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A COMPREHENSIVE REVIEW ON EXPLORATION OF PHOTOVOLTAIC THERMAL TECHNOLOGY: PERFORMANCE ANALYSIS AND CONTEMPORARY ADVANCEMENTS

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Abstract

With the accelerating biodiversity loss and escalating costs of traditional sources of energy, global attention is now focused on resilient and sustainable alternatives.
Solar energy is the most affordable, clean, readily available, and ecologically friendly of the several renewable energy sources. Photovoltaic Thermal (PVT) technology is a major advancement in this field. It uses solar thermal collectors and photovoltaic (PV) cells in a synergistic way to generate electricity and collect useable heat energy simultaneously. Higher operating temperatures considerably diminish the electrical efficiency of conventional photovoltaic (PV) systems. By using a working fluid (such as water or air) to actively cool the PV cells, PVT systems solve this problem and increase electrical production while capturing waste heat. Researchers have created cutting-edge designs for heat collectors and novel PV materials to improve system performance overall.
This paper presents a comprehensive review of PVT systems, highlighting their principle of operation, material advancements, categorization (air-based, water-based, nanofluid-based systems), and the range of analytical and experimental methods employed in their assessment. Additionally, the research highlights the technical and economic benefits of PVT systems and highlights their potential for large-scale, building-integrated use. The findings validate the contribution of PVT technology toward the development of the future of sustainable, high-efficiency solar energy solutions.

Keywords: PVT photovoltaic thermal cells, Solar energy, water and air .

1. INTRODUCTION

Global population growth is leading to a rise in energy demand. The use of petroleum, natural gas, and carbon to generate heat and power raises concerns due to their finite resources and their significant greenhouse gas emissions, which contribute to global warming, air pollution, and ecosystem degradation [1]. Solar energy appears to be the most promising renewable energy source currently accessible. It is a renewable, eco-friendly, and easily available energy source. To describe circuit-based simulation for solar cells, this paper addresses the issues of allowing interaction with power converters [2]. Photothermal and photovoltaic (PV) are the two basic ways for absorbing sunlight and converting it into electrical and thermal energy. The most practical method for harnessing solar energy is photovoltaic (PV), which converts it directly into electricity. Using the photoelectric effect, energy conversion devices known as solar cells use sunlight to generate electricity. A photovoltaic system is made up of solar cells and other parts. The sun radiation is directly transformed into electrical power. With efficiency ranging from 5% to 25%, solar PV systems collect sunlight and convert it directly into electrical energy, suggesting that a significant amount of sunlight is transformed into thermal information. PV cells either absorb the remaining 80% of the solar energy or emit it into the environment [3].

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PVT systems initially emerged in the 1970s by Kern and Russell Recent developments have led to increased efficiency in PVT systems. The PVT hybrid plate solar system was widely used at the time. The system is separated into three distinct components.

Solar cells can be manufactured from many materials, such as monocrystalline Si (m-Si), amorphous Si (a-Si), polycrystalline Si (p-Si), copper indium gallium selenide (CIGS), and CdTe . Encapsulation materials used include EVA copolymer, PDMS, PET, and PVB. Thermal absorbers or receiver tubes can be manufactured from several materials, including as aluminium, copper, copper-aluminium, stainless steel, galvanised steel, and polymer [1].

2. MATERIALS

Choosing the fluid medium—which might include either water or air—for the solar thermal collector is a critical choice in PVT system design. Both options have unique benefits and drawbacks. The eco-friendliness of solar PV systems in particular makes them incredibly promising. However, one needs to take into account the trade-offs that come with each strategy. The temperature vulnerability of PV panels is a relevant challenge. A 0.5% decrease in panel efficiency occurs with even a small temperature increase above the optimal operating range. Additionally, solar cells experience thermal stress from excessive heat, which shortens their lifespan [4]. There are several forms of PVT under investigation. Because of its availability and thermodynamic qualities, water-based systems have received more attention than any other type [5].

1. AIR BASED PVT

PVT (photovoltaic-thermal) systems that are air-based use solar energy to generate electricity and heated air. However, because air has a limited thermal conductivity, their thermal efficiency is comparatively low. Because of their straightforward construction, air-based PVT systems use air to cool PV panels, which results in cheaper startup costs and simpler maintenance. An efficient way to raise an air-based PVT system's thermal efficiency is to increase the heat transfer area. Installing parallel fins in a PVT system greatly improves its thermal performance, as shown by Othman et al [6]. In a numerical study of a PVT system with vertical fins, Kumar and Rosen [7] discovered that adding such fins might increase thermal efficiency by 10% [8]. Both electrical and thermal performance are improved by using more fluid [9].

The new amorphous silicon solar air-cooled PV/T collector that was created by Huang et al. The authors compared the new PV/T collector with a traditional air-type PV/T collector and standalone amorphous silicon PV panels in order to assess the energy efficiency and useful efficiency as goals. The findings show that while the innovative PV/T collector's overall usable efficiency is higher than that of the standard air-type PV/T collector, its average thermal efficiency is lower. Furthermore, compared to freestanding amorphous silicon PV panels, the amorphous silicon air-cooled PV/T collector had a greater power generation efficiency [23]

In order to heat the air in a school classroom, Choi et al. optimised a heat recovery ventilator that was coupled to an air-type solar PV/T collector. The results of the study show that the system successfully raises the classroom's air temperature while lowering the heating pump's energy usage. At the same time, the system's PV/T power generation efficiency was improved, which improved the system's total energy-saving capabilities [23].

2. WATER BASED PVT

Water-based PV/T systems use water or water-based fluids as the coolant, circulating through channels or pipes attached to the back of the PV panel. These systems have higher heat transfer efficiency due to the greater heat capacity of water. The kind of flow and the thermal absorber's design determine a PVT system's thermal performance. Direct flow, oscillatory flow, spiral flow, serpentine flow, parallel-serpentine flow, web flow, and modified serpentine-parallel flow are among the different forms of flow, and their thermal efficiency ranges from 48% to 68%. Kazem et al. looked into how different flow configurations affected PVT system efficiency. The findings indicated that the overall efficiencies of traditional PV, web, direct, and spiral flow were roughly 7.8%, 18.5%, 28.0%, and 35.0%, respectively. After the mass flow rate exceeded 1.5 LPM, the water temperature significantly decreased. Across a range of solar radiation levels, PVT water collection efficiency generally showed an upward trend as mass flow rates increased [10]. An experimental investigation of a water-based PVT cooling agent with copper blades was conducted by Jaiganesh and Duraiswamy. The electrical efficiency was shown to have increased from 10.95% to 11.65% [12].

A unique tube-and-sheet PV/T collector arrangement has been proposed by Qin et al. They developed a

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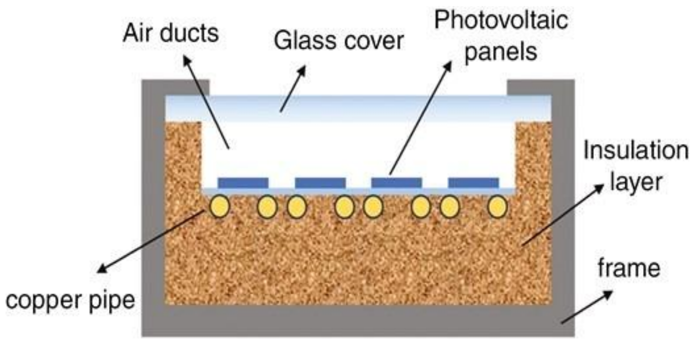
mathematical model for a system that runs simultaneously with air and water, and they integrated an air channel into a traditional tube-and-sheet PV/T collector. According to the study's findings, the PV/T collector module's overall PV/T efficiency peaked at 15 mm for the air channel's height[23]



3. HYBRID PVT WITH PHASE CHANGE MATERIAL

The goal of the hybrid photovoltaic thermal with phase change material (PVT-PCM) is to simultaneously provide thermal and electrical power. Through the use of cooling fluid and phase change material (PCM), this dual function reduces the cell's temperature. The enthalpy-porosity method is used to describe the melting of PCM [11]. By utilising its latent heat, PCM material may absorb the excess heat from the PV module and maintain the panel at a predetermined temperature for an extended amount of time. Utilising PCM has become a significant method in solar energy research due to its exceptional properties, such as its high energy storage capacity per unit of mass. Ma et al. reviewed the use of PCM in solar energy in their article [12]. The study discovered that combining phase change material (PCM) and multi-walled carbon nanotubes (MWCNTs) with a copper foam matrix (CFM) enhances the PCM's performance and effective thermal conductivity. This enhanced the PV panel's capacity to absorb heat and increased electrical efficiency, which in turn improved power generation and filling factor [13].

4. CONCENTRATED PHOTOVOLTAIC THERMAL SYSTEM

Concentrators' ability to collect solar energy directly affects a concentrating photovoltaic/thermal system's performance [14]. We can significantly reduce the space needed for PV receivers while still utilising the same amount of solar light by focusing solar radiation onto PV cells, a process known as CPV (Hmouda et al., 2022). The fundamental idea behind CPV is to use inexpensive concentrator optics in place of the more expensive PV cell material. By focusing sunlight onto PV cells, this optics enables them to absorb the same amount of solar radiation while using fewer PV receivers. The main issue with CPV technology is that concentrated solar radiation causes the PV surface to become extremely hot, requiring active cooling. Utilisation of a nanofluid spectral splitter has improved the concentrated PVT system's performance [15]. In the realm of concentrated photovoltaics, the fixed compound parabolic concentrator (CPC) is currently frequently utilised to capture solar energy. When compared to the conventional flat-plate PVT system, the CPC-PVT system delivers higher water temperatures (inlet temperature of 26.6 °C and output temperature of 70 °C) and more efficiency. Zhang et al. evaluated the thermal and electrical performance of a low-concentration CPC-PVT (LCPC-PVT) system with a geometrical concentration ratio, 4 under dual-axis tracking to that of a flat-plate PVT system. The results demonstrated that the LCPC-PVT system's thermal and electrical powers rose by a factor of 1.9–2 and 3, respectively, in comparison to the flat-plate PVT system[16].

5. BUILDING INTEGRATED PVT SYSTEM

BIPVT is a clean, green solar technology that is currently receiving a lot of attention. It generates heat and electricity using photovoltaic/thermal (PVT) modules as building envelopes. When using solar energy to generate electricity, a cooling medium cools the photovoltaic (PV) modules. It can, on the one hand, lower the temperature of PV modules, increase the efficiency of power generation, and guarantee the system's safe operation; on the other hand, the heat gathered by the cooling medium can be utilised for hot water supply, fresh air heating, and space heating, achieving energy cascade utilisation. To accomplish many purposes, photovoltaic thermal modules can be easily connected with windows, roofs, facades, shading systems, and other structures [17]. Depending on where the PVT collectors are

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installed, BIPVT systems can be categorised as roof-based, façade-based, window-based, or shading-based systems, according to Yu et al [18]. Three main factors—electrical, thermal, and optical—determine how well BIPV systems function [19]. According to certain authors, BIPVT has exceptional long-term benefits and may have a quicker investment payback period. They also expect a few chances for research and development: The PV technology's attractiveness is enhanced by its lightweight and modular design, delamination of the PV module for easier replacement and greater sustainability, integration of the BIPVT support system with the plumbing and structural support systems, smart control, and microgrid integration. Therefore, even though glass-Ethylene-Vinyl Acetate (EVA)-silicon PV currently dominates PV packaging in BIPVT systems, new and lightweight PV modules based on polycarbonate materials are being developed that appear to offer benefits in terms of reliability, installation and maintenance costs [18].

3. APPLICATIONS OF PVT CELLS

PV-T cells can be used in a variety of settings, including residential and commercial properties. This paper focus on two main uses of PVT systems: photovoltaic-thermal (PVT) systems in renewable energy and pressure-volume-temperature (PVT) cells in petroleum engineering

* Dual Energy Generation: The primary application is to generate electricity (from the photovoltaic end) and thermal energy (via the heat collector) from the same surface area. This makes PVT systems remarkably effective, with recent studies demonstrating overall efficiencies of up to 76%. Thermal energy can be used to heat domestic water, heat a space, or even drive absorption chillers for cooling [3].
* Increased Electrical Efficiency: One significant disadvantage of standard PV panels is that their electrical efficiency decreases as temperature rises. By including a thermal collector, the PVT system actively cools the solar cells, resulting in a 3-5% improvement in electrical production over a normal PV panel [3].
* Space Optimisation: PVT systems are especially useful in urban locations with limited roof space since they enable for the more compact and efficient use of a single installation to meet both energy and heating needs [3].
* Nanofluids: Some studies is exploring at the usage of nanofluids, which are fluids with suspended nanoparticles (e.g., Al_2O_3, CuO), to improve thermal efficiency and heat transfer within a system [20]
* Reservoir Fluid Analysis: PVT cells are used to simulate reservoir conditions and calculate essential fluid parameters such as bubble point pressure, dew point pressure, and viscosity. This information is critical for classifying reservoir fluids (such as black oil and volatile oil) [20].
* Enhanced Oil Recovery (EOR): One major application is to research and optimise EOR techniques. PVT cells contribute to determining the miscibility pressure for gas injection, which is an important factor in maximising oil recovery from a reservoir.
* Production and Reservoir Modelling: The information acquired from PVT analysis is critical for developing accurate reservoir models, forecasting reservoir performance, and constructing efficient production facilities [20].

4. CONCLUSION

To sum up, PVT technology is an attractive option for the future of renewable energy since it provides a small and incredibly effective means of using solar energy to generate heat and power. Even if there are still issues with material selection, pricing, and design optimisation, continuous improvements are progressively enhancing their functionality and financial feasibility. PVT systems have the potential to be extremely important in distributed energy generation and building-integrated applications, helping to create a more sustainable and energy-efficient future and perform well. Second, it is a clean technology that doesn't produce any harmful waste, such radioactive elements. In addition, the system requires less maintenance.

5. STATEMENTS & DECLARATIONS:

Use of AI Statement

The authors declare that they have not used generative artificial intelligence, specifically ChatGPT in the writing of this manuscript and/or in the creation of images, graphics, tables, or their corresponding captions

Conflict of Interest and Declarations:

Authorship contribution statement: Chinna Devi C N, Devika Rani G Shetty, Annapoorna L, Kusuma C, Ranjith Kumar S: Carrying the Experimental work, Data curation and writing the original manuscript and original draft.

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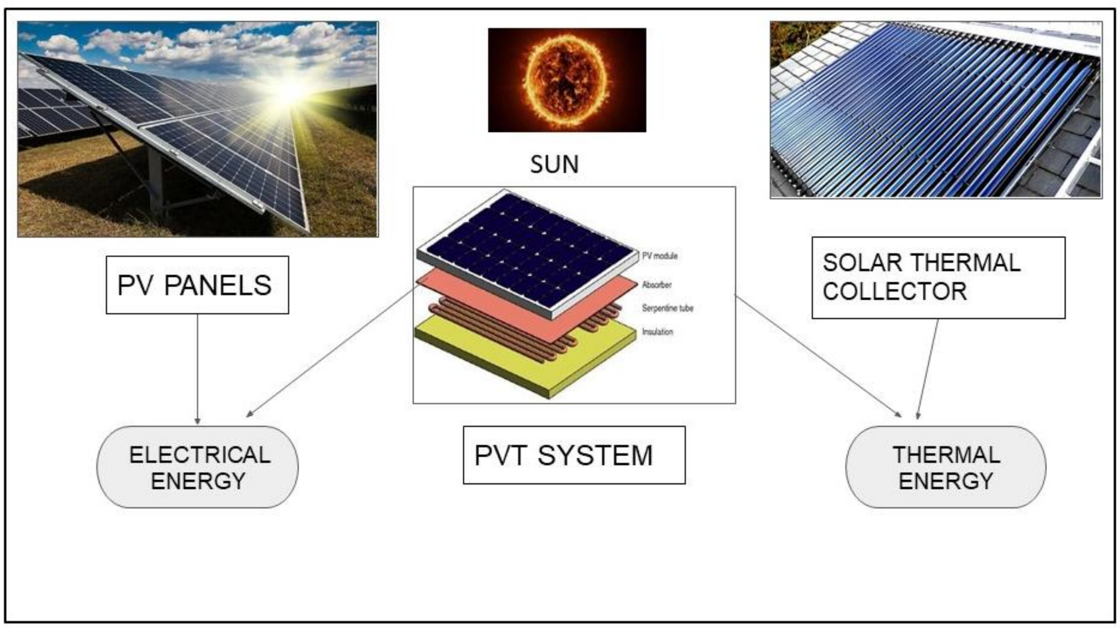
8. GRAPHICAL ABSREACT



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