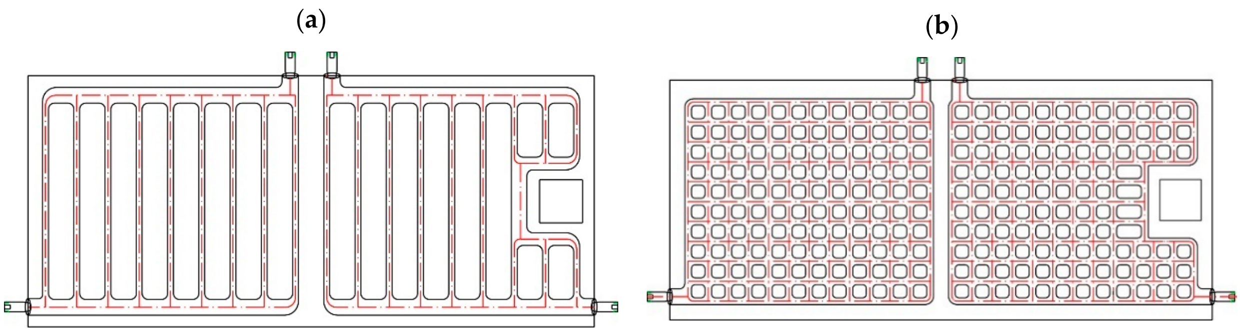


Figure 17. (**a**) Harp-channel absorber plate; (**b**) grid-channel absorber plate (reprinted from [101], with permission from publisher).

A detailed study of optical properties and heat transfer between PV cells and fluid in a PVT system was carried out by Dupeyrat et al. [106]. A single-package EVA layer lamination was proposed in the study replacing conventional three-layer (encapsulant, TPT and adhesive layer) to reduce the thermal resistance while avoiding an electrical contact. A solar absorption coefficient of 0.94 was achieved with polymer/EVA/cell/EVA/black-coated aluminium packaging structure. The electrical efficiency and thermal efficiency of the hybrid PVT system was reported to be 8.7% and 79% at zero reduced temperature, respectively. Yu et al. [107] designed a roll bond absorber plate PVT prototype with two layers of EVA and one layer of TPT between solar cells and plate. It was reported that the current design offers a better heat transfer coefficient compared to gluing bonding, while lower than the package lamination proposed in the study [106]. However, the current design is economical and commercially feasible. The prototype was tested in the Sichuan basin with a moderate climate and consistently low annual solar radiation, and the system achieved a thermal efficiency of 85% and electrical efficiency up to 15%.

The effects of meteorological conditions, design and optical parameters on electrical and thermal efficiencies were studied by Rejeb et al. [108] by evaluating different PVT collector designs, traditional solar thermal collector and photovoltaic module. The influence of wind speed on the performance parameters was observed where the electrical efficiency was improved at higher wind speeds due to better cooling of PV cells, and simultaneously, thermal efficiency was reduced due to high heat convection to ambient. Figure 18 shows different PVT configurations studied in the paper.

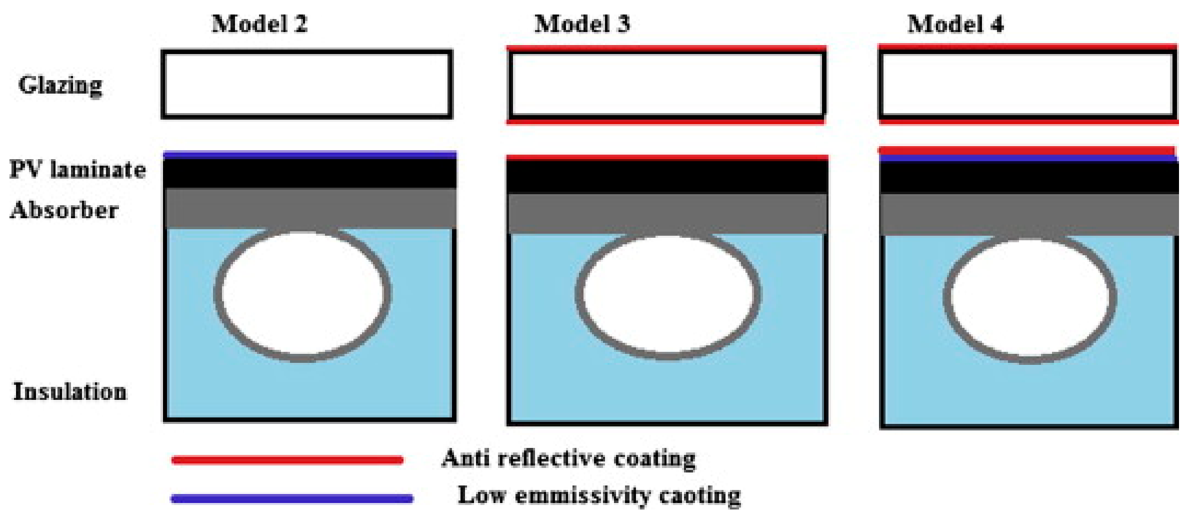


Figure 18. Different configurations of PVT plate (reprinted from [108], with permission from publisher).

The concept of artificial neural network (ANN) is used for predicting the energy performance of grid-connected PVT system in heating-dominated regions of Iran by Motahar et al. [109]. A multilayer perception (MLP) feed-forward neural network based on the Levenberg–Marquardt (LM) algorithm was implemented using the simulation results from Polysun software to train the ANN model. A root mean square (RMS) and analysis of variance (ANOVA) was conducted to estimate the capability of the ANN model. Khani et al. [110] have conducted a 2D- based numerical study for bi-objective optimisation of PVT parameters using a genetic algorithm. In this study, 2D temperature distribution is considered, and the transient system is solved, and these results are fed to a genetic algorithm code to find the optimised system. A non-uniform temperature distribution with a 10 °C difference on the PV layer of the PVT collector was observed, stressing the importance of 2D modelling compared to lumped solutions. It is observed that the key criteria, i.e., weather conditions, number of tubes, tube diameter, tube spacing and mass flow rate of coolant, plays a vital role in the performance of PV. Figure 19a illustrates the increase of thermal efficiency for larger mass flow rate values. The annual electrical performance of the numerical model was reported to be 3% better than the method proposed by [108]. The design parameters critical for PVT feasibility were analysed by Tamayo et al. [111] using the genetic algorithm NSGA-II for multi-objective optimization. The key parameters chosen for this study were mass flow rate of water, PVT collector length, aspect ratio, air gap, the capacity of the storage container and the number of PVT collectors. The authors observed from Figure 19b that the water mass flow rate had a lower impact on the system thermal efficiency than the daily hot water load profile, highlighting that larger mass flow rates do not necessarily lead to a better thermal solar fraction in all cases. However, Zarei et al. [92] have reported an overall efficiency increase from 66.7% to 75.8% when the mass flow rate of water increases from 0.011 kg/s to 0.03 kg/s and G = 945 W/m^2. A similar observation was noted [87], with the overall efficiency rising by 3.25% when the flow rate is increased from 3 L/min to 17 L/min. It is important to highlight that the increase is mostly attributed to better thermal efficiency at higher flow rates.

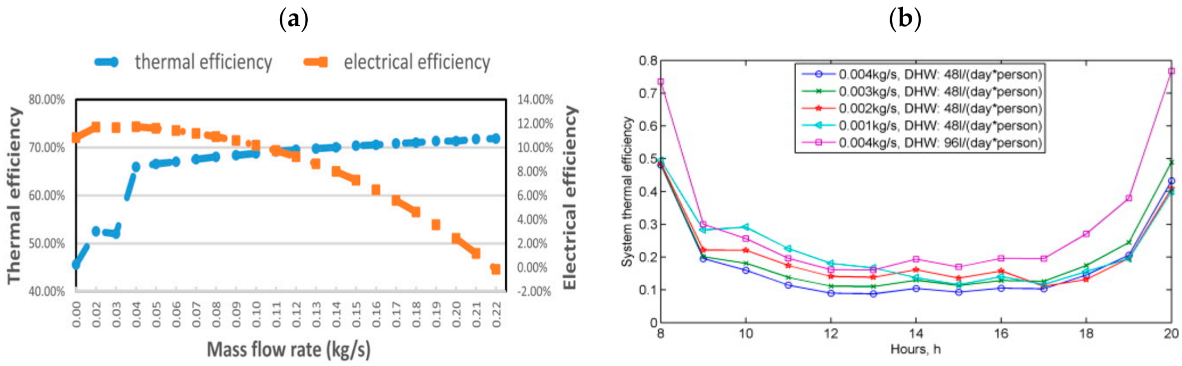


Figure 19. (**a**) Thermal and electrical efficiency of the system for different mass flow rates (reprinted from [110], with permission from publisher); (**b**) thermal efficiency profile for various mass-flow rate and hot water profile (reprinted from [111], with permission from publisher).

Similarly, Chen et al. [112] used the NSGA- II algorithm for multi-objective optimisation of glazed PVT domestic hot water system. The two main objectives considered in the optimisation are primary energy savings and life cycle savings. It was observed that tank volume impacts the temperature level of the system and consequently the electrical and thermal efficiency. Souliotis et al. [113] also reported that the PVT system is more efficient with a larger storage tank capacity.

Yu et al. [114] developed a two-dimensional (2D) temperature–irradiance coupling model to analyse the influence of the non-uniform distribution of irradiance and temperature simultaneously in the PVT collector. The effect of shadow (Figure 20b) due to the frame used to create an air gap between the glass and PV layer was studied, and the authors observed a significant decrease in electrical efficiency with the increase of shadow ratio (Figure 20a). The non-uniform temperature distribution on PV cells was also observed by Guarracino et al. [115] through a simulation of a dynamic 3-D numerical model of PVT in a UK domestic installation. The authors identified that parameters like fluid flow rate, operation strategy of the pump, and the temperature at which the pump switches ON/OFF are key for the control strategy. The type of covering on the collector and emissivity of solar cells significantly affects the electrical and thermal efficiencies, as shown in Figure 21a,b, respectively.

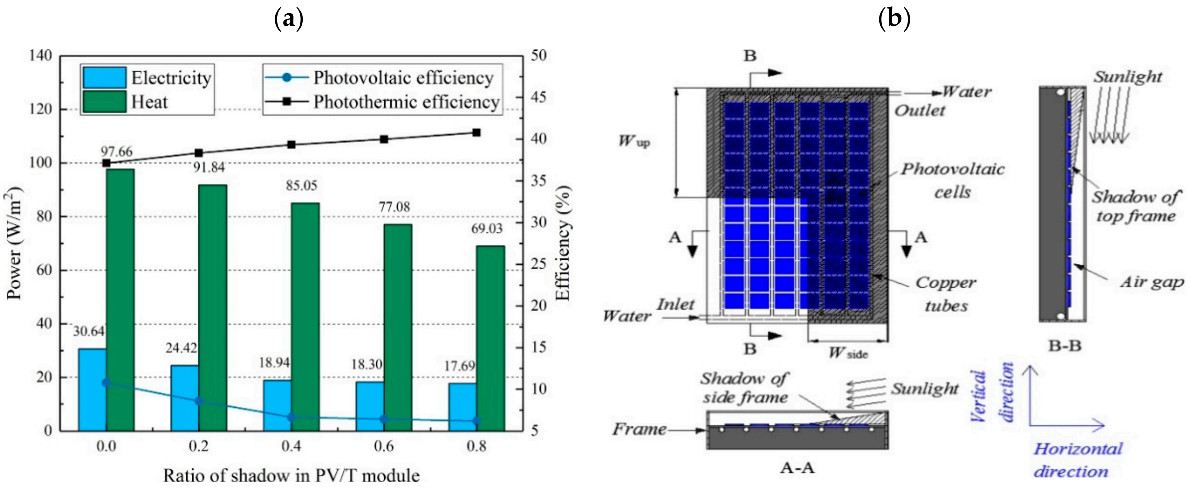
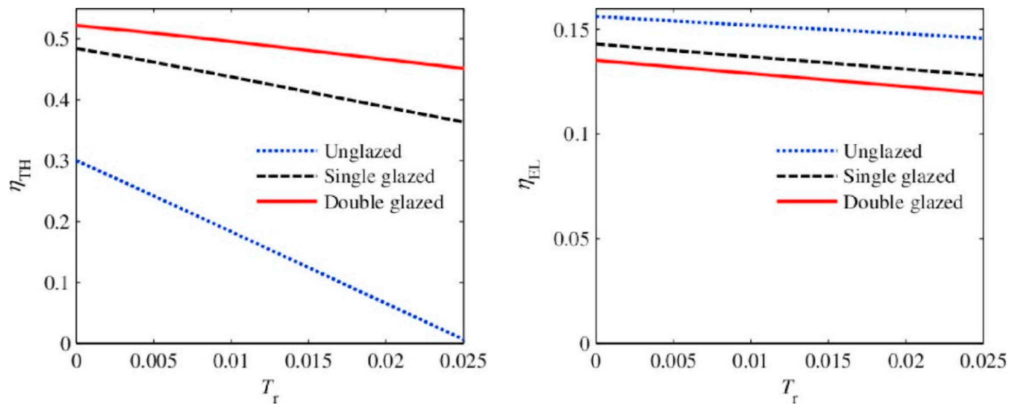


Figure 20. (**a**) Change in electrical and thermal efficiency as a function of shadow ratio; (**b**) frame shadow on PV/T collector surface (reprinted from [114], with permission from publisher).

Preet et al. [116] conducted an 11 h experimental comparative study of PV, PVT-water and PVT-PCM-water-based systems (Figure 22) to investigate the electrical and thermal performances. The experiment was carried in real environment conditions, and the corresponding data are collected at 30-min intervals. Figure 23a,b shows the three systems' electrical and thermal efficiency varying over the time of day. It was observed that electrical efficiency was higher for PVT-PCM-water compared to PVT-water because more heat was transferred to the PCM and then to the water column cooling the PV cells. However, it was the opposite in thermal efficiency where PVT-water was superior to PVT-PCM-water because the heat was being extracted directly from the PV panel to the solar thermal attachment.

(**a**)



(**b**)

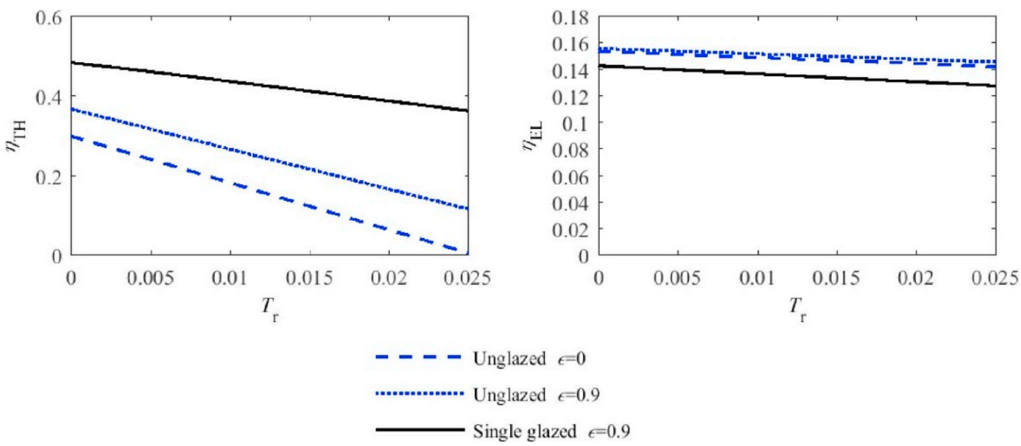


Figure 21. (**a**) Thermal and electrical efficiency of PVT for different covering on the top, (**b**) thermal and electrical efficiency of PVT for different cell emissivity values and covering on the top (reprinted from [115], with permission from publisher).

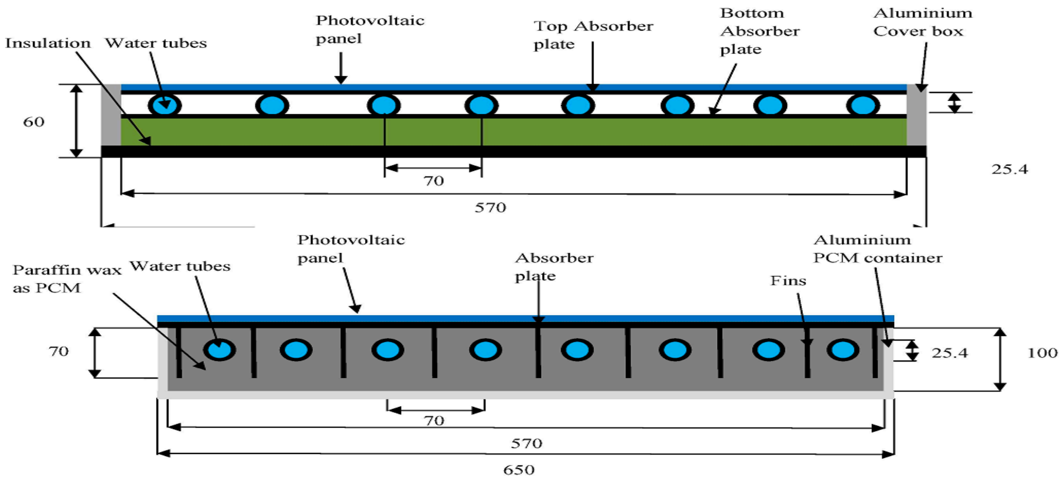


Figure 22. PVT-water and PVT-PCM-water configurations (reprinted from [116], with permission from publisher).

(**a**)

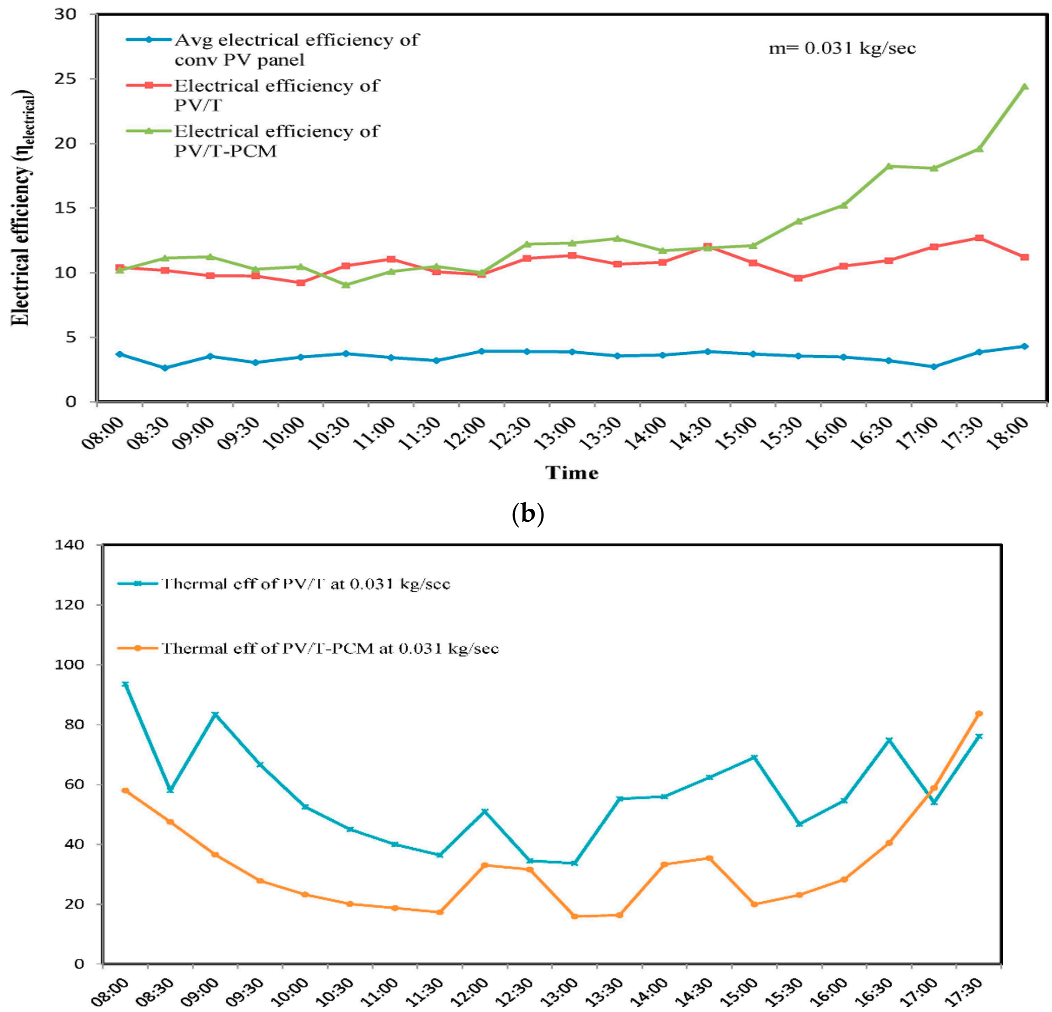


Figure 23. (**a**) Electrical efficiency at 0.031 kg/s; (**b**) thermal efficiency at 0.031 kg/s (reprinted from [116], with permission from publisher).

He et al. [117] conducted an experimental study comparing PV, PVT and thermal collector under the natural circulation of water using a thermosiphon system. The results indicated that the thermal collector's thermal efficiency was superior to PVT (40%) and the electrical efficiency of the PV plate was better than PVT (10%). However, the primary energy saving efficiency of PVT (60–75%) was much better than that of the conventional thermal collector and the individual PV system. Primary energy saving efficiency concerns both the quality and quantity of energy, and it is evaluated as the sum of thermal efficiency and electrical efficiency of PVT (normalised to electric power generation efficiency (~38%) of the conventional power plant). Good et al. [118] conducted a comparative study for three buildings (six variations shown in Figure 24), intending to achieve a net-zero energy balance. The authors concluded that the building with high-efficiency PV panels is the closest to a net-zero energy building, followed by a building with average quality solar thermal collectors and high-efficiency PV. The study also supported the idea that PV and heat pump combination is more efficient than solar thermal collectors for residential buildings. The PVT options could not reach high operating temperatures even during summer, and there is a necessity of auxiliary heating, making the PVT system suitable for preheating applications only.

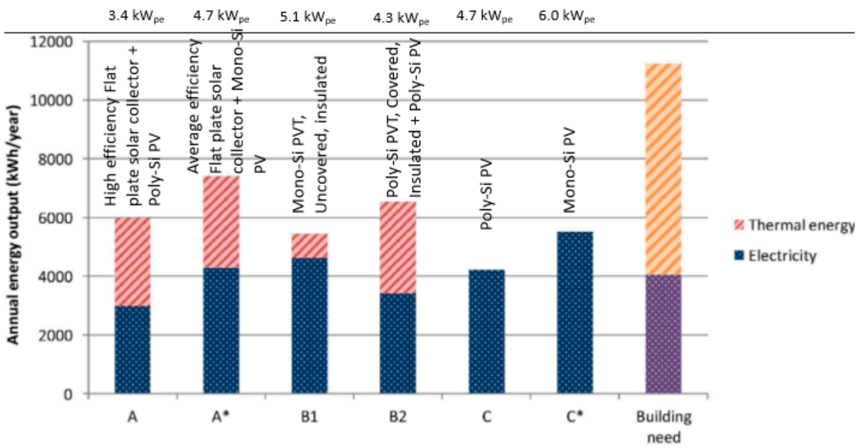


Figure 24. Annual thermal and electricity generation of different variants (reprinted from [118], with permission from publisher and information is added).

A techno-economic assessment of PV and BiPVT for retrofits in Canadian housing stock was conducted by Asaee et al. [119] to assess the potential to convert existing houses into net-zero energy buildings. It was observed that if all eligible houses implement retrofits, there would be an equivalent annual energy savings of 3% in PV and 18% in BiPVT. BiPVT systems are characterized by both active and passive effects on the building performance. Active effects are the ones generally focused upon, i.e., energy production and efficiency. However, the phenomena such as a change in thermophysics of the building walls and thermal comfort after PVT integration are often less studied, leading to passive effects. Barone et al. [120] studied a novel low-cost BiPVT by investigating both active and passive effects with regards to a reference dwelling and proposed dwellings. The reference dwelling did not have PVT systems installed. The authors adopted the predicted mean vote thermal comfort index to study the passive effects and reported that thermal discomfort increases in hot weather and decreases in a temperate climate, as shown in Figure 25. It was recommended to install thermal insulation layers on the back of the solar devices in hot weather zones for comfort and energy reasons, while it is not advantageous in colder climates. Transient energy and exergo-economic analysis of façade integrated PVT collectors was performed by Buonomano et al. [121] to a high-rise building using TRNSYS. Heat pumps and chillers were integrated as auxiliary components. The simple payback period of the system was about four years, and the destroyed exergy of the BIPVT collectors was higher than the one obtained by the thermal and electricity storage systems. Exergy is the measure of the capacity of energy to do useful work. Kim et al. [122] have investigated the performance of a building heating system combined with an unglazed

1.5kW$_P$ BIPVT collector experimentally. The hot water is circulated using a differential temperature controller and maintained at 10 litres/minute with the thermal efficiency of 30% and 17%. In addition, the BIPVT collector enhanced the energy performance of the building by increasing the electrical efficiency of the entire heating system by 16%, while the storage tank temperature rose to 40 °C. Ibrahim et al. [123] designed a new BIPVT with spiral flow thermal absorber (Figure 26b) considering its simple tube design but with 2% lower efficiency than other channels, free flow and twin absorbers. The study aimed to enhance the thermal and electrical characteristics of the BIPVT by conducting energy and exergy analysis. Energy analysis is based on the first law of thermodynamics, while exergy analysis is based on the second law of thermodynamics. The energy efficiency (55–62%) (Figure 26a) of this spiral flow absorber BIPVT system is on par or sometimes better than efficiency (47–62%) reported in many other studies in the literature [74], [124], [125]. Yin et al. proposed a novel building integrated multifunctional PVT [126] that can harvest solar energy and act as a structural roof component. The setup has been updated over the years by the research group. In the first design, the hybrid system (Figure 27a) consisted of a PV panel with functionally graded material (FGM)—a mixture of aluminium and insulating high-density polyethylene with water tubes casted, plywood substrate and PCM for energy storage. However, it was observed that the layering method used for the fabrication of the FGM panel did not allow for continuous gradation leading to low heat transfer between PV cells to the composite panel. Moreover, the water tubes setup caused non-uniform temperature distribution [127] near the outlet. So, to overcome the barriers, the authors [128] used the vibration and sedimentation approach to fabricate the FGM layer and opted for double serpentine water tubes to achieve better temperature distribution in the new BIPVT (Figure 27b). The system reached an electrical efficiency of 15.82% and thermal efficiency of 59.41% at a flow rate of 150 mL/min.

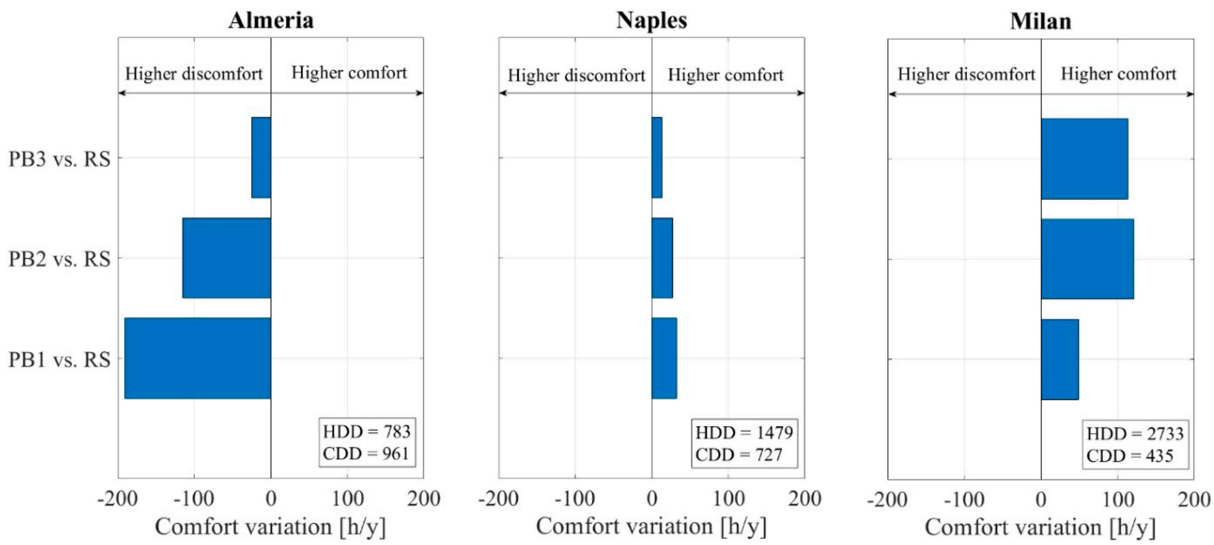


Figure 25. Thermal comfort variation in all the proposed dwellings compared to reference dwelling (reprinted from [120], with permission from publisher).

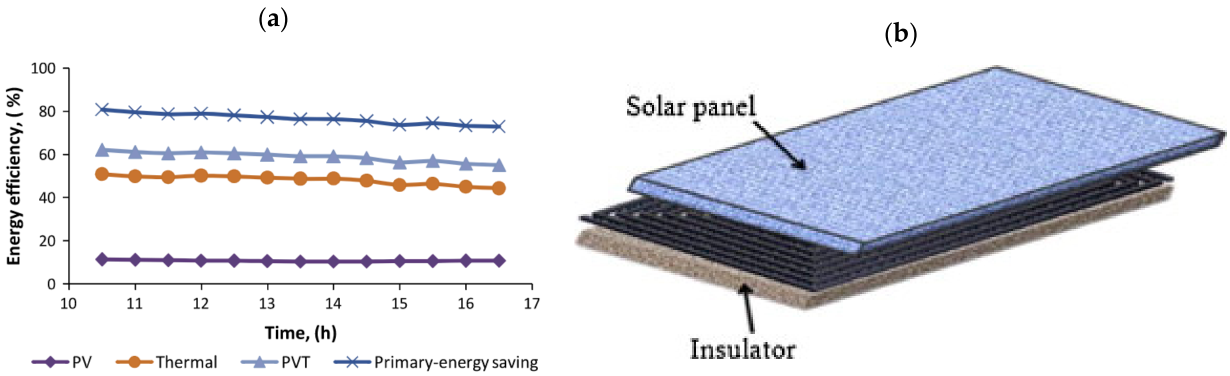


Figure 26. (**a**) Variation of efficiencies over the time at a mass flow rate of 0.027 kg/s; (**b**) spiral flow absorber (reprinted from [123], with permission from publisher).

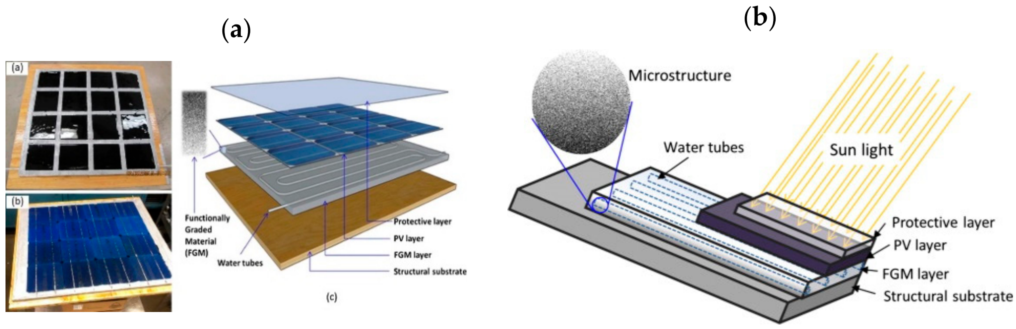


Figure 27. (**a**) Hybrid PVT FGM schematic—first design; (**b**) layers of BIPVT—second design (reprinted from [126], with permission from publisher).

Microchannels (MC) and heat pipes (HP)/loop heat pipes (LHP) [129], which were widely applied in the areas of satellites, spacecraft, electronics and semi-conductor devices, have seen their way into the solar thermal applications, where the research group at University of Hull conducted a series of investigations [130–133] through numerical simulations and experiments. Yu et al. [133] combined the latest advancements in LHP to develop an MC-LHP-PVT, and the system designs shown in Figure 28a,b mainly contain a PV-integrated micro channel tube array acting as an evaporator, a tubular heat exchanger as a condenser, a liquid header for liquid-water separation and a vapour header as a vapour collector. PCM particles are installed at the outside channel to absorb and release additional heat when required. The experiment is carried out for a day, i.e., duration of 6:30 h, and the novel system obtained absolute overall efficiency improvement of 33.31% and 17.2% compared to the conventional PVT [117] system and a building integrated PVT system [126]. It was observed that electrical efficiency was reduced with higher cell temperatures, and solar thermal efficiency varied with inlet temperature, coolant flow rate, ambient temperature and height difference between condensation and evaporator. In another study [131], the performance of an MC-PVT-based direct expansion solar heat pump was studied by Zhou et al. and they reported an electrical efficiency of 13.1–13.7% and thermal efficiencies of 55–56.6%. The coefficient of performance was observed to be 4.7–5.0. Chen et al. [134] employed a phase change slurry (PCS) as a working fluid for the heat pipe PVT. A 30% alkyl hydrocarbon PCS exhibited good stability, and the overall efficiency of the system was reported to 59.3%, at a 9.7% improvement compared to a water-based PVT collector. The simple payback period was also shorter by 0.5 years compared to water PVT. Gang et al. [135] carried out modelling and simulation of two HP-PVT systems with and without auxiliary heating equipment for three cities of China and reported that available solar radiation and hot water load per unit collecting area

(HWLA) affects the solar thermal contribution. As the HWLA increases, the solar thermal contribution decreases for an HP PVT system with auxiliary heating support.

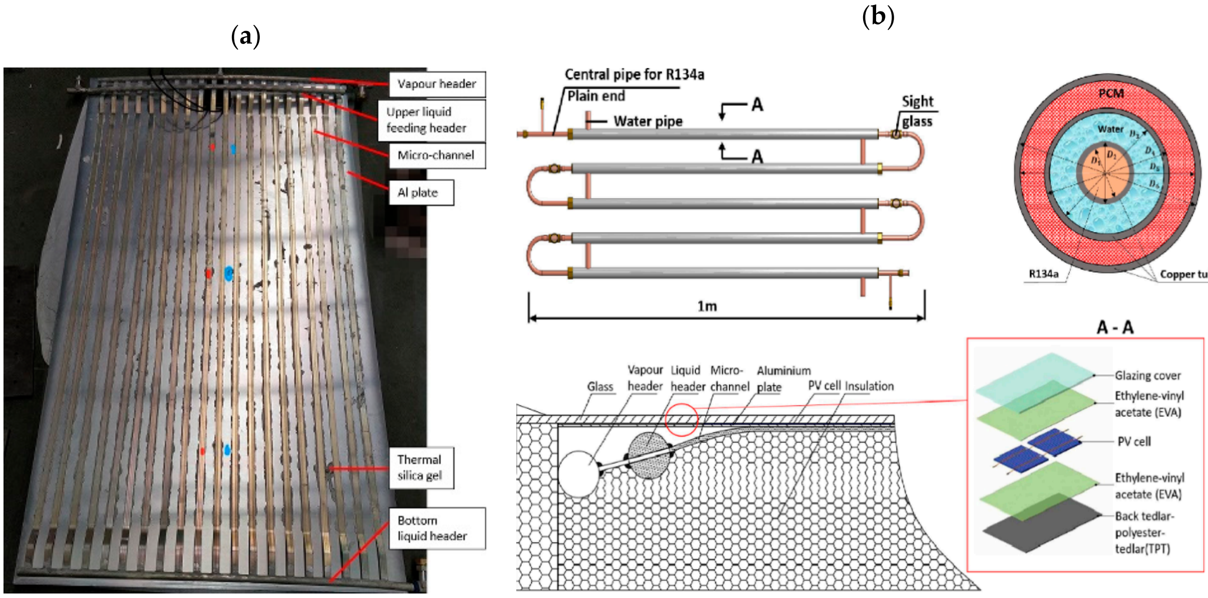


Figure 28. (**a**) Microchannel evaporator; (**b**) structure of triple-pipe heat exchanger and microchannel module (reprinted from [133], with permission from publisher).

3.2. PVT Air

Touafek et al. [136] studied a simple and cost-effective air-type PVT with a galvanized iron absorber. The system used natural air circulation for extracting heat from the panel and achieved a thermal efficiency of 48% at the cost of electrical efficiency. The operating temperatures of photovoltaic modules were high, leading to a drop in the electrical output. An experimental and numerical study of three different air-type BIPVT systems was studied by Pantic et al. [137]. The three configurations were compared in both winter and summer seasons for energy performance, and the results can be seen in Figure 29a,b. It can be inferred that configuration 1 (unglazed BiPVT) and 2 (vertical glazed solar air collector added to configuration 1) have better electrical efficiency, while configuration 3 (Glazed BiPVT) has better thermal efficiency. The air to water heat exchange was done in all three configurations, and the water temperature could reach 40 °C from 12 °C in configurations 1 and 2. It was recommended that cavity fan control strategies play an important role in the design of air BIPVT systems. Furthermore, the control algorithms may be designed for the exit air temperature as a function of solar insolation and air speed in the air cavity.

(**a**) (**b**)

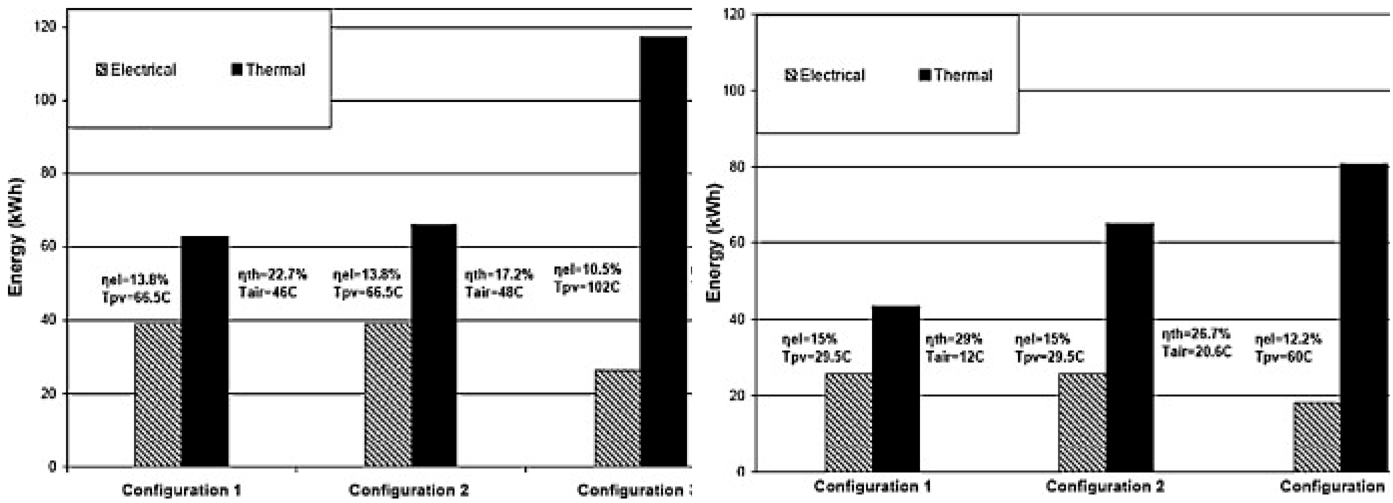


Figure 29. (**a**) Electrical and thermal efficiency of BIPVT in summer; (**b**) electrical and thermal efficiency of BIPVT in winter (reprinted from [137], with permission from publisher).

Farshchimonfared et al. [138,139] conducted optimisation studies of PVT air system by investigating the effective thermal energy output and the maximum overall rate of exergy gain by varying the mass flow rate per unit area and channel depth. The authors concluded that an optimally designed PVT system would generate nearly the same amount of energy for different air mass flow rates and meet the temperature rise requirements for the residential application. The effective thermal energy output was reduced by 3.2% only for a 71% reduction in the mass flow rate per unit area.

3.3. PVT Bi-Fluid

Tripanagnostopoulos et al. [140] have initially proposed using two fluids in PVT collectors to leverage both air and water benefits as a coolant. A new bi-fluid PVT system (Figure 30) was studied numerically and experimentally by Assoa et al. [141] and they reported that the mass flow rate of water had very little impact on the PVT bi-fluid system's performance. Moreover, the efficiency of the PVT system was able to reach 80% for a specific combination of collector length and mass flow rate.

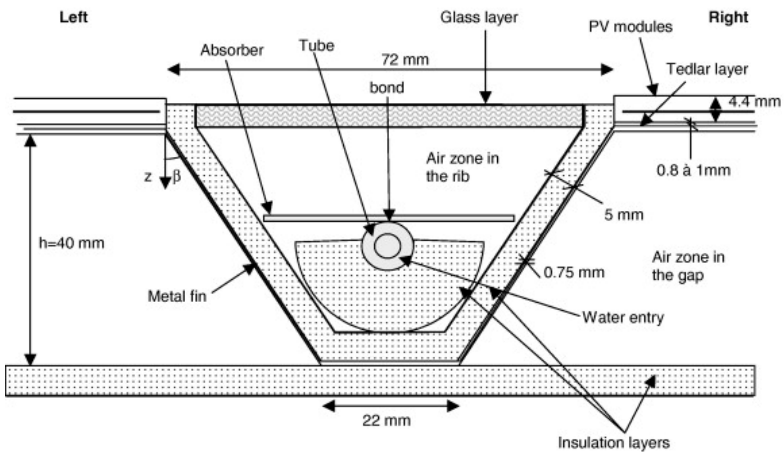


Figure 30. Cross-section of PVT bi-fluid system (reprinted from [141], with permission from publisher).

3.4. Concentrated PVT

It is known that PVTs can generate power and electricity simultaneously, and hence these systems are widely applied in the application of combined cooling, heating and power (CCHP). It is also called solar trigeneration and requires high-temperature thermal energy for better performance. Hence, CPVT, due to its high thermal efficiency, is more appropriate than PVT. Some of the studies using the CPVT for CCHP applications in residential homes and buildings are discussed here.

A CPVT collector was used for hybrid solar air-conditioning application in the research done by Al-Alili et al. [142] using the TRNSYS simulation program. The study's novelty lies in decoupling the latent and sensible loads since air conditioning loads comprise significant latent loads. In this study, the thermal energy from the collector was used in the solid desiccant wheel cycle and electricity was utilized to run the vapour compression cycle (VCC). The novel concept was compared with the conventional system where the VCC is run by a set of PVs and a solar absorption cycle (SAC) run by the evacuated tube collectors. The coefficient of performance of the novel application was observed to be 0.68, much higher than the conventional VCC system driven by PVs and SAC (0.34 and 0.29) discussed above.

Renno et al. [143,144] studied the electric, heating and cooling performance of a CPVT for domestic applications. The high-temperature thermal energy from the CPVT system coupled to an absorption heat pump was used to satisfy the cooling demands. It was reported that the reflective optics allowed to generate 10% more electrical energy than the reflective optics shown in Figure 31a due to the Fresnel lens chromatic aberration for higher concentration values. The fluid temperatures from the CPVT system are higher than the conventional PVT systems as shown in Figure 31b. The concentration factor (CF) was correlated to the global area occupied by the CPVT system and required a fluid outlet temperature for the first time in research using fuzzy logic followed by using the Levenberg–Marquardt parameter estimation technique to find the optimal CF for a working condition.

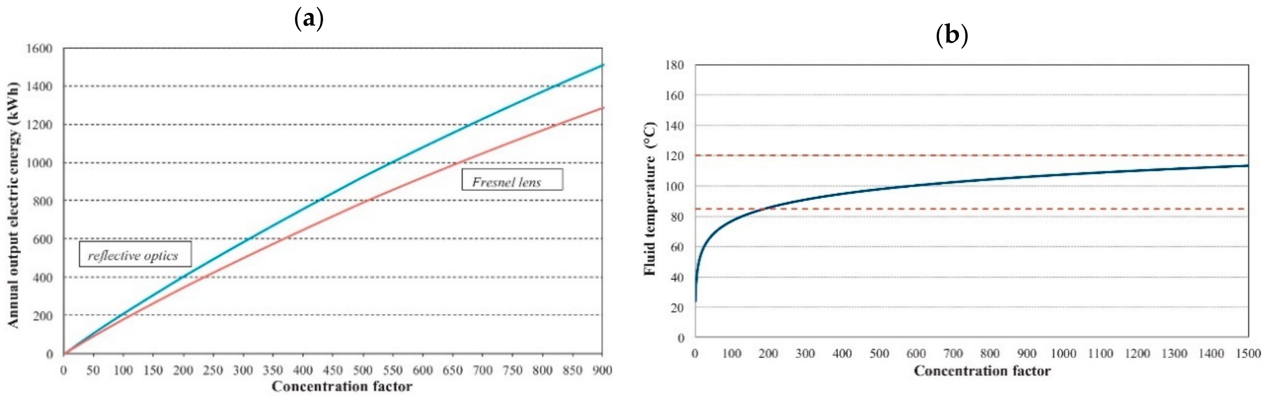


Figure 31. (**a**) Electrical energy output from two types of lenses; (**b**) fluid temperature with changing concentration factor (reprinted from [133], with permission from publisher).

A concept of trigeneration was proposed by Calise et al. [145] using the CPVT collectors, and they conducted a dynamic simulation to provide electricity, space heating, cooling and domestic hot water for a residential building. It was reported that the system was sensitive to beam radiation and generated a high fluid temperature (<170 °C) for increased intensity of radiation. The excess thermal energy was utilized for domestic hot water when required, and sometimes it had to be rejected due to less demand from the building. The primary energy savings ratio achieved was 84.4%, while the electrical and thermal efficiencies were 13.3% and 32%. If sole beam radiation was considered, the electrical and thermal efficiencies were 20.8% and 50%, respectively.

A linear Fresnel collector CPVT with a water-ammonia absorption refrigeration cycle was simulated by Moaleman et al. [146] and compared the performance with a conventional flat plate collector. The authors reported that the electrical efficiency of the PVT collector was superior to the CPVT-CCHP system, while the thermal efficiency of CPVT was significantly higher than PVT. It was also observed that PVT could not be used for cooling applications due to less temperature thermal energy. The overall efficiency was 71%, with 12.8% electrical efficiency and 58.01% thermal efficiency.

CPVT systems using nanofluid optical filtering can absorb a specific range of wavelengths of the solar spectrum, and Rodrigues et al. [147] investigated the long-term performance of a small-scale CPVT system for domestic electricity generation and water heating. The gold and ethylene glycol nanofluid acted as an optical filter and was selected such that spectral transmittance and absorption spectrum of nanoparticles match the spectral window of silicon cells. The long-term analysis of the system confirmed that hot water demand was met over 97% of the year, and the failure rate (lack of high temperature enough to provide heating to hot water system) was 2.71% for a 287-L storage tank.

Hydrogen production is considered critical for clean energy transitions, and currently, most of the hydrogen production is through coal gasification and natural gas reforming. These routes require carbon capture, utilization and storage to limit the life cycle emissions of hydrogen. On the other hand, electrolysis of water also produced hydrogen at higher costs compared to conventional processes. Khan et al. [148] analysed a multigeneration CPVT system by using the nuclear pool boiling heat transfer for thermal energy. The multigeneration system (Figure 32) consisting of CPV, heat transfer setup and thermal energy storage using PCM, absorption cooling system, space cooling, a dehumidification and ventilation system, space heating and hot water production, an electrolyser and hydrogen storage is expected to meet the combined cooling, heat and power demands of a residential community. The electrical efficiency of the CPV cell was 36.85%, while the overall energy and exergy efficiency values of the multigeneration system were 67.52% and 34.89%. The authors reported that using the nuclear pool boiling heat transfer technique allowed using higher concentrations up to 1869 times at standard design conditions of 870 Wm^{-2} irradiation and 100 °C boiling heat exchange temperature.

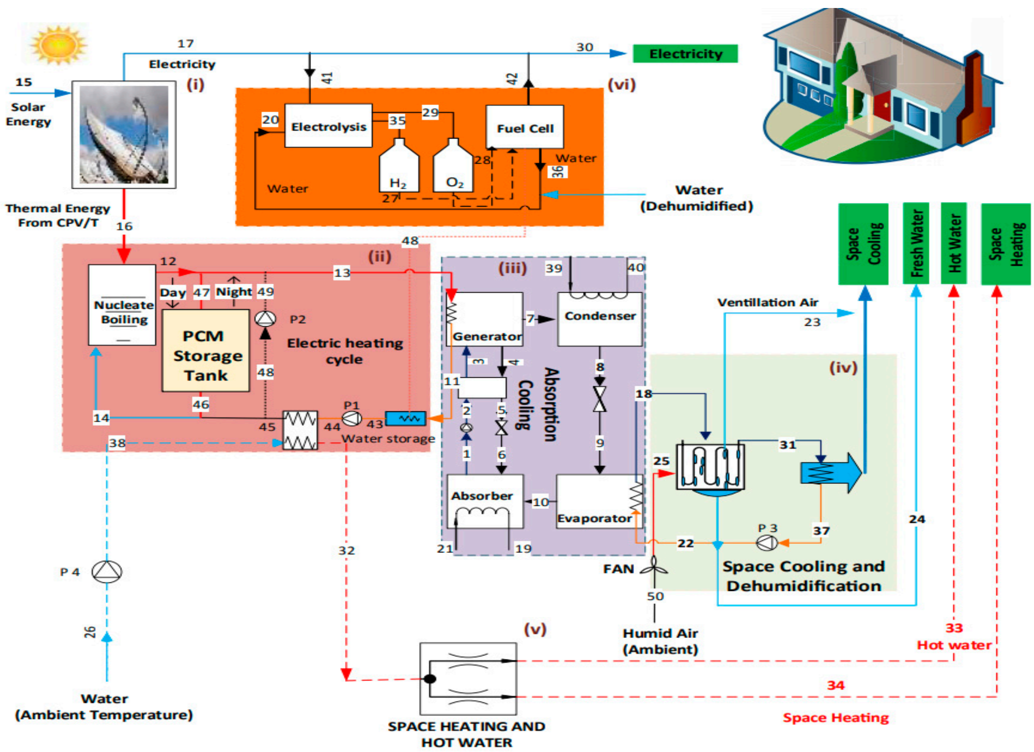


Figure 32. Schematic of the multigeneration CPVT system (reprinted from [148], with permission from publisher).

Raja et al. [149] have proposed a standalone, novel parabolic trough solar collector and PVT multigeneration system for CCHP, fresh water and hydrogen production. The system's overall energy and exergy efficiencies were reported to be 12.9% and 54.72%, with a hydrogen production rate of 0.07518 g/s from the PVT electrolyser. It was reported that the thermal energy losses reduced the energy efficiency of the proposed system in subsystems and components, and it is important to have a compact structure for modules and other system units.

3.5. Economics of PVT and CPVT Systems

The demand profile of a residence and existing technology being used in the household are vital for the viability of the PVT system. Generally, a life-cycle analysis will give an idea about potential savings of the system and is a useful exercise to compare the technologies and aid in investment decisions about potential savings of the system. Kalogirou et al. [72] performed a detailed cost analysis of the PVT system with 100% payment of system cost at the beginning and no mortgage payment. The investment costs include a PV module, a heat extraction unit, an inverter, pipes, pumps, cables, installation and a thermostat. The results were computed for three different locations using a-Si and p-Si photovoltaics. From Figure 33, it is evident that an a-Si based PVT system has better payback time due to its low initial cost despite less electrical efficiency. In a similar study conducted for Bangkok city, Nualboonrueng et al. [73] reported a payback time of 6.4 years, 11.8 years and 13.4 years for an a-Si, pc-Si and c-Si-based PVT system, respectively. Rahou et al. [150] also confirmed a better cost/benefit ratio of a-Si based PVT systems over pc-Si. Axaopoulos et al. [151] studied the commercially available PVT systems for three locations: (Athens, Munich and Dundee), using TRNSYS, and reported that the PVT system investment is more beneficial when the existing auxiliary heating system is powered by electricity instead of oil and natural gas. The authors identified that the climatic conditions, fuel prices in the location, and governmental support determine the economic viability of PVT systems.

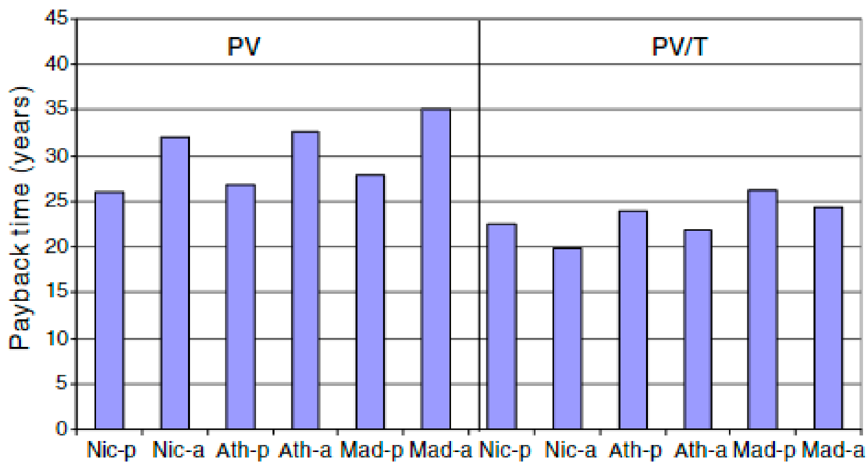


Figure 33. Payback times of conventional PV and hybrid PVT system for three different locations (Ni—Nicosia, Ath—Athens, Mad—Madison) and two PV technologies (p—polycrystalline, a—amorphous) (reprinted from [72], with permission from publisher).

Fraisse et al. [76] studied the economics of four different configurations, as shown in Table 2, which include the cost of operations and auxiliary system and excludes the investment costs. Table 2 considers the annual operating expenses with an average electricity cost of 0.08 €TTC/kWh (TTC stands for Toutes taxes comprises in French and all taxes included in English) and PV electricity selling benefits at the price of 0.55 €TTC/kWh. It was observed that the options with hybrid PVT were more encouraging than the juxtaposed PV and thermal collectors. The balance column of Table 2 illustrates the benefits offered by four options, and clearly, the uncovered glazed PVT had a better cost to benefit ratio.

Table 2. Annual financial costs and benefits including auxiliary system (electrical) (Data from [76], with permission from publisher).

	Heating	DHW	Pump	PV	Balance (€TTC)
Without solar collector	1032	256	-	-	-1650
PV+T (16 m² + 16 m²)	813	137	14	1030	-295
Uncov- PVT- 32 m²	951	198	9	2186	+666
Cov- PVT- 32 m²	827	140	14	1559	+216
Cov-LE- PVT-32 m²	799	130	15	1487	+181

Dubey et al. [77] conducted a detailed cost analysis of four different configurations (Figure 10a) and calculated the annualized uniform cost. According to Figure 34, case A is economical if the primary energy requirement is thermal yield and case D is economical if electrical energy is required. Hence, it is necessary to choose the correct type of configuration depending upon the users' needs. A universal PVT collector type like a conventional collector or PV is not recommended for obtaining the maximum benefits from the PVT technology.

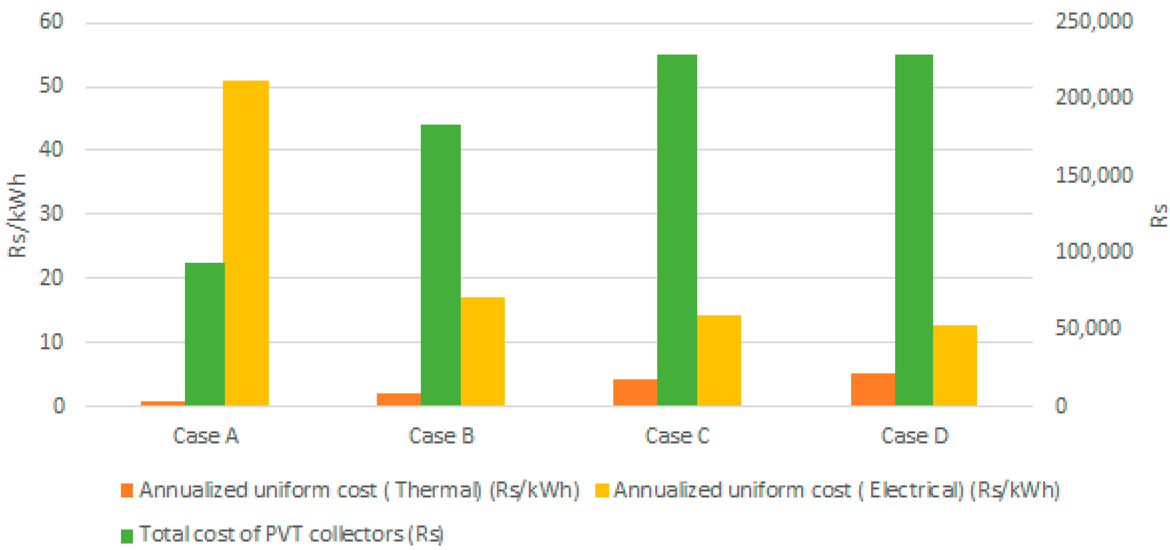


Figure 34. Annualized uniform cost of different PVT configurations (data taken from [77]).

A life-cycle assessment of an air-type BIPVT system was carried out by Agrawal et al. [18], where six different PV cells were used to assess the performance. From Figure 35, the unit power cost of amorphous silicon BIPVT is lower than other options due to its low investment costs. Moreover, these values are very close to the BIPV and can be suitable for residential applications from an economic perspective.

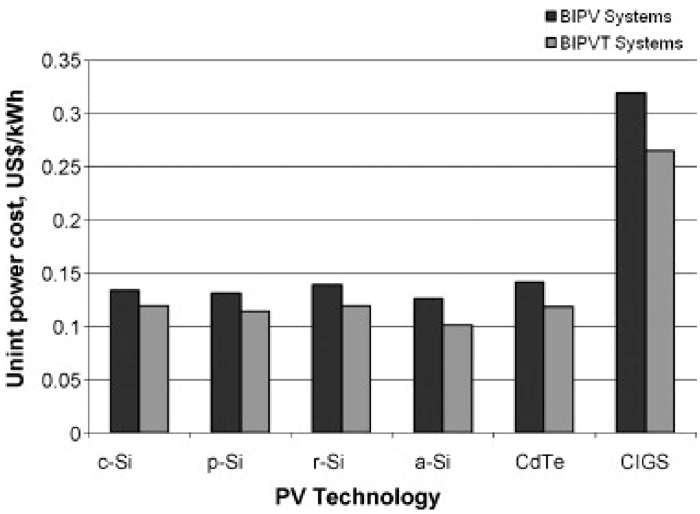


Figure 35. Unit power generation cost of the BIPV and BIPVT systems with different solar cells (reprinted from [18], with permission from publisher).

Noguchi et al. [152] studied different configurations of air-sourced PVT systems based on the UK government's standard assessment procedure for energy ratings of dwellings. It was concluded that the operational energy use and cost and carbon dioxide emission levels were significantly minimised in an air PVT system with rigid ducts. Lari et al. [103] reported a favourable result for the silver/water nanofluid-based PVT system where it resulted in an 82% decrease in the energy cost with respect to the domestic energy price with a simple cost payback time of nearly two years. Similarly, Cui et al. [153] investigated the life cycle costs of a PVT-assisted heat pump system using Monte Carlo simulation to account for the uncertainty and risk in the quantitative model for investment decisions. The input parameters for the economic assessment were initial cost, system energy cost, mortgage payment, maintenance expense, periodic cost, system income tax savings and the present value of money under the feed-in tariff (FiT) and renewable heat incentive schemes. The UK government has come up with a new smart export guarantee (SEG) scheme to replace FiT under which the suppliers pay the users for exporting electricity to the grid through fixed and flexible export tariff options. As per Figure 36, the energy savings and payback time were far better under the FiT scheme than the SEG scheme. However, SEG was believed to be an important factor for the solar industry after the closure of the FiT scheme in the UK.

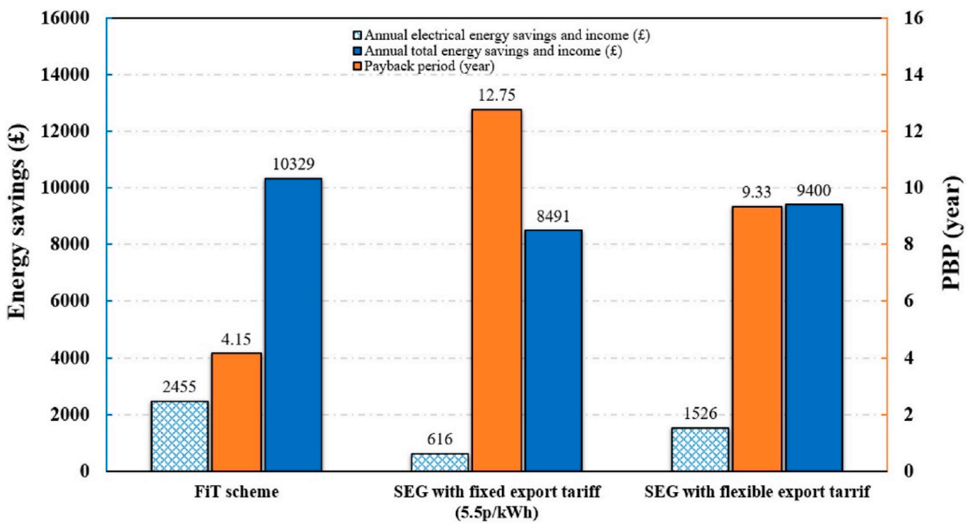


Figure 36. NPV variation as a function of PBP (reprinted from [153], with permission from publisher).

An environmental life-cycle assessment of a free-standing PVT and a vertical-mounted BiPVT in Hongkong by Chow et al. [154] estimated a cost payback time of 12.1 years for the free-standing case and 13.8 years for BiPVT. Rejeb et al. [108] considered capital costs, expected useful life, inflation rate, interest rate and energy prices as key input parameters for calculating economic efficiency and payback period of different PVT configurations. The PVT model with 0.0473 economic efficiency had 10.5 years of payback period, while the conventional thermal collector with 0.0117 economic efficiency resulted in a payback period of 50 years. It was reported that PVT technology is beneficial in the region of study due to high levels of solar radiation and onerous electricity price.

Renno et al. [143] presented an economic analysis of the CPVT system coupled with a heat pump to satisfy the energy demands of a four-person household in Palermo, Italy. The CPVT modules occupy an area of 28.87 m^2 on a 120 m^2 house, and the proposed system has an expected lifetime of 20 years. The discounted payback time was reported to be eight years for IRR equal to 13% and a discount rate of 3%.

A solar trigeneration CPVT system proposed by Calise et al. [145] was tested for economic feasibility under different policy conditions and they reported that the system was not profitable without public funding policies. The authors stressed the importance of FiT for improving the system feasibility. The effect of different policies on simple payback time as a function of the PVT area was studied.

A simple payback index (SPI) was used to assess the performance of a low cost PVT prototype made with low-cost materials [155] for three different locations: Freiburg, Naples and Almeria. The economics of the proposed prototype were tested with the commercially available collector, and the authors observed remarkable savings and low SPI with the low-cost design. The SPI for the commercial collector in three locations was 12, 14 and 20 years, while it was 15, 10 and 7 years for the author's design. It was recommended that lower initial costs for the collector can be attained by considering prices that exploit economies of scale. A comparative study involving the PV, PVT and (PV + ST) was done by Gagliano et al. [156] for three locations: Catania, Freiburg and Split. The analysis highlighted that the investment costs and the cost of electricity and gas in the location affect the investment return. The PVT system was found to be competitive in the colder climate of Freiburg, while the economics of PVT in Split was negative due to the low local costs of electricity and gas.

Gautam et al. [157] compared BiPVT, BiPV and ST for Aarhus, Denmark and Seville, Spain, locations representing typical cold weather with low solar radiation and warm weather with high solar radiation. The authors concluded that the BIPVT system is competitive only under warm weather and has a favourable electricity to heat price ratio, installation size and lower cost of the PVT system.

Ramos et al. [158] analysed the techno-economic challenges of coupling the PVT system to heat pumps or absorption refrigeration system with an aim to achieve low cost per kWh of cogeneration. The authors reported that the PVT system with its overall output had 30–40% lower levelized cost of energy when compared to an equivalent PV system.

A novel PVT cascade heat pump domestic water heating system was proposed [159] and analysed for locations Edmonton and Toronto (Canada) and Washington DC and Phoenix (USA). The payback periods for all the locations were estimated, and except for Phoenix, and none of the locations had a payback period of less than 20 years. The long payback periods were attributed to the low cost of natural gas in those locations (energy cost in Phoenix is nearly six times more than the energy costs in Toronto), and it is expected that the value of simple payback periods may be reduced for a better price of PVT and associated equipment. Conti et al. [160] presented a multi-objective optimization of PVT coupled with a heat pump and a storage tank for cost–benefit analysis in near-zero energy buildings (NZEB). It was reported that the PVT system was able to reduce the non-renewable primary energy requirements and meet the needs of the NZEB, thanks to both electrical and energy generation from PVT, even with higher installation costs. Pardo et al. [161] analysed the potential of a PVT water system to produce combined heat and power and offer benefits in terms of sustainability, energy security, carbon reduction and costs. The study was performed using TRNSYS for a multi-family building in the central European context with different configurations considering PVT collector, heat pump, space heating, and district heating network. The configuration where all the produced heat is exported to the district heating network is more favourable, followed by the configuration where the direct consumption is prioritized over the export.

4. Discussion

PVT technology has been considered in many energy-system studies during the last four decades due to its ability to combine the advantages of photovoltaic and solar thermal collector technologies for electrical and thermal energy production. Table 3 lists the key performance indicators studied in the PVT performance research. Photovoltaic efficiency is negatively affected by high temperatures, and hence, the PVT technology facilitates the cooling of PV cells for enhanced electrical efficiency. In addition, the extracted heat is used generally for low-temperature applications. The temperature of fluid from the heat recovery system can be maximised using concentrators. The CPVT system needs innovative absorber designs and better heat transfer to avoid a high stagnation temperature usually caused by high thermal resistance. The materials used for heat extraction should be of high thermal conductivity and high electrical resistivity. The literature review reveals that the thermal efficiency of 80% and the electrical efficiency of 20% can be achieved in water- and nanofluid-cooled PVT collectors. It is important to note that the output from PVT depends highly on the climatic conditions.

During summers, PVT systems typically produce adequate amounts of electricity and thermal energy depending upon the available solar irradiation. In addition, the PVT systems may generate excess energy during sunny days, which can be stored for future use. However, in temperate climates, a PVT system needs the support of an auxiliary system during winter. Moreover, the demand profile of the residential building plays a key role in the design of the PVT system. The robust control algorithms used for operating the different components of the PVT cogeneration system will aid in maximising the potential of the overall system.

The type of photovoltaic cell used in the construction of the PVT collector determines the electrical performance and reliability over the long-time operation. The PVT collector can be retrofitted to existing buildings but needs significant optimisation depending upon several factors such as demand profile, existing heating system, geographical location, energy prices and local government incentive schemes. The life-cycle and environmental analysis of PVT systems are usually examined through energy payback time and carbon dioxide emissions. Many studies reported better payback time for PVT over a separate PV and solar thermal collector. A summary of the selected works that analysed the different types of PVT systems both numerically and experimentally is presented in Table 4. For each case, the details of the PVT collector system are given, and the corresponding performance results reported.

Table 3. Performance indicators of PVT system.

Ref	Purpose of Study	Selective Performance Indicators
[79]	Thermal performance of an active building with PVT modules	Net heat gain of wall, System's COP
[148]	Analysis of multigeneration system with CPVT and hydrogen storage	Energy efficiency, Exergy efficiency, Exergy COP, Exergy destruction rate
[86]	Performance analysis of heat pump coupled PVT and PCM storage	Thermal efficiency, Electrical efficiency, Solar irradiation intensity, Investment and operation and maintenance costs, Output power to grid
[82]	Optimisation of unglazed PVT coupled with heat pump and storage tanks	Solar electrical fraction, renewable energy fraction, Inverse seasonal performance factor

[97]	PVT and ST coupled for combined heat and power	Primary energy saving efficiency, Temperature of PV, Outlet water temperature
[87]	Performance assessment of PVT & heat pump for combined heat and power	Heat pump COP
[149]	Novel parabolic trough solar collector and PVT for multigeneration systems	Exergy destruction ratio, exergy destruction rate, Hydrogen production rate
[162]	Performance analysis of PVT in Iraq	Electrical demand fraction, Auxiliary and electrical power
[109]	ANN based assessment of grid-connected PVT in Iran	Performance ratio, solar fraction
[96]	Dynamic analysis of ground source heat pump coupled to ST and PVT	COP of heating and cooling
[95]	PVT organic Rankine cycle power generation	Overall efficiency
[94]	Glazed PVT for domestic hot water production in multifamily building	Useful electrical gain
[93]	Techno-environmental assessment of PVT on a residential home	Annual carbon dioxide reduction
[153]	Life cycle assessments of PVT coupled heat pump	Net present value, System lifespan expense including investment and maintenance costs, mortgage payment, periodic costs, and income tax savings
[120]	Energy, economic and comfort analysis of BiPVT	Discounted payback period, Indoor thermal comfort
[91]	PVT with thermal storage for a smart building energy system	Hot water volume, Energy utilisation factor
[71]	Analysis of residential PVT in two similar climates	Global efficiency
[155]	Experimental analysis and simulation of PVT	Primary energy savings
[163]	Thermodynamic analysis of PVT-fuel cell system for CHP, fresh water and hydrogen production for buildings	Heat rate
[164]	PVT system for net zero building and freshwater production	Monetary benefit
[165]	Energo-econmic analysis of PVT coupled to heat pump, adsorption chiller and battery storage	Economic Savings, Payback period, State of battery charge
[166]	Utilisation of low temperature heat from BiPVT system for operation of an adsorption chiller	System electric energy exchange to electricity demand ratio
[167]	Analysis of PVT system integrated to phase change material with rotary desiccant cooling	Solar thermal contribution
[168]	Energy analysis of PVT coupled to exhaust air heat recovery system and a thermal wheel	Fractional pressure drops in the channel
[121]	Exergetic and thermo-economic modelling of façade integrated PVT	Storage tank exergetic efficiency, Battery exergetic efficiency
[99]	Analysis of micro-PVT system	Optical efficiency of PVT, Heat loss coefficient
[156]	Comparison of PVT and PV plants	Primary energy reduction, Primary efficiency
[147]	Long term environmental impacts of spectral filtering CPVT	Spectral transmittance of nanoparticles
[169]	Roadmap for next generation PVT collectors	Annual energy yield, Target cost at which PVT becomes competitive
[145]	Simulation of high temperature multi-generation system based on CPVT collectors	Profit index
[113]	Life cycle assessment of PVT system for domestic applications	Mean daily efficiency, Environmental impact

[119]	Techno-economic assessment of PV and BiPVT system retrofit in Canada	Energy savings
[157]	Performance comparison of BiPVT and other solar technologies	Cost of energy saved
[118]	A comparative study of PV, ST and PVT systems for net zero buildings	Energy import/Energy export ratio
[72]	PVT system for domestic hot water and electricity production	Life cycle savings
[77]	Analysis of series connected PVT collectors	Instantaneous efficiency
[123]	Improvement potential of BiPVT system	Improvement potential
[73]	Performance of PVT system based on cell type for residential applications	PV cell efficiency
[154]	Environment life cycle analysis of PVT	Energy payback time, greenhouse gas payback time
[67]	Simulation of PVT based trigeneration system	Energy fraction for hot water
[135]	Annual study of heat pipe PVT system	Average electrical gain

Table 4. Summary of the PVT systems.

Ref	System & Location	Study Type	Cooling Fluid	Type of Collector	Type of PV	Performance Results
[141]	PVT & France	N	Air and water	Copper flat plate	p-Si	$\eta_{th} = 80\%, \eta_e = 11\%$ @ $G = 625 \frac{W}{m^2}$
[74]	Glazed PVT & Hongkong	E	Water	Aluminium flat box with fins	mc-Si	$\eta_e = 9 - 11\%$, $\eta_{th} = 49 - 52\%$
[77]	Glazed PVT & New Delhi	N	Water	Flat plate	$\eta_c = 12\%$	$T_f = 85^o$ C, $\eta_e = 8.75\%$, $\eta_{th} = 51\%$ @$800 \frac{W}{m^2}$ and $\dot{m} = 0.04$ kg/s
[18]	Glazed BiPVT & New Delhi	N	Air	-	mc-Si p-Si a-Si	$\eta_{th} = 52\%$ $\eta_{th} = 48\%$ $\eta_{th} = 34\%$
[170]	Glazed Reflector PVT & Maragheh city	E	Water	Evacuated tube and brass channels in Flat Aluminium box	mc-Si	$\eta_{th} = 61\%, \eta_e = 11.9\%$, $T_f = 50^o$ C
[171]	PVT & Pisa, Italy	E	Water	Polycarbonate box	p-Si	$\eta_e = 8.8\%, T_{f,avg} = 42^o$ C
[172]	Glazed PVT with heat pump, storage tank and gas heater & Lvliang, China	E	Water	Aluminium flat plate	$\eta_c = 17\%$	$\eta_e = 13.1\%$, $\eta_{th} = 31.9\%$ and $COP_{HP} = 4.9$ @ $G = 762\ W/m^2$
[173]	Glazed PVT & Hefei, China	N	Water	Aluminium flat plate	mc-Si $\eta_c = 17.8\%$	$\eta_e = 14.3\%, \eta_{th} = 53.4\%$
[106]	Glazed PVT	E	Water	Aluminium flat box	mc-Si	$\eta_e = 8.8\%, \eta_{th} = 79\%$
[91]	Glazed PVT with storage tank & Esbjerg, Denmark	N	Water	-	$\eta_c = 20\%$	$\eta_e = 12 - 15\%, \eta_o = 61\%$, $T_f = 40^o$ C
[153]	Glazed PVT, heat pump & Nottingham, UK	N	Water	Ethylene vinyl acetate plastic back and polyethylene heat exchanger	p-Si $\eta_c = 15.4\%$	Payback period is 4.15 years. Feed in tariff is better scheme than the smart export guarantee scheme for energy generation.
[93]	1.25 kW_P Glazed PVT, storage tank & Kuala lumpur	E	Water	-	p-Si	$\eta_e = 16.7\%, \eta_{th} = 51.1\%$, $T_f = 43.5^o$ C @ $G = 1232\ W/m^2$
[162]	Glazed PVT, storage tank & Mosul, Iraq	N	Water	Copper sheet	-	Thermal solar fraction = 56.4% @ Area= $6m^2$

[87]	Glazed PVT, storage tank, Heatpump & Belfast, UK	N	Water	Copper sheet	mc-Si	$\eta_e = 14.5\%, \eta_o = 61\%$
[71]	Glazed PVT, storage tank, battery & Strasbourg, France	N	Water and glycol	-	mc-Si	$\eta_e = 13.5\%, \eta_o = 64\%$
[99]	Glazed PVT, storage tank & Warsaw, Poland	N	Water	Copper sheet	p-Si	$\eta_e = 12.1\%, \eta_{th} = 47.8\%$
[101]	Unglazed PVT & Chengdu, China	E	Water	Aluminium plate (grid channel)	p-Si	$\eta_e = 11.8\%, \eta_{th} = 25.2\%$
[107]	Unglazed PVT, storage tank & Sichuan, China	E	Water	Roll bond aluminium plate	p-Si	$\eta_e = 15\%$ (peak)
[100]	Glazed PVT, seasonal storage system & Newcastle upon Tyne, UK	N	Water	Aluminium plate	mc-Si	$\eta_e = 13\%$, $T_f = 40^oC$, 133 litre per day. m^2
[113]	Glazed and Unglazed PVT, storage tank, Greece	E	Water	Copper sheet	p-Si	The differences between maximum electrical efficiencies for glazed and unglazed setups for the operational temperature range (40–60 °C) are 0.3–0.4% only.
[146]	Fresnel lens concentrated PVT and unglazed PVT, Tehran	N	Water and glycol	Copper sheet	mc-Si	$\eta_{e,CPVT} = 12.8\%, \eta_{th,CPVT} = 58\%$, $\eta_{e,PVT} = 14.6\%, \eta_{th,PVT} = 34\%$,
[112]	PV, Glazed and Unglazed PVT	E	Water	Aluminium sheet	mc-Si	$\eta_{e,PV} = 12.5\%$, $\eta_{e,gPVT} = 11.8\%, \eta_{th,gPVT} = 49.4\%$, $\eta_{e,ugPVT} = 13.3\%, \eta_{th,ugPVT} = 39.8\%$ G= 1000 W/m^2, V_w=2 m/s, T_a= 35 °C, $T_{f,i}$= 40^o C
[103]	Glazed PVT & Dhahran, Saudi Arabia	N	Nanofluid and Water	Stainless steel plate	p-Si	Nanofluid : $\eta_e = 13-14\%$, $\eta_{th} = 55-63\%$ Water: $\eta_e = 12.5-14\%$, $\eta_{th} = 47-54\%$
[102]	PV, Glazed and unglazed PVT, storage tank & Chennai, India	E	CuO/water nanofluid and water	Copper sheet	p-Si	PV: $\eta_e = 9\%$ Unglazed PVT: $\eta_e = 8.8\%, \eta_{th} = 19.4\%$ (water) $\eta_e = 7.6\%, \eta_{th} = 28.2\%$ (nanofluid) glazed PVT: $\eta_e = 6.4\%, \eta_{th} = 21\%$ (water) $\eta_e = 6.2\%, \eta_{th} = 30.4\%$ (nanofluid)
[139]	Unglazed PVT & Sydney, Australia	N	Air	-	mc-Si	The air duct delivery system accounts for more than 23.4% of energy necessary for operating the fan for an optimised PVT air system.
[150]	Unglazed PVT with dual tracker & Bandar Baru Bangi, Malaysia	E	Water	Aluminium plate	a-Si	$\eta_o = 70-81\%$ @ $T_{f,i} = 30^o\ C$, ṁ=3 litre per minute
[98]	PV, PVT & Copenhagen	E	Water	Aluminium layer	mc-Si	$\eta_e = 13.6\%$ (PV), $\eta_e = 15.3\%$ (PVT) $\eta_{th} = 36.6\%$

[123]	Unglazed PVT & Malaysia	E	Water	Stainless steel	p-Si	$\eta_o = 73 - 81\%$
[151]	Glazed PVT, storage tank & Athens, Munich, Dundee	N	Water	Aluminium box	mc-Si	$\eta_e = 9.6\%, 9.6\%$ and 10.2%
[136]	Glazed PVT & Ghardaia, Algeria	E	Air	Galvanized iron	mc-Si	$\eta_{th} = 48\%$

η_o-Overall efficiency, η_e-Electrial efficiency, η_{th}-Thermal efficiency, G-Irradiation, V_w = wind speed, $T_{f,i}$ = Fluid inlet temperature, T_f = Fluid outlet temperature, $\dot{m}$-Mass flow rate, E—Experimental, N—Numerical .

5. Progress and Opportunities

1. The thermal efficiency of a typical solar thermal collector is higher than that of a PVT collector of similar thermal capacity. The following factors contribute to the lower thermal efficiency of PVT collectors. First, in PVT collectors, part of the solar energy is converted into electricity. Moreover, the materials used in PVT modules have a low absorption coefficient and high emissivity. Furthermore, there is additional heat transfer resistance between the cell/absorber plate and the coolant, reducing the heat removal factor. Additionally, PVT modules have a low heat loss coefficient due to the selective absorption characteristics of PV cells, where long-wave radiation is offered through low emissivity by the largely reflective metallic contacts on the back of the panel. Reflective losses from cover glass (~5% loss in optical efficiency) also contribute to the lower thermal efficiency of PVT collectors [32,35–37]. The fluid outlet temperatures suitable for space heating and domestic hot water are above 60 °C, and in this case, the cell temperature would be around 70° C [169]. However, the achievable system temperature is limited by the desired cell temperature to maintain optimum electrical efficiency, making the PVT collector suitable for low-temperature applications (25–40 °C). According to Sandnes et al. [59], for the desired cell temperature of 45 °C, the inlet fluid temperature cannot exceed 40 °C for unglazed PVT collectors and 30 °C for glazed PVT collectors, depending on thermal characteristics and the given conditions (solar radiation = 800 Wm^{-2}, ambient temperature = 20 °C, wind speed = $1ms^{-1}$). Moreover, it happens that the electrical efficiency of PVT systems drops during the summer due to the high temperatures of the working fluid [99], [155]. It has been observed in this review that crystalline solar cells were used more in the study of PVT systems. However, since the temperature coefficient of these solar cells are not the best and will lead to efficiency losses at higher temperatures, it may be possible to consider the solar cells (heterojunction) with better temperature coefficients [67,169].
2. The majority of studies used direct contact, thermal adhesive or mechanical fixing to integrate the PV cells and the thermal absorber. However, these methods are characterized by poor thermal removal, formation of bubbles/gaps in the case of high solar intensity and increased thermal resistance, leading to decreasing the overall performance of the PVT system. Thus, EVA lamination with mechanical press-fitting has been proposed instead of a three-layer (encapsulant, TPT and adhesive layer [135]) joining to enhance the heat transfer between PV cells and the absorber metal, and is supposedly the best option. It has been reported that the thermal resistance is reduced by 9.9% [102] when compared to conventional integration techniques. However, during the summer, the PVT collector surface temperatures can be higher than 130–140 °C, leading to stagnation temperature and damage of structural material such as EVA resin, which starts degrading from 135 °C. This degradation may lead to accelerating ageing and the reduction of absorption and then delamination. In addition, the sensitivity of mono-crystalline and polycrystalline cells to mid and high temperatures is a significant concern for overall PVT performance [76], since they have a negative temperature coefficient [95], and the efficiency drops by 0.45% $°C^{-1}$. Due to this phenomenon, the reliability of the PV module may be affected since the

nominal lifetime of silicon cells is assured only for PV temperatures lower than 85 °C [174], [106]. On the other hand, amorphous silicon cells facilitate the use of metallic substrate, reducing the thermal resistance of PVT and exhibiting a positive power temperature coefficient in the long-term operation at medium and high temperatures reaching higher efficiencies at a degraded steady state. Hence, a detailed durability analysis under stagnation conditions and amorphous solar cells used in conjunction with the modern solar collectors or heat pumps with temperature requirements higher than 98 °C can be studied both numerically and experimentally in the future [95,106,175].

3. Radiative cooling of buildings has been considered at the research level for many years; however, it is not commercialized because of the low power density involved. So, it is essential to research cost-effective solutions for radiative cooling applications using PVT, similar to the study by Eicker et al. [176]. However, their study did not perform any cost analysis, and it is an interesting area of research to explore whether the proposed radiative cooling PVT systems are techno-economically feasible for domestic applications.
4. The design of the absorber and the flow channel significantly affected the temperature distribution and cooling rate of PV panels. Honeycomb, grid and harp channels were found to be better than the conventional circular-shaped channels [38,101].
5. High heat flux on the cells in the CPVT systems limits the high-temperature applications, and this can be reduced by spectral beam splitting by using a bandpass or bandstop filter [177]. However, even after the splitting, most radiation falling on the cells is converted into heat and need better cooling technologies than those used in a conventional flat plate PVT collector. Radiation flux distribution is another challenge in designing CPVT systems affected by non-uniformities due to mirror shape error, gaps between mirrors and receivers support posts.
6. The coupling of the CPVT system with heat pumps for meeting the cooling demands has been studied in few articles for domestic applications. It was observed that there needs to be a compromise between the electrical and thermal energy to enable the AHP coupling because the temperature required (reported to be 90 °C in one of the studies [143]) to make the heat pump work is significantly higher than the outlet fluid temperature from the conventional PVT systems. Thus, in these cases, the temperature required for the AHP limits the electrical efficiency of the CPVT system. In addition, further theoretical and experimental studies need to be carried out on the optimization of the CVPT system for different climatic conditions.
7. PVT and CPVT systems have the potential for applications in CCHP. However, as discussed in many studies, conventional PVT collectors do not have the same ability for cooling applications as it is and will require modifications because the amount of solar energy received by the PVT panels is lower than what is the case with CPVT. Additional equipment [146] is needed to ensure more solar energy is incident on the PVT collector, leaving scope for new designs in PVT systems for CCHP.
8. The use of nanofluids as an optical filter and heat transfer coolant has been an interesting area of research for the last few years. However, most of the studies are based on parametric analysis, and it is often not sufficient to define the best operating parameters for given climatic conditions. Hence, multi-objective optimization [147] studies considering the selection of base-fluid, type of nanoparticles, selection of PV cells, system size, coolant channel location, nanoparticle volume fraction and thermal storage unit size can be conducted to investigate the impact on efficiencies. In addition, the existing studies involving parametric analysis will act as a framework for both multi-criteria optimization and experimental research. Spectral filtering CPVT systems have shown the ability to displace a significant amount of carbon emissions due to their better thermal efficiencies. However, a detailed life-cycle assessment and multi-criteria decision analysis studies will help in understanding the actual techno-

economic, environmental, social and legal aspects of the proposed system for residential applications.

9. Many studies in photovoltaics cooling have used the laminar and turbulent flow characteristics to extract heat. However, CPVs operate at higher temperatures, and it is required to apply other heat transfer techniques such as nucleate boiling heat transfer [148] for thermal management. There is sufficient evidence of its potential for high-temperature systems, and it should be studied for different residential buildings and energy demand profiles. In addition, the cost–benefit analysis of such novel systems, multi-objective optimization, and exergo-economic analysis can be performed in the future.
10. PVT systems are generally coupled with heat pumps, as discussed earlier, to use them for CCHP applications, and increase the primary energy savings. However, this increases the overall system costs, and hence, alternative smart building energy business models involving the selling of energy to local communities or grids using output from PVT technology [91,178,179] are necessary. The techno-economic opportunities and barriers of building and managing such small power and heat grids can be studied in detail in the future. In addition, the number of studies aimed at optimal control strategies using a model-based approach is limited in the area of PVT, and it is noted that this would be a useful approach to find the optimal solution of the multi-objective optimisation problem [180].
11. As discussed in Section 2, numerous earlier studies were focused on converting a conventional PV into PVT by integrating a heat recovery and storage system. However, as the demand for new PVs grows, the number of decommissioned or end-of-life solar panels and batteries will also increase, which in turn will result in increases in the PV panel waste. This situation will not make the energy transition sustainable since the cumulative PV panel waste by 2050 was expected to be at least 60 million tons at a 4500 GW PV capacity [181]. In addition, it has been predicted that 80% of the PV waste stream would constitute prematurely failed products [182]. Therefore, it is useful to conduct techno-economic and environmental studies on second-life PV panels for PVT systems. Since the economic value of PVT systems also depends on PV panels [73] and much of the environmental impact is from the fabrication of PVT collector [113], second-life PV panels can promote the circular economy to reduce environmental impact. Generally, PVT systems have lower electrical efficiency if the water temperature requirements are high. Thus, second-life PV panels can be a potential candidate for integrating into the PVT system and leveraging the benefit of overall energy efficiency and a possible improvement in the payback time of greenhouse gas emissions. PVT systems do not generally perform well during winter like other solar energy technologies. Therefore, integrating the PVT with upconverter and downconverter [183], [184] materials, which can used with both direct and diffuse light, can help in improving the annual electrical and thermal efficiencies. In addition, the PVT structure, including the packaging factor, is an area where significant developments are needed, as demonstrated in [162].
12. The techno-economic analysis studies that were analysed in this review focused mainly on the NPV and cost payback period. However, few studies have reported the negative environmental impact of PVT systems [101]. It is important to study the energy payback time and greenhouse gas emissions payback time to understand the positive effects on pollution and environment, which will make it possible to assess the environmental superiority of PVT over other green energy generation technologies.
13. Most novel designs in both PVT and CPVT are either short of experimental validation, or lack experimental studies involving sufficiently long terms. This is due to limited time and higher costs. Moreover, several parameters influence the system's performance in a residential setup, and it is often cumbersome to study all these the relevant parameters in a single study. Hence, statistical approaches such as artificial

neural networks [185] are being developed to forecast the performance under various weather conditions, as they can model engineering systems without the need to solve complicated mathematical models. Research using ANN for PVT or CPVT performance and predictive maintenance is limited and has scope for many future studies focussing mainly on long-term analysis and multi-objective optimisation.

14. Research on PVT systems for CHP and CCHP applications for residential households lacks sufficient experimental investigations using real-time loads and supply conditions. Detailed energy and exergo-economic studies for residential homes by considering the local electrical and heat incentive schemes will optimise the systems for given climatic conditions. It is also useful to assess the co-generation ability of different hybrid energy systems involving PVT or CPVT technology. The heat storage potential of PVT-PCM systems is 50% higher than conventional PVT-water systems, and PVT-PCM offers better power output and period of thermal energy availability. However, PVT-PCM systems have issues including low thermal conductivity and improper charging and discharging cycles when the PCM is not properly selected. This can be improved by using the nanoparticles along with the PCM. Furthermore, the integrity of the PVT-PCM system during long-term operation and the risk of leakages should be studied experimentally [50,104].
15. Integrating different renewable energy sources increases the system's versatility and will contribute to the energy security of the site. However, this increases the system complexity, and sometimes it might be useful to have a standalone multi-generation system that could meet the end-user demands. Accordingly, there were few studies [148,149,186] on multi and tri-generation using solar energy where the PVT and CPVT elements exhibited great potential for meeting the energy and heat demands. Future perspectives include extensive studies on the geometry of collector entrapment to reduce thermal energy losses, nanofluids as working fluids and detailed economic, exergo-economic and exergo-environmental assessment of these systems to improve the overall energy efficiency.
16. Standalone solar energy systems also involve integrating the PVT with seasonal energy storage systems [100]. These systems are very useful where the grid connection is not feasible or returns on the sale of energy are not competitive. Few demonstrations proved the ability to store and shift the heat load across the seasons without detailed modelling of the storage systems. Prospects include life-cycle analysis of such systems at high operating temperature, focusing on the thermal energy storage system.

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