

Performance Optimization of Photovoltaic-thermal (PVT) Systems: A Comprehensive Review of Design and Efficiency Enhancements

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Abstract

The desire for renewable energy solutions and the rising demand for energy worldwide have driven important developments in hybrid photovoltaic-thermal systems. Photovoltaic-thermal systems provide the advantages of both thermal energy collection and electrical energy generation as they integrate photovoltaic and thermal collectors into a single module. However, a number of variables, including system architecture, material choice, cooling systems, and ambient circumstances, affect how well they function. The goal of this article is to present a thorough overview of the important design techniques and technical developments for photovoltaic-thermal system performance optimization. Recent advancements in absorber materials, cooling strategies, and hybrid configurations are highlighted in particular, along with new studies on how to increase efficiency using spectrum splitting, nanotechnology, and sophisticated manufacturing techniques. The need for sustainable and renewable energy solutions is greater than ever as the world's energy consumption rises. Because it is abundant and environmentally friendly, solar energy is one of the most promising renewable energy solutions. Solar thermal collectors, which collect solar heat, and solar photovoltaic (PV) systems, which turn sunlight into electricity, have become popular energy-producing technologies. All of these technologies, however, have drawbacks when used in isolation. PV systems lose efficiency when the temperature of the solar cells rises, notwithstanding their effectiveness in converting sunlight into power. Conversely, thermal collectors are not able to produce energy, but they are good at absorbing heat.

Keywords: Photovoltaic, thin-film PV modules, concentrator photovoltaics, air-based thermal collectors, phase change materials

INTRODUCTION

PV-thermal (PVT) systems have become an increasingly prominent hybrid solution that combines the advantages of thermal and PV technologies into one cohesive unit. PVT systems can achieve greater total energy efficiency than standalone PV or thermal systems since they can produce electricity and heat energy at the same time. Their dual purpose makes them especially desirable for uses like industrial operations, commercial buildings, and residential structures where both heat and power are needed [1].

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Considering the benefits of PVT systems, the intrinsic trade-off between electrical and thermal efficiency makes performance optimization of these systems extremely difficult. PV cells lose efficiency

as they heat up, therefore to keep them operating at their best, efficient cooling techniques must be developed. PVT system designs also need to take into account the needs of the thermal and electrical components, which often function in distinct ways.

PVT system optimization is a complicated issue that encompasses developments in system architecture, materials, integration strategies, and cooling methods. To increase total system efficiency, researchers have concentrated on creating novel absorber materials, optimizing hybrid arrangements, and strengthening PV cell heat management. Furthermore, new opportunities for enhancements in performance have been made possible by the deployment of cutting-edge technologies including sophisticated manufacturing techniques and nanotechnology [2].

The main design gets closer technical advancements, and efficiency-boosting methods that have helped optimize PVT systems are all thoroughly reviewed in this study. This article offers a thorough grasp of how PVT systems may be improved for the generation of both electrical and thermal energy by examining present developments in cooling techniques, absorber materials, and hybrid system topologies. The study also examines new developments in spectrum splitting, nanofluids, and innovative methods for manufacturing, emphasizing how these areas of study have the potential to completely transform PVT system performance.

DESIGN CONSIDERATIONS IN PVT SYSTEMS

PV cells, which change solar energy into electricity, and thermal collectors, which take up surplus heat, are the two primary parts of PVT systems. The performance of PVT systems is influenced by many components of design.

PV MODULE SELECTION

The performance of Renewable-Thermal (PVT) systems are significantly influenced by the selection of PV modules. PV modules convert solar radiation into electrical energy, and the choice of module affects the system's thermal capacity as well as electrical efficiency since the heat produced by the PV cells must be properly controlled to avoid efficiency losses. The relationship between heat dissipation and electrical output is crucial in a PVT system, and selecting the appropriate PV technology is crucial to increasing the system's overall performance [3].

Crystalline Silicon (c-Si) PV Modules

Crystalline silicon (c-Si) PV cells, both monocrystalline and polycrystalline, are the most widely used in PVT systems due to their relatively high electrical efficiency and commercial availability.

1. *Monocrystalline silicon*: These cells are made from a single crystal structure, which allows for a more uniform arrangement of silicon atoms. This results in higher electrical efficiency, typically between 18% and 22%, but also leads to increased heat generation, as the high efficiency comes with a significant amount of waste heat. For PVT systems, this high heat generation necessitates advanced thermal management techniques, such as water or air cooling, to prevent temperature-induced performance drops.
2. *Polycrystalline silicon*: In contrast, polycrystalline cells are made from multiple silicon crystals, which gives them a lower electrical efficiency, typically in the range of 15% to 18%. While they generate less electricity compared with monocrystalline cells, they also produce less heat, making thermal management easier in PVT systems. However, due to lower efficiency, they may not be suitable for applications where maximizing electrical output is critical [4].

With a temperature correlation of around -0.4% to -0.5% per $^{\circ}\text{C}$, crystalline silicon photovoltaic cells lose efficiency as degrees rise. Thus, even if they are a desirable option for producing electricity, it is essential in PVT applications to mitigate the increase in temperatures through efficient thermal management.

Thin-Film PV Modules

Thin-film PV technologies, including cadmium telluride (CdTe), amorphous silicon (a-Si), and copper indium gallium selenide (CIGS), offer a different set of advantages and trade-offs compared with crystalline silicon cells (Figure 1).

1. *Cadmium telluride (CdTe)*: CdTe is one of the most popular thin-film technologies due to its relatively low production cost and better performance at high temperatures. The efficiency of CdTe modules typically ranges from 10% to 12%, which is lower than crystalline silicon. However, CdTe cells exhibit a lower temperature coefficient (around $-0.2\%/^{\circ}\text{C}$), meaning they experience less degradation in performance with increasing temperature. This makes them more suitable for PVT systems where heat dissipation is a challenge [5].
2. *Amorphous silicon (a-Si)*: a-Si cells have lower efficiency (typically 6% to 8%) but are less sensitive to temperature changes. They also have the advantage of better performance under low light conditions. In PVT systems, their lower efficiency may be offset by easier thermal management, as they generate less waste heat. However, for applications requiring higher electrical output, a-Si may not be the best choice.
3. *Copper indium gallium selenide (CIGS)*: CIGS modules offer higher efficiency (up to 14% to 16%) than other thin-film technologies, combined with better temperature tolerance than crystalline silicon cells. CIGS also has the potential for flexible module design, making it an attractive option for building-integrated PVT systems (BIPVT) where the modules need to conform to architectural designs. However, the higher cost of CIGS compared with other thin-film technologies may limit its widespread use.

Bifacial PV Modules

Emerging technology known as “bifacial PV modules” has the ability to collect sunlight from both the front and rear surfaces, potentially improving the total energy production. Bifacial modules in PVT systems can be especially useful in arrangements where the back of the module is exposed to extra light, such reflected sunlight from nearby buildings or the ground. As a result, more electricity may be produced without having a major effect on thermal management.

However, the integration of bifacial modules into PVT systems presents unique challenges. The rear surface may be harder to cool due to its exposure to sunlight, which could require more advanced cooling strategies [6]. Additionally, the placement of thermal collectors behind bifacial modules may block rear-side light absorption, reducing the potential electrical gain. Careful design considerations are therefore necessary to fully leverage the benefits of bifacial PV modules in PVT systems (Figure 2).



Figure 1. Thin-film PV modules.



Figure 2. Bifacial PV modules.

Concentrator Photovoltaics

Concentrator photovoltaics (CPV) concentrates sunlight onto extremely effective photovoltaic cells (PV cells) that may attain efficiencies of over 40%. These cells are often multi-junction cells. Although CPV systems provide a notable increase in electricity production, they necessitate active cooling because of the high solar concentration, which produces a considerable amount of heat. Because of the significant thermal management issues posed by the high heat concentration, CPV is less frequently employed in PVT systems. However, when cutting-edge cooling strategies are used, CPV-PVT systems can deliver exceptional performance in particular niche applications where both power and high-temperature heat are required.

Emerging PV Technologies

Emerging PV technologies, such as perovskite solar cells, offer exciting possibilities for PVT systems. Perovskites have demonstrated high efficiencies (above 20%) at low cost and can be manufactured using flexible materials, making them suitable for building-integrated applications. Additionally, perovskite cells have a lower temperature coefficient compared with crystalline silicon, which may reduce the thermal management burden in PVT systems. However, the long-term stability of perovskite cells under real-world conditions, including their degradation under heat and UV exposure, is still an area of active research, and further development is needed before they can be widely adopted in PVT systems.

ABSORBER PLATE AND THERMAL COLLECTOR DESIGN

The absorber plate and thermal collector are integral components of a Photovoltaic-Thermal (PVT) system, responsible for capturing and transferring the excess heat generated by photovoltaic (PV) cells. The design of these components directly influences the thermal efficiency of the system, which in turn affects the overall energy output and performance. The absorber plate must efficiently absorb heat from the PV module, while the thermal collector must transfer this heat to a working fluid (air, water, or other medium) for effective utilization or storage [7].

This section provides an in-depth analysis of the key factors involved in the design of absorber plates and thermal collectors, including material selection, surface treatment, fluid circulation methods, and system configurations.

Material Selection for Absorber Plates

The choice of material for the absorber plate is a crucial factor in maximizing heat absorption and minimizing thermal losses. The material must have high thermal conductivity to ensure efficient heat transfer while maintaining structural integrity and durability.

1. *Copper*: Copper is widely used in PVT systems due to its excellent thermal conductivity (around 385 W/mK). It allows rapid heat transfer from the PV module to the working fluid. Copper is highly durable and resistant to corrosion, making it suitable for long-term operation. However, the cost of copper is relatively high, which can increase the overall system cost.
2. *Aluminum*: Aluminum is another common material for absorber plates, with a thermal conductivity of about 205 W/mK. Although not as conductive as copper, aluminum is lighter and more cost-effective. Its corrosion resistance is lower, but it can be enhanced through surface treatments. Aluminum is often used in large-scale PVT systems where cost and weight considerations are critical.
3. *Steel*: While steel has lower thermal conductivity compared with copper and aluminum, it is occasionally used in PVT systems for applications where cost is the primary concern. Steel can also be treated with special coatings to enhance its heat-absorbing capabilities.

The thermal conductivity of the absorber plate material is vital for achieving efficient heat transfer to the working fluid. The faster heat is absorbed and transferred, the lower the operating temperature of the PV module, which improves its electrical efficiency.

Surface Treatment and Coatings

To maximize the thermal efficiency of the absorber plate, surface treatments and coatings are applied to enhance the plate's ability to absorb solar radiation while minimizing radiative heat losses.

1. *Selective coatings*: Selective coatings are designed to have high absorptivity for solar radiation and low emissivity, meaning they absorb most of the incoming sunlight while minimizing heat loss through infrared radiation. These coatings typically consist of multiple layers of metals and dielectric materials, optimized to absorb a broad range of the solar spectrum. Common selective coatings include black chrome, black nickel, and titanium oxide.
2. *Black paint*: While less effective than selective coatings, black paint can be applied to absorber plates to enhance heat absorption. Black paint has a high absorptivity but also a high emissivity, leading to significant radiative losses. As a result, black paint is mainly used in low-cost systems where efficiency is not the primary concern [8].
3. *Anti-reflective coatings*: It is possible to mitigate the absorber plate's surface reflectance by applying anti-reflective coatings. These coatings increase the amount of solar energy absorbed by reducing its reflection, and raises the system's thermal efficiency.

Surface treatments play a critical role in reducing optical and thermal losses. By applying advanced coatings, the absorber plate can maintain high heat absorption while minimizing the loss of captured thermal energy, leading to higher overall system efficiency.

Thermal Collector Configurations

The thermal collector in a PVT system is responsible for transferring heat from the absorber plate to the working fluid. Various configurations exist, each with distinct advantages and challenges. The choice of collector configuration depends on the application, the required thermal output, and the operating environment.

Water-based Thermal Collectors

Water-based thermal collectors are among the most common configurations in PVT systems due to the high heat capacity of water, which allows for efficient heat transfer and storage.

1. *Flat-plate water collectors*: In flat-plate water collectors, water flows through pipes or channels embedded in or attached to the absorber plate. These collectors are simple in design and are well-suited for residential and commercial applications, such as water heating and space heating. Flat-plate water collectors typically provide moderate temperature heat, making them suitable for domestic hot water applications [9].
2. *Flow channel design*: In water-based collectors, the design of the flow channels is critical for maximizing heat transfer. Parallel flow, serpentine flow, and meandering flow are common configurations. Parallel flow provides uniform heat distribution, while serpentine and

meandering flow designs increase the fluid's contact time with the absorber plate, leading to enhanced heat transfer.

3. *Heat exchangers and storage tanks:* Water-based PVT systems often integrate heat exchangers and thermal storage tanks. The heat exchanger transfers the thermal energy from the water to another medium, such as space heating systems, while the storage tank allows excess heat to be stored for later use.

Water-based thermal collectors are highly efficient at extracting heat, and their simplicity makes them cost-effective. However, water-based systems are prone to freezing in cold climates, necessitating the use of antifreeze solutions or freeze protection mechanisms.

Air-based Thermal Collectors

Air-based thermal collectors use air as the working fluid to extract heat from the absorber plate. Although air has a lower heat capacity than water, it offers several benefits, such as ease of installation, no risk of freezing, and reduced maintenance.

1. *Direct air cooling:* In direct air cooling, air is blown over the back of the PV module and the absorber plate to remove excess heat. This method is often used in passive systems where low-cost cooling is required. However, the low heat capacity of air limits its effectiveness for high-temperature applications.
2. *Active air circulation:* Active air-based collectors employ fans to force air over the absorber plate, improving heat extraction. Active systems can achieve higher thermal efficiency than passive systems but require additional energy to operate the fans, slightly reducing the overall energy gain.
3. *Duct design:* The design of the air ducts or channels plays a crucial role in air-based collectors. Larger ducts reduce pressure drop, while narrower ducts increase the velocity of air, improving heat transfer. Optimizing duct size and airflow is essential for enhancing the thermal efficiency of air-based PVT systems.

Air-based thermal collectors are often used in applications where low-cost, low-maintenance cooling is required, such as in agricultural drying or industrial ventilation systems. However, their lower thermal efficiency compared with water-based systems can be a drawback for applications requiring high thermal output.

Dual-Fluid (Hybrid) Collectors

Dual-fluid collectors use both air and water as working fluids to enhance the thermal performance of the PVT system. These systems allow for greater flexibility, as they can extract heat using either air or water, depending on the application and availability of the working fluid (Figure 3).

1. *Hybrid cooling:* Water is usually utilized in hybrid designs for high-efficiency heat extraction, while air is used for supplementary cooling or ventilation. The simultaneous use of fluids can improve overall thermal performance, particularly in regions where varying cooling techniques are required due to seasonal temperature fluctuations.
2. *Layered collector design:* Some dual-fluid PVT systems use layered designs, where water circulates in channels near the PV module, and air circulates in separate ducts at a different level. This allows the system to optimize heat extraction by using the fluid best suited to the operating conditions [10].

Dual-fluid collectors offer versatility and enhanced performance in diverse environmental conditions. However, they are more complex to design and install, leading to higher initial costs.

Heat Transfer Fluids

In addition to water and air, several advanced heat transfer fluids are being researched to enhance the thermal efficiency of PVT systems. These include the following:

1. *Nanofluids:* Nanofluids are liquids containing nanoparticles, which increase thermal conductivity and improve heat transfer rates. When used in water-based systems, nanofluids can significantly enhance thermal performance, although cost and stability are key challenges.

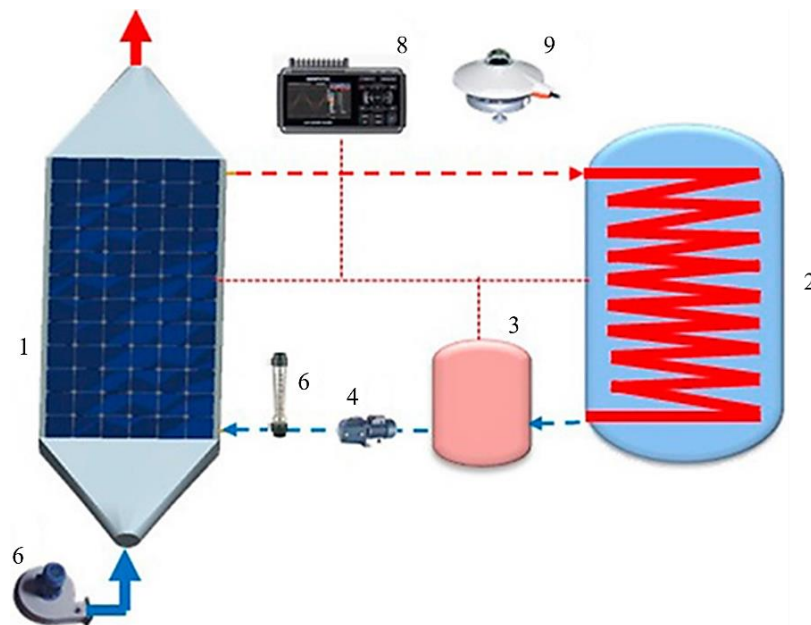


Figure 3. Dual-fluid (hybrid) collectors. (1) PV/T collector, (2) pressurized water tank, (3) auxiliary tank, (4) pump, (5) air blower, (6) flow meter, (8) data logger, (9) pyranometer.

2. *Phase change materials (PCMs)*: PCMs can store and release heat during phase transitions, such as melting or solidifying. By integrating PCMs into the absorber plate or thermal collector, PVT systems can maintain stable operating temperatures, reducing thermal fluctuations, and increasing system efficiency.

SYSTEM INTEGRATION AND HYBRID CONFIGURATIONS

There are two main formats for the integration of PV and thermal components: hybrid, which combines separate PV and thermal modules, or monolithic, which mixes PV and thermal components into a single unit. Greater system design flexibility is possible with hybrid systems, but the PV and thermal subsystems mismatched operating conditions may result in lower overall efficiency.

COOLING TECHNIQUES FOR PVT SYSTEMS

One of the primary challenges in PVT systems is mitigating the detrimental effect of heat on the performance of PV cells. Elevated temperatures reduce the electrical efficiency of PV cells, making thermal management a critical aspect of system optimization. Various cooling techniques have been developed to address this issue.

Air-based Cooling

Air-based PVT systems use air as the working fluid to cool the PV module. The simplicity of air as a coolant makes this method cost-effective, and it can be employed in both active and passive configurations. Active air cooling, which uses fans to enhance airflow, improves heat dissipation but increases operational costs. Passive cooling relies on natural convection and is less effective but more energy-efficient.

Water-based Cooling

Water-based cooling is a highly effective method for heat extraction, as water has a higher heat capacity than air. In such systems, water flows beneath the PV module, absorbing excess heat and transferring it to a storage tank or a heat exchanger. Water-based PVT systems are particularly suited for applications that require both electricity and hot water, such as residential heating and industrial processes.

Phase Change Materials

In PVT systems, PCMs have become an exclusive cooling technique. These substances retain a steady operating temperature for photovoltaic cells by absorbing latent heat during phase transitions (such as those from solid to liquid) at specific temps. PCMs may be included into the absorber plate or thermal collector and have a high thermal storage capacity. The cost and material compatibility of PCMs, however, continue to be obstacles to their adoption across industries (Figure 4).

Nanofluids and Advanced Cooling Materials

Recent research has focused on nanofluids, which are fluids containing nanoparticles, for enhancing heat transfer in PVT systems. Nanofluids improve the thermal conductivity of conventional fluids (such as water or air) by introducing metallic or carbon-based nanoparticles. This allows for better heat absorption and dissipation, leading to higher thermal and electrical efficiency.

EFFICIENCY ENHANCEMENT STRATEGIES

Improving the overall efficiency of PVT systems requires innovations not only in cooling but also in the materials and mechanisms involved in energy conversion.

Spectral Splitting

By dividing the sun, the spectrum into distinct wavelength bands, a process known as spectral splitting makes it possible to use light energy more effectively. Thermal collectors absorb infrared radiation, while photovoltaic cells (PV cells) predominantly convert visible light into energy. To minimize energy losses, spectral splitting devices utilize optical filters or concentrators that send the proper wavelengths to each component.

Nanotechnology Applications

Nanotechnology plays a pivotal role in enhancing the efficiency of both PV and thermal components. Nanostructured materials, such as quantum dots and nanowires, can be used to tune the bandgap of PV cells, optimizing them for specific spectral regions. Similarly, nanocoating on absorber plates and thermal collectors can improve heat absorption while minimizing radiative losses.

Building-Integrated PVT (BIPVT) Systems

The integration of PVT systems into building facades and rooftops, known as building-integrated PVT (BIPVT) systems, has gained traction as an energy-efficient solution for urban environments. BIPVT systems reduce the need for additional mounting structures, enhance aesthetic appeal, and improve space utilization. The key challenge is optimizing the thermal performance of these systems without compromising the building's architectural integrity.

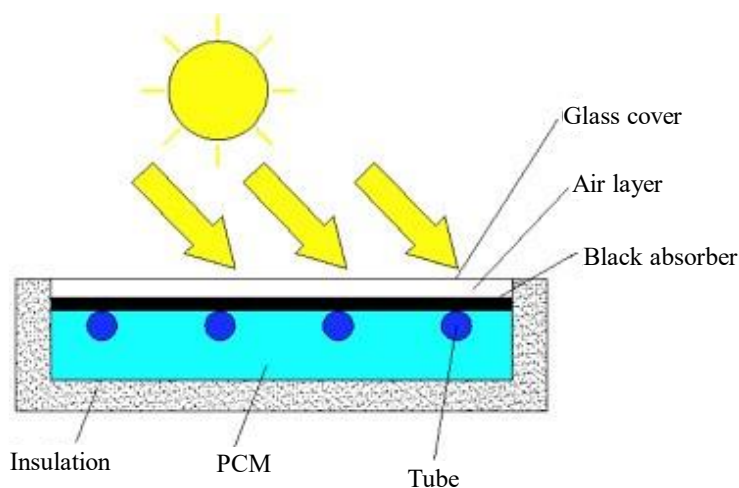


Figure 4. Phase change material.

CONCLUSION

PVT systems have a great deal of possibilities as a sustainable energy source that may satisfy the rising need for both heat and power. A multidisciplinary strategy is used to maximize the performance of these systems, incorporating developments in thermal management, material science, and system design. The creation of more effective cooling methods, the use of nanotechnology to improve performance, and the incorporation of PVT systems into smart energy grids are important topics for future study.

These technologies' capacity to consistently improve PVT system performance will be essential to furthering their economic viability and wider adoption. Lifecycle analysis and cost-cutting techniques should be the main topics of future study to make PVT systems competitive with other renewable energy sources.

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