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A Comprehensive Review of Photovoltaic–Thermal (PVT) Technologies: Classification, Performance Evaluation, Challenges, and Research 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 (PV) are mature technologies used to harness solar energy. However, the efficiency of photovoltaics decreases as operating temperatures increase. To overcome these limitations, photovoltaic–thermal (PVT) systems have been developed to simultaneously generate electricity and thermal energy. This paper provides a comprehensive review of PVT systems, including their fundamental principles, classification, performance evaluation methods, and modelling approaches. The review highlights different system configurations based on working fluids such as air, water, and nanofluids, as well as advanced technologies including phase change materials (PCM). Additionally, special applications such as concentrating photovoltaic–thermal (CPVT) and building-integrated photovoltaic–thermal (BIPVT) systems are also discussed. The analysis shows that PVT systems can improve overall energy efficiency by reducing the temperature of the PV cells and recovering useful thermal energy. However, several challenges remain, including system complexity, high initial costs, and the need for efficient thermal management and system optimization.

I. Introduction

Over the past few decades, most countries have been heavily dependent on fossil fuels for energy, leading to a significant increase in their consumption and the associated environmental impacts, which have intensified alongside the rapid growth of the world's population. Reports from the International Energy Agency indicate that fossil fuel resources are being depleted at an alarming rate, while, in 2024 nearly 730 million people still lacked access to electricity. The overuse of primary energy sources has not only damaged the environment but has also contributed significantly to severe climate change issues such as global warming, glacier melting, and ozone layer depletion [1]. Thus, it can be stated that, to address environmental issues and to reduce our dependency on fossil fuels we must turn to solar energy which is harnessed via photovoltaic technology. This technology has shown great success, especially in high solar radiation areas, as it is a clean and abundant resource [2].

However, despite their advantages, photovoltaic technology has a major limitation, which is its relatively low efficiency in converting solar energy into electricity. PV panels, mainly based on silicon, typically convert only 15–18% of the incident solar energy into electricity, while multi-junction cells can achieve higher efficiencies of about 44.4–46% [3]. The rest of the radiation is converted into heat, which increases the cell temperature and reduces performance [4]. To address this, PVT systems have been developed by integrating thermal collectors or fluid channels. These systems simultaneously produce electrical and thermal energy while cooling the PV cells, thereby improving overall performance. [5]. The performance of PVT systems is affected by many parameters, including weather conditions (solar irradiance, ambient temperature, wind speed), design and operating conditions (orientation, tilt angle, incidence angle), and the thermophysical properties of the working fluid (such as fluid type and mass flow rate) [6].

Many researchers have investigated PVT technology through a wide range of system designs [7]. PVT systems are also classified based on the type of heat transfer medium, which includes air- and water-based collectors. Air-based systems are simple and low-cost but exhibit lower heat transfer performance, with overall efficiencies ranging from 20% to 40%. Water-based systems provide better thermal performance due to the higher heat capacity of liquids, resulting in improved efficiency [8]. To further enhance performance, recent studies have investigated nanofluid-based PVT systems, where the addition of nanoparticles significantly improves thermal conductivity and overall efficiency [9]. In addition, significant research has been conducted on the use of phase change materials (PCM), which help regulate temperature fluctuations and improve thermal energy storage [10]. Moreover, CPVT systems have been developed to increase solar energy utilization, although they require effective cooling strategies. Building-integrated PVT systems also show promising performance by combining energy generation with building integration. Despite these advancements, challenges remain in terms of system optimization, economic viability, and long-term performance under real operating conditions [11].

This comprehensive review is structured around four main aspects. First, it presents the fundamental principles and classification of photovoltaic–thermal (PVT) technologies. Second, it discusses the performance analysis and evaluation of PVT systems. Third, it reviews the main modelling and analysis approaches, as well as the associated challenges and research opportunities. Finally, the paper concludes with key findings and future perspectives.

II. Fundamental Principles of PVT Systems

The concept of photovoltaic-thermal (PVT) systems, introduced in the 1970s, aims to improve the efficiency of conventional photovoltaic panels by producing both electricity and heat, as shown in Figure 1 [12]. A PVT system combines a PV panel with a thermal collector to recover excess heat. This helps reduce the temperature of PV cells, improving electrical efficiency, while using the recovered heat for thermal applications. As a result, PVT systems provide higher overall efficiency, better space utilization, and greater energy output compared to separate PV or thermal systems. The operation of PVT systems is governed by strong electrical–thermal coupling: part of the incident solar radiation is converted into electricity, while the remaining portion is transformed into heat, which raises the cell temperature and negatively affects electrical performance.

In a PVT system, heat transfer occurs as a result of a combination of conduction, convection, and radiation taking place across the different components of the system [13], as shown in Figure 2. Solar radiation incident on the glass cover is partly reflected, partly absorbed, and partly transmitted to the PV cells. The absorbed energy is used for electricity production, the rest is converted into heat. This heat is transferred through the different components via conduction, which results of temperature gradients. In addition, convective heat transfer takes place in the fluid channels, which may be natural or forced via the use of pumps. Radiative heat exchange also occurs between different surfaces within the system as well as between the system and the environment. The absorber layer plays an important role in heat exchange with the working fluid, thereby enabling efficient heat recovery. The main thermal losses to the environment occur through convection and radiation at the outer surfaces. These coupled heat transfer processes play a key role in the thermal performance of the system and, consequently, in its overall performance.

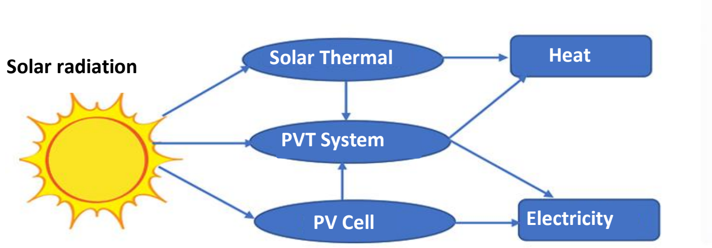

Figure 1: Concept of PVT technologies.

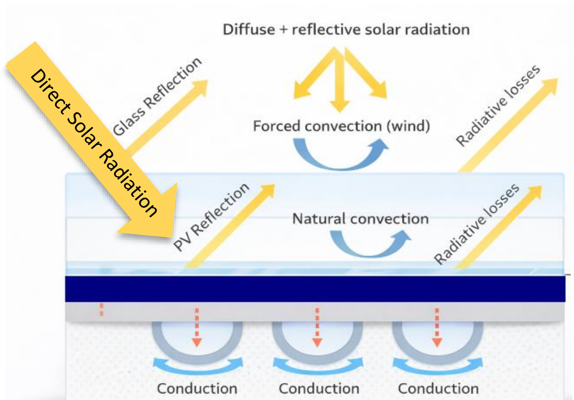

Figure 2: Fundamental heat transfer mechanisms in a PVT system.

III. Classification of PVT Systems

The classification of PVT systems, as shown in Figure 3, depends on several criteria reported in the literature, including the type of heat transfer fluid (water, air, nanofluid), solar cell type, intended application, presence of glazing, solar radiation capturing technology, operating mode, integration of cell cooling mechanisms, the presence of thermal storage such as phase change materials (PCM), and the level of integration within buildings. In addition, Figure 4 presents the research trends since 2020 associated with different PVT types, which were extracted from the OpenAlex database, a large-scale open-access index of scientific literature.

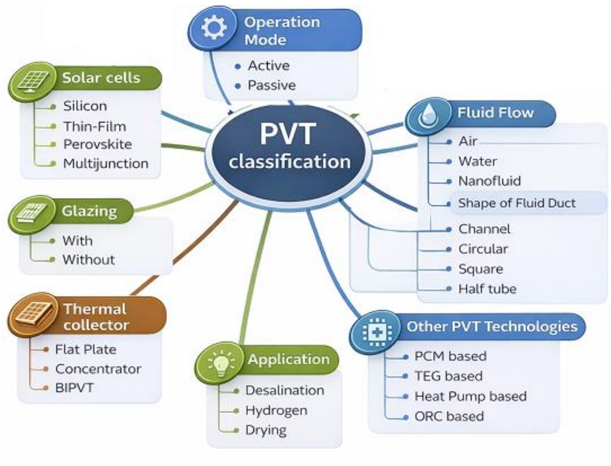

Figure 3: Classification of PVT systems

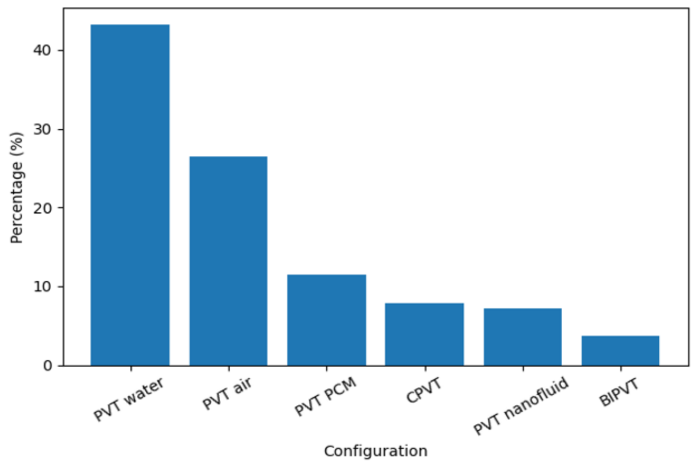

Figure 4: Statistical research trends extracted from the OpenAlex database.

a. Based on Working Fluid

Numerous studies have used different fluids as working fluids in PVT systems configurations, particularly air, water, and nanofluids. Air-based PVT systems are widely used due to their simple design, low cost, and ease of integration, with overall efficiencies typically ranging from 20% to 40%, where electrical efficiency contributes about 10–12%. However, various studies focus on the enhancement of air-based PVT systems through different configurations, including glazed, unglazed, and geometrical modifications such as fins, single-pass, and double-pass designs. Generally, double-pass systems provide the best thermal performance, while glazing enhances heat recovery at the cost of electrical efficiency [14]. Moreover, system performance is sensitive to design and operational parameters, including air mass flow rate and channel depth, although near-optimal energy output can be achieved under different conditions [15].

In contrast, water-based PVT systems provide higher thermal performance due to the superior thermophysical properties of water, particularly its high heat capacity and thermal conductivity [16]. The efficiency of these systems strongly depends on the flow configuration and channel design. Lee et al. [17] studied the effect of water flow rates on PVT performance and showed the highest efficiency at 3 L/min compared with 1, 2, and 4 L/min. The effect of the absorber design has been widely analyzed. Hermann et al. [18] studied PVT system focusing on three different absorber designs: serial, parallel, and bionic. The results showed that the PVT system with bionic channels achieved higher electrical efficiency (up to 14.5%) compared to the others.

Nanofluid-based PVT systems represent an advanced approach to further enhance thermal performance. By dispersing nanoparticles into the base fluid, thermal conductivity is increased, leading to more efficient heat extraction and lower PV operating temperatures. A study conducted by Rajakumar et al. [19] demonstrated that the MnO_2 nanofluid-based PVT collector achieved superior power output (ranging from 80.42 W to 202.91 W) compared to a water-cooled PVT system (72.48 W to 176.17 W). Nevertheless, despite their promising performance, nanofluids still face challenges related to stability, cost, and large-scale implementation.

b. Based on Thermal Enhancement Techniques

PCM-based PVT systems are designed to regulate the operating temperature of photovoltaic modules by storing excess thermal energy during periods of high solar irradiance and releasing it when temperatures decrease. PVT-PCM hybrid configurations demonstrate a 28% increase in thermal efficiency, a 15% rise in electrical output, and a 12 °C reduction in temperature fluctuations compared to conventional PVT systems [20]. The reverse process during PCM solidification releases the accumulated thermal energy, making it available for secondary applications, including building heating systems and hot water generation.

On the other hand, hybrid cooling techniques combine multiple heat transfer enhancement methods to achieve superior performance. These approaches may involve the simultaneous use of active and passive cooling, for example, by combining fluid circulation (air or water) with phase change materials (PCM), nanofluids, or advanced surface geometries such as fins and microchannels. Bassam et al. [21] utilized a cooling nanofluid circulation system with a micro-fin tube (inner-grooved) encapsulated with nano-PCM (Phase Change Material). The study shows that the system reached a thermal efficiency of 77.5%.

c. Based on System Design

Flat plate PVT systems are the most commonly used due to their simple structure, reliability, and ability to operate under direct and diffuse solar radiation. They are characterized by a simple configuration: an absorber plate coated with a selective layer, transparent glazing to reduce convective losses, and insulation at the rear and sides. They are cost-effective, reliable, and easy to integrate into building envelopes, and are used in domestic hot water systems and solar space heating [22]. Flat plate PVT collectors offer greater efficiency than CPVT at lower operating temperatures, but at higher operating temperatures flat plat collectors face increased thermal losses due to their wide exposed area [23].

Concentrating PVT (CPVT) systems employ optical devices such as parabolic trough collectors, linear Fresnel reflectors, and compound parabolic concentrators, which use reflective or refractive surfaces to focus solar radiation onto high-efficiency photovoltaic cells. This concentration significantly increases the solar flux, making CPVT capable of providing significantly higher thermal and electrical outputs compared to PV or hybrid PVT systems, as incoming solar energy is maximized within the system via energy-efficient concentrators [24]. CPVT require precise solar tracking and are generally employed in industrial or large-scale solar thermal power plants.

d. Based on Application

Photovoltaic–thermal (PVT) systems can be broadly categorized based on their field of application, primarily into building-integrated systems (BIPVT) and industrial applications, each targeting specific energy needs. The BIPVT system is an energy-producing technology that integrates photovoltaic-thermal solar modules into building components such as windows, roofs, facades and shading devices during the design phase. Benefits of BIPVT systems include energy efficiency, enhanced thermal comfort, environmental benefits, and cost savings. They can potentially provide considerable thermal and electricity energy for building use. The electricity generated is supplied to the building's electrical devices, while the heat produced can be used for air conditioning and domestic hot water production [25]. The major challenge of BIPVT systems is managing thermal performance while maintaining high energy efficiency. This includes controlling heat retention, cooling and heating demands, thermal bridging, and the urban heat island effect, which can be mitigated through optimal module orientation, tilt, and the use of spectrally selective or reflective coatings [26].

Similarly, hybrid PVT systems can be utilized for a wide range of applications, including water heating, space heating, drying, solar desalination, textiles, solar power plants, the agricultural sector, preservation of food and pharmaceutical products, automobiles, and medical applications [27]. For both building and industrial applications PVT technologies offer cost-effective solutions compared to other solar options. In industry, higher outlet temperatures (often above 60 °C) and fewer space constraints favor specialized designs rather than building-integrated systems. Industrial collectors must also be more robust to withstand harsh environments, including dust and debris, while technical and economic barriers remain for wider adoption [18].

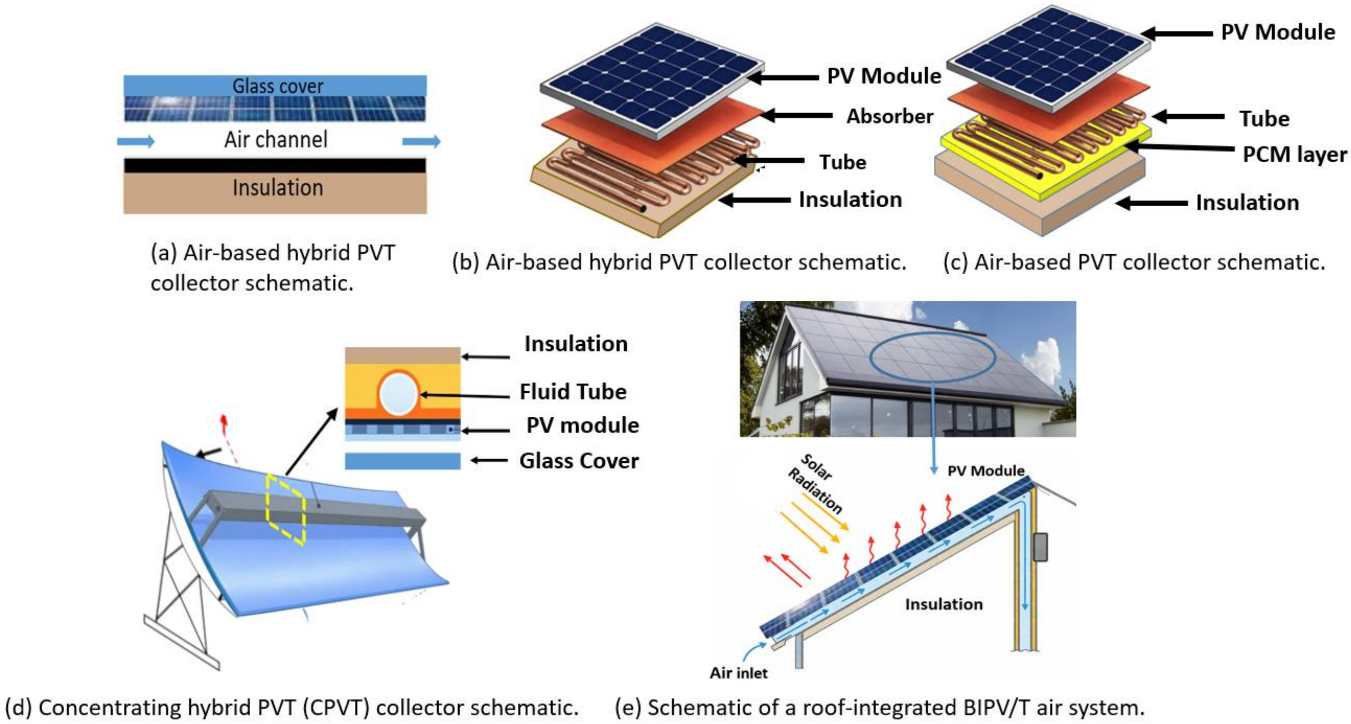

Figure 5: Different types of PVT systems.

IV. Performance Analysis and Evaluation

a. Electrical, thermal and overall efficiency

Characterizing the performance of a PVT solar collector involves establishing an energy balance that accounts for all incoming and outgoing energy fluxes:

$$Q_S = Q_e + Q_{th} + Q_l \tag{1}$$

Here, Q_S, Q_e, Q_{th}, and Q_l represent, respectively, the solar energy incident on the collector, the electrical energy generated by the collector, the thermal energy carried by the heat transfer fluid, and the energy lost through the three modes of heat transfer.

The following equations allow the calculation of the electrical and thermal efficiencies of PVT systems for accurate performance analysis [28]:

$$\eta_e = \frac{P_{max}}{E \times A_{PV}} \quad and \quad \eta_{th} = \frac{\dot{m}\, C_p (T_{out} - T_{in})}{E \times A_{th}} \tag{2}$$

where E [W·m^{-2}] is the incident solar irradiance, A_{PV} is the surface area of the photovoltaic panel, and A_{th} is the surface area of the solar thermal collector. Here, ṁ denotes the mass flow rate of the heat transfer fluid, C_p [J·kg^{-1}·K^{-1}] is its specific heat capacity, and T_{in} [K] and T_{out} [K] are the fluid temperatures at the collector inlet and outlet, respectively. P_{max} is the maximum electrical power generated by the hybrid system.

The overall efficiency η_0 of the hybrid PVT collector is given by the sum of the system's electrical and thermal efficiencies:

$$\eta_0 = \eta_{th} + \eta_e \tag{3}$$

b. Exergy analysis

Exergy analysis is a crucial approach for evaluating the efficiency of a system in thermodynamic equilibrium with its environment. Electrical and thermal exergy efficiencies depend on the balance between exergy inputs (namely solar exergy and fluid flow exergy) and exergy losses (electrical exergy, thermal exergy, and exergy destruction). Solar exergy is determined from the absorbed solar radiation, while fluid flow exergy corresponds to that of the incoming cooling fluid:

$$Ex_{solar} = EA_{PV}\left(1 - \frac{T_{amb} + 273}{T_{Sun}}\right) \quad (4)$$

Where T_{amb} (in °C) and T_{Sun} (in K) are the ambient and solar temperatures ($T_{Sun} \cong 5777$ K).

The electrical and thermal exergy rates of the PVT system can be evaluated using the following expressions [28]:

$$\eta_{Ex_{el}} = \frac{Ex_{el}}{Ex_{solar}} \quad \text{and} \quad \eta_{Ex_{th}} = \frac{\dot{m}\, C_p(T_{out} - T_{in})\left(1 - \frac{T_{amb} + 273}{T_{out} + 273}\right)}{Ex_{solar}} \quad (5)$$

According to equation (3), the overall exergy efficiency of the system is the sum of the electrical and thermal efficiencies [28]:

$$\eta_{Ex} = \eta_{Ex_{el}} + \eta_{Ex_{th}} \quad (6)$$

c. Key factors influencing PVT system performance

The performance of a hybrid Photovoltaic/Thermal (PV/T) system is influenced by a complex interaction between environmental and operational variables that dictate both electrical output and heat recovery.

Environmental Factors

Local climatic conditions are the primary drivers of energy production:

- **Solar irradiance:** This is the dominant factor. High intensity increases electrical current linearly but also raises the heat input to the system.
- **Ambient temperature**: High temperatures reduce electrical efficiency, typically by about 0.4–0.5% per °C above standard test conditions**.**
- **Wind**: Wind helps to cool the PV module, increasing electrical efficiency.
- **Humidity**: High humidity reduces solar irradiance and promotes dust adhesion.

Operational and Design Factors

These factors depend on the technical choices made during installation:

- **Tilt angle and orientation**: These are critical for maximizing solar energy capture.
- **Soiling:** Dust, sand, and bird droppings can block solar radiation and reduce system performance.
- **Partial shading**: Even small shaded areas significantly reduce power output and create hotspots that may damage the cells.
- **Cooling technique:** The choice of coolant (e.g., water, air, or nanofluids) and its flow rate directly impact cell temperature and overall system efficiency.

V. Modelling and Analysis Approaches

a. Experimental Methods

Despite the growing body of theoretical and numerical studies exploring PVT system performance, there remains a significant lack of comprehensive experimental evaluations that assess real-world applicability [29]. Experimental methods are based on real measurements performed on a photovoltaic–thermal (PVT) system under outdoor or controlled laboratory conditions. In this experimental approach, several parameters are measured using different instruments, such as **thermocouples** for **temperature measurement**, a **pyranometer** for **solar irradiance measurement**, an **anemometer** for **wind speed measurement**, a **flow meter** for **measuring the fluid flow rate**, and voltage and current sensors for electrical measurements. All these sensors are connected to a data acquisition system or a data logger. Experimental studies provide accurate and realistic results and are mainly used to validate numerical and theoretical models.

b. Physics-Based Modelling

Physics-based models help to understand the thermal and electrical behavior of the PVT system and to study the influence of different parameters, such as flow rate, solar radiation, and material properties. Physics-based modelling relies on the fundamental physical equations governing heat transfer, fluid flow, and electrical conversion. These models are developed using energy balance equations, heat transfer equations, and fluid mechanics equations. In some cases, Computational Fluid Dynamics **(CFD)** is used to simulate heat transfer and fluid flow inside the PVT collector. These models are very useful for system design and optimization. However, they require simplifying assumptions and must be validated using experimental data.

c. Data-Driven Approaches

Data-driven approaches, including Machine Learning and Deep Learning, are increasingly used in PVT systems. These approaches make it possible to model phenomena that are difficult to represent using physical models, such as uncertainties and nonlinear behavior. In this method, experimental data are used to train mathematical models that can predict the performance of the PVT system without directly using physical equations. The input data typically include solar radiation, ambient temperature, wind speed, and fluid flow rate, while the outputs include PV temperature, outlet fluid temperature, electrical power, and overall system efficiency. Machine learning models are very fast and perform well when large datasets are available. However, they do not explain the physical phenomena occurring within the system and are therefore considered **black-box** models. They are mainly used for performance prediction, optimization, and real-time control of PVT systems.

VI. Challenges and Research Opportunities

The Hybrid Photovoltaic–thermal (PVT) systems face several challenges that provide opportunities for research and innovation.

Technical Limitations

PVT systems face technical challenges. One major challenge is the **heat removal efficiency** of the thermal collector, which can limit the electrical efficiency of the PV module due to increased operating temperatures. Additionally, PVT systems require proper **design and integration** of both thermal and electrical components, including fluid channels, heat exchangers, and insulation.

Cost and Profitability

Another significant challenge is the **initial investment cost** of PVT systems compared to conventional PV or solar thermal systems. The high initial cost of PVT systems, due to additional components (heat exchangers, pumps, piping), affects their profitability. Reducing costs and improving efficiency are key research directions.

Despite these challenges, PVT systems also offer significant opportunities for sustainable energy development and advanced energy management.

Sustainability

Photovoltaic-Thermal (PVT) systems enhance sustainability by generating both electricity and heat simultaneously, achieving high overall efficiencies **(60–80%)** and reducing **greenhouse gas emissions** [30].

Smart Grid Integration

In addition, PVT systems can be integrated into smart grids, enabling better energy management through real-time monitoring, demand-side control, and hybrid energy systems. This integration enhances grid stability and supports the transition toward decentralized energy systems.

VII. Conclusion

This work presents a comprehensive overview of hybrid photovoltaic–thermal (PVT) systems, covering their fundamental principles, classifications, performance evaluation methods, and modelling approaches, while highlighting their different types, working fluids, and applications in both building-integrated and industrial sectors. It also discusses the key factors affecting system performance, including environmental conditions, system design, and operational parameters, as well as their associated challenges.

The review emphasizes that PVT systems can significantly improve overall energy efficiency by simultaneously producing electricity and thermal energy while mitigating PV cell overheating. Moreover, advanced configurations, such as

PCM integration, nanofluids, and concentrating PVT, demonstrate promising potential to enhance thermal recovery and electrical output.

However, the literature analysis reveals several research gaps:

- **Underexplored advanced PVT technologies:** Systems such as PVT/PCM, CPVT, and hybrid configurations require further investigation.
- **Limited experimental validation under real operating conditions:** More large-scale and long-term experimental studies are needed.
- **Lack of optimization studies:** Few works focus on identifying optimal configurations and operating parameters for different climates and applications.
- **Limited integration with smart systems:** Real-time monitoring and smart grid integration remain insufficiently explored.
- **Need for cost-effective and scalable PVT technologies:** Further efforts are required to improve economic feasibility and large-scale deployment.

Addressing these challenges will contribute to the development of more efficient, reliable, and economically viable PVT systems, supporting their wider adoption in sustainable energy applications.

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