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Review

Classification and Parametric Analysis of Solar Hybrid PVT System: A Review

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Abstract: A Hybrid Photovoltaic Thermal (PVT) system is one of the most emerging and energy-efficient technologies in the area of solar energy engineering. This review paper provides a comprehensive review of hybrid PVT systems in the context of the history of PVT, general classification, and parameter analysis. Several cell technologies with spectrum analysis are discussed to understand the application's ability and energy efficiency. Hybrid PVT concept, characteristics, and structure analysis is also discussed in this study. An extensive analysis on the classifications of hybrid PVT systems from the recent literature is also presented here. These literatures are identified based on several criteria. In order to provide a complete and energy-efficient technology, an innovative classification of the hybrid PVT system is proposed in this paper. This proposed classification is a combination and upgrade of various existing classifications mentioned in recent research studies. Parameters have a significant and unavoidable impact on the performance and efficiency of the hybrid PVT system. A brief analysis of different parameters and the optimization of the system is conducted after reviewing recent research articles. This analysis provides insights into the impact of parameter variations on the system. A novel parameter model comprising parametric and optimistic analyses is also presented in this paper. It provides a detailed parametric description that significantly affects the performance and efficiency of the hybrid PVT system. Finally, the assessment focuses on a critical analysis of the main challenges in adopting PVT technology and suggests ways to overcome these barriers.

Keywords: PVT system; classification; parametric analysis; optimization; efficiency

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1. Introduction

A crucial fact today is that the whole world is gripped by the concern of dwindling energy stocks, leading to efforts to conserve fossil fuels through the exploration of new methods and resources. The drive for conservation is not solely due to the rapid depletion of resources but also stems from the harmful impact of certain resources on the ecosystem. In addition to these factors, the prices of fossil fuels exhibit high volatility, often experiencing significant inflation [1]. Many human activities driven by energy consumption and resulting pollution have contributed to swift alterations in weather conditions, including global warming, the thawing of polar ice caps, and the depletion of the ozone layer. In the future, the issues of environmental pollution and global warming could be mitigated by the adoption of renewable energy sources like solar power, particularly those using photovoltaic (PV) technology. Solar PV technology is utilized for the conversion of light energy into DC energy for electricity. The fundamental unit of PV technology is the solar cell, which can be arranged in series and parallel connections to create a PV module.

Multiple PV modules can also be linked in series and parallel configurations to form larger PV arrays [2].

PV power plant shares have surged globally, with numerous countries now aiming to extend the utilization of alternative energy sources for generating electricity. The European Union has committed to creating a blueprint that raises the contribution of renewable energy sources in energy production to no less than 30% by 2030, with the final goal of achieving 100% by 2050 [3]. The economic and environmental advantages of PV technology have made it a highly sought-after solution for clean power generation, drawing immense interest from researchers, manufacturers, and decision-makers alike [4]. Numerous regions across the globe possess the potential to implement high-efficiency PV plants, owing to the high intensity of solar radiation in these areas. The high degree of flexibility exhibited by PV technology sets it apart from other solar applications, as it can be deployed in diverse geographical locations, ranging from deserts and plains to mountains and even marine environments. This adaptability allows it to function independently or connected to an electrical grid, thereby expediting its widespread global adoption, particularly following the decrease in manufacturing costs and the rise in electrical efficiency [5]. PV technology is increasingly favored due to its numerous promising benefits, including minimal maintenance requirements, low operating costs, a long lifespan, and a significant reduction in CO_2 emissions, thereby promoting a cleaner environment for future generations.

In 2019, a record 22% increase in the PV solar market was witnessed, while China was the world's largest market for PV during that time [6]. Additionally, in the European Union (EU), solar technology had a highly successful year in 2019 due to a rise in installed capacity, which increased by 104% compared to the previous year. The rise in installed capacity prices was linked to several factors, including the member states targets for 2020 emissions, the competitive price of solar energy, tendering and auctioning mechanisms, storage, digitalization, and self-consumption. Figure 1 shows the top 10 solar PV markets of EU27 in the assessment year 2021–2022. It shows Germany is at the top, followed by Spain, and at the end, Sweden is in the market [7].

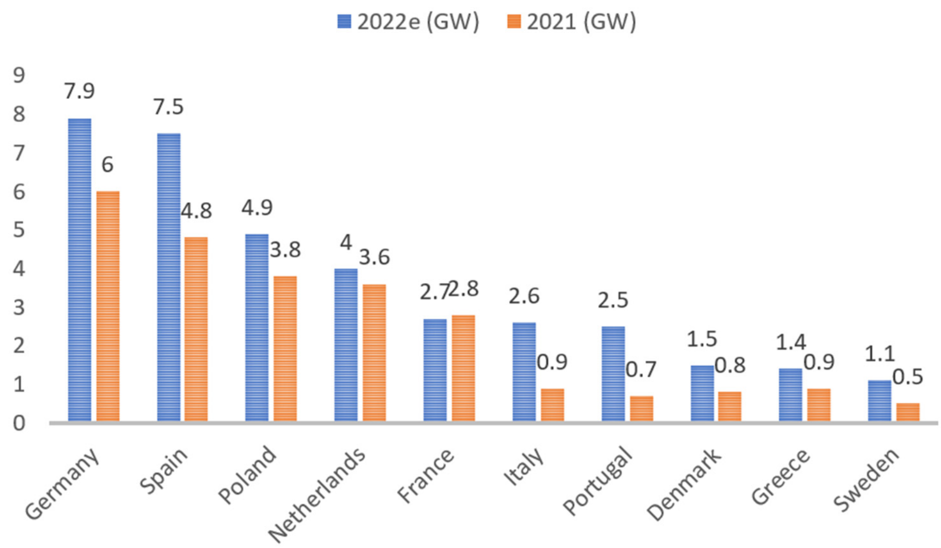

Figure 1. PV markets of top EU27 countries [7].

The capacity of electrical power generation at a PV power station is subject to variability, which is dependent on various factors such as the PV plant's location, meteorological conditions, the PV technology deployed, and the power station's capacity. Despite its numerous advantages, PV technology faces several notable challenges, including its intermittent productivity and the unpredictability of solar radiation. The fluctuations in output are primarily attributed to variations in the level of solar radiation [8] that the panel receives [9].

The integration PV plants into the existing electricity grid has led to a rise in technical challenges. One of the most crucial challenges is ensuring the stability of the power supplied either directly or indirectly. The problem starts with the solar radiation intensity and temperature fluctuations over time which hamper network reliability. In some cases, productivity disruption occurs due to environmental and seasonal issues. The considerable variations in weather conditions amplify the uncertainty of PV energy generation systems. Thus, energy storage systems are imperative for PV to mitigate fluctuations in electricity production [10,11].

The development of photovoltaic technology over the past two decades is briefly discussed in [12]. The price of solar modules decreased, which helped PV technology become more widespread. The competition seen among the manufacturers is the main reason for this cost reduction. Several types of useful products based on photovoltaic technology that produce electricity exists in the current market. A selection of silicon and non-silicon-based PV systems is briefly covered in [13]. A detailed classification of PV technologies is shown in Figure 2.

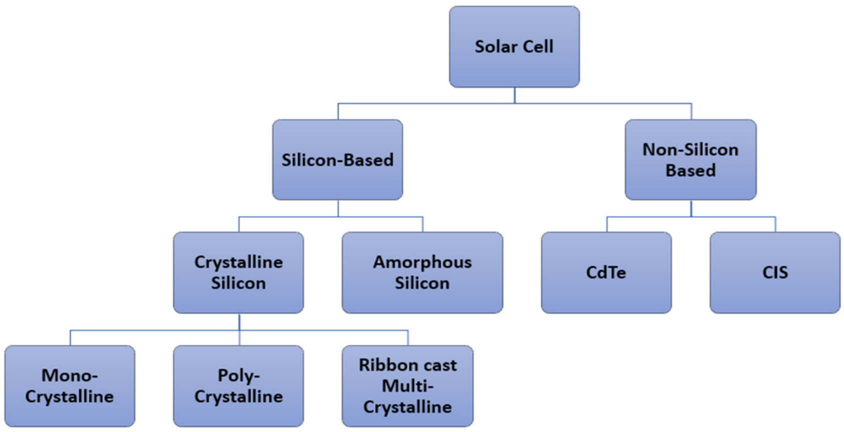

Figure 2. PV technologies classification.

In comparison to other solar cell technologies, the crystalline silicon technology is far more widely accepted due to its lower price and better performance.

According to the most recent research, multi-crystalline silicon technology can achieve an efficiency of up to 23% [14]. In the work of [15], the most recent method of photovoltaic generation and its applications are explained. Also, it evaluates the most recent studies on photovoltaic generation and its uses and integration in buildings in [16]. Additionally, cell technologies are also quite interesting in the analysis of their kinds and characteristics.

Gallium and arsenide components combine to form the composite semiconductor known as gallium arsenide (GaAs). GaAs can be alloyed with other elements, including aluminum, phosphorous, and antimony, to boost their efficiency. However, it's very high manufacturing cost makes GaAs less popular [16].

In 1991, Michael Gretel and Brian Oregano discovered Dye-sensitized solar cell (DSSC) technology. It is developed using a semiconductor, an electrolyte, and a photosensitized anode. Due to its reduced production costs, improved efficiency, and ability to react to low radiation levels, this recent technology has drawn interest. Certain dye-sensitized materials such as those based on porphyrins and polythiophene dyes are known to enhance power conversion efficiency and commercial application stability [17].

Perovskite solar cells (PSC) are being developed to produce solar cells with lower costs and higher efficiency. There are two methods to fabricate PSCs such as mesoporous architecture and thin-film architecture. PSCs demonstrate a very high power conversion efficiency, around 22.1% even though PSCs are made using a simple chemical process [18].

Organic solar cell (OSC) is the latest technology that is popular due to its low price and conversion efficiency of roughly 9%. Further improvement in efficiency is necessary for commercial application. Semiconductor fabrication requires a p-n junction while OSC requires acceptor materials and an electron donor [16].

Numerous studies have shown that the effectiveness of PV systems is associated with geographical disparities in both urban and rural areas. Variations in geographical location directly impact solar radiation strength and cause changes in wind velocity, moisture levels, dust, and the accumulation of air pollutants on PV panels. These factors lead to reduced productivity and performance fluctuations in PV systems [19,20].

The impact of climatic conditions on PV systems has been studied and analyzed in several research works. Intense sunlight exposure and high temperatures over extended periods have been found to significantly impact PV efficiency. Studies have also determined that wind has a negligible effect on panel temperature during the testing period [21]. With an increase in air temperature, there is a notable decrease in voltage and a negligible increase in current. It leads to a significant reduction in power.

The crystalline silicon technology dominates the solar cell market but thin-film or amorphous technologies are now broadly used in photovoltaic applications. Unlike polycrystalline and monocrystalline silicon-based PV cells, these technologies do not exhibit significant efficiency changes with temperature variations. However, they have drawbacks compared to crystalline silicon including shorter lifespan and limited efficiency. Producing electricity using PV technology is significantly more expensive than generating heat energy. Consequently, researchers are particularly interested in the capacity of photovoltaic applications to produce thermal energy. A major limitation of current PV technology is its inability to absorb energy across the entire spectrum. A large portion of incident light is lost as heat. It increases cell temperature and thus lowering electrical efficiency [22]. The absorption model for organic solar cells in thin-film PV technologies is shown in Figures 3–5 below [23].

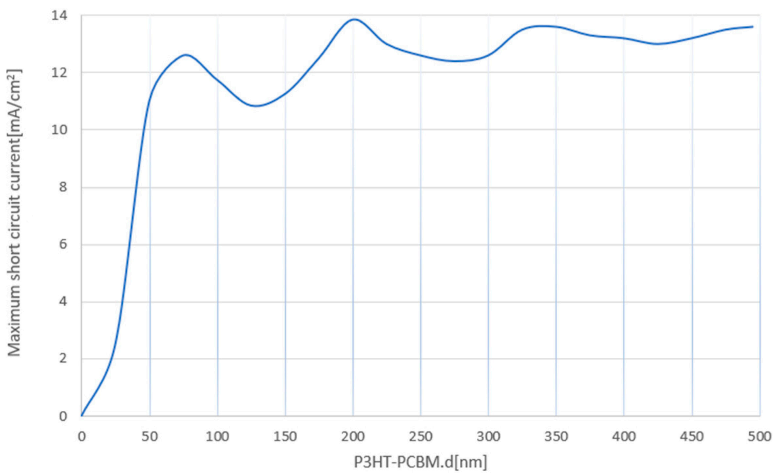

Figure 3. Absorption model for organic solar cells [23].

Several studies have found that due to high initial setup costs and lower efficiency compared to fossil fuels the advancement of photovoltaic systems is constrained. Such inefficiencies are mostly caused by the PV cells rising temperature during operation, which is primarily caused by ambient temperature, the strength of solar radiation, and the quantity of the reflected radiation. Ultimately, by taking measurements in the laboratory, these adverse effects can be drastically decreased. Research on PV systems has been effective in evolving various forms of PV cell cooling strategies as a result of these efficiency perceptions, which usually improve the output of a complete PV/T system [1].

It is required to install thermal collectors on the backside of the photovoltaic panel as it is easy to control the heating and cooling procedures. This process is required to absorb surplus heat to maintain a sufficient temperature level at the user end. The "base fluid" that exists inside the tubes of the solar thermal system collects thermal energy, which is then delivered to a container. This system has a heat exchanger in addition to the heat extraction material and a container where heat is transmitted. Its job is to separate the fluid from the rest of the system and collect it in the insulated tanks. The drive to develop a system that was incredibly effective and productive can be traced back to the early 1970s, when efforts to improve the PV/T system's performance and actively apply it started. It has been demonstrated that lowering the PV module temperature significantly raises PV's efficiency. PV/T collectors, which can produce electrical and thermal energy while converting solar energy in a single process and are sometimes thought of as hybrid systems, are nevertheless a straightforward system that incorporates PV cells and solar thermal collectors. However, improving the PV module's efficiency and coming up with a way to meet the demand for energy are what led to the emergence of a PV/T system [24].

Many different forms of study on PV/T systems have been conducted in the modern era, with an emphasis on the system's design and operation. These growing studies are a reflection of people's increased desire to use renewable energy sources wisely. As a result, more emphasis is placed on talking about and researching the thermal and electrical efficiency of this system. In addition, a significant portion of the spectrum of sunlight will be utilized, eventually resulting in the generation of both heat and power [25].

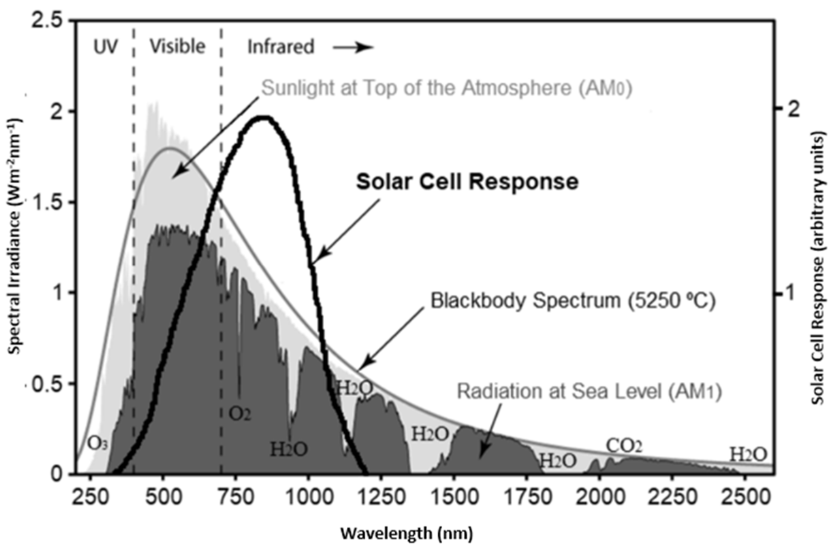

Figure 4. Silicon Solar cell spectrum and spectral response of solar radiation [26].

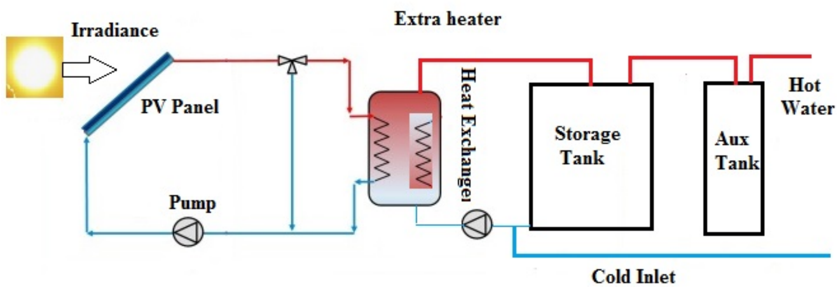

Figure 5. A constructive diagram of Hybrid PVT system.

The radiation at sea level with the sun directly overhead (0°) and the radiation with AM1 and the 5250 °C blackbody spectrum, in addition to the spectral arrangement of extraterrestrial solar radiation with an Air Mass coefficient (AM) of 0. It is important to remember that the sun's emission spectrum can be compared to a blackbody having a temperature of roughly 5800 Kelvin. The energy absorbed by airborne gases such as ozone, carbon dioxide, water vapor, and different greenhouse gases can also be explained by providing a dedicated figure.

The next part of this paper discusses the core analysis of the investigated work. Section 2 provides classifications and a hybrid Photovoltaic Thermal (PVT) system review. It also provides the PVT concept, mathematical modeling [27], and a new proposed classification in the results part. Section 3 discusses parameters and optimization analysis that reveals the parameters mentioned in the existing literature. The results analysis of this part explains the proposed parameter analysis and optimization model, and it shows several other proposed parameter models. At the end, the conclusions are described in Section 4.

2. Hybrid PVT System and Classifications

The utilization of solar power in renewable energy systems can be employed to produce electrical and thermal energy using solar PV panels and thermal panels [28,29]. In general, solar photovoltaic technology collects solar radiation and converts it into electrical energy [30,31]. On the other hand, irradiance is captured by the solar collector and converted to heat that can be used for a variety of purposes. In the middle of the 1970s, after various studies, the PVT system was discovered [32]. A liquid-type of solar collector of hybrid PVT was investigated in 1976 by observing the performance of the collector in a single-family home over the course of a full year [33]. The primary parameters of the "Hottel Whillier model" which is considered flat plate collector thermal modeling [34], are modified in [35], and the thermal performance of hybrid PVT, including electrical performance, is studied. PVT solar collectors are an idea that has been around for more than 40 years, although they have not yet reached full commercialization. Recently, different forms of research were conducted to enhance the PVT collector's functionality and reduce its cost [36–38]. PV systems are now regarded as a desirable idea that reduces reliance on traditional energy sources and is harmless to the environment.

Heat and electricity are produced by using a PVT collector, which is designed and combined with a PV cell and thermal collector. It is also known as a PVT hybrid system, which mitigates the energy losses [39,40]. While the thermal collector transforms the captured energy into heat, solar photovoltaic transforms it into electrical energy. By making the most use of solar energy, a system similar to this proposed system is also efficient and may produce more energy in a given area than thermal systems or PV alone. To better understand the construction of a PVT system, a diagram is shown in the figure below:

Figure 5 above describes an overview of the PVT system's construction, which considers mainly fluid flow mechanisms for extracting heat and cooling purposes. This system has mainly two parts: the upper and lower portions. The upper part produces electricity, and the lower part is responsible for producing thermal energy. Any type of fluid suitable for heat extraction can be used for heat extraction purposes in this type of system. The main parts of this type of system are the PV panel, heat exchanging mechanism part that could be established either by fluid or any other heat extraction medium, active/passive flow, extracted heat storage, output inlet, and so on. A developed and updated mechanism of the concept of the PVT solar system is shown in Figure 6.

One of the main purposes of using a hybrid PVT system is to create an efficient system and maximize solar energy extraction. Comparing PVT to traditional PV or thermal collectors, PVT uses less space. In other words, PVT can create greater power and heat in the same space than a normal PV panel or thermal collector can. This clarifies that PVT functions more effectively than when two systems are utilized independently. It is also suitable for places with a smaller surface area. Additionally, the PVT system integrates into one, which lowers the cost of installation and has a short payback period, and both technologies are combined [39].

PV modules usually appear in a variety of system architectures, including grid-connected, standalone, hybrid, and tracking systems. PV panel/module, battery, charge controller, maximum power point tracker (MPPT), and inverter are the typical elements of a PV system. PV has gained popularity over time and is now utilized in numerous applications. On the other hand, PVT systems are predicted to be a reliable and significant source of energy in the very near future, though there are existing plants that are not so efficient yet. Many research investigations indicate that high temperatures decrease a PV system's open-circuit voltage, which lowers electrical efficiency [41,42]. The integration of cooling systems will help reduce the temperatures, increasing the PV system's overall effectiveness. Additionally, it helps to recover the lost energy of the system. Air, water, and both air and water can be utilized in PVT systems for cooling purposes.

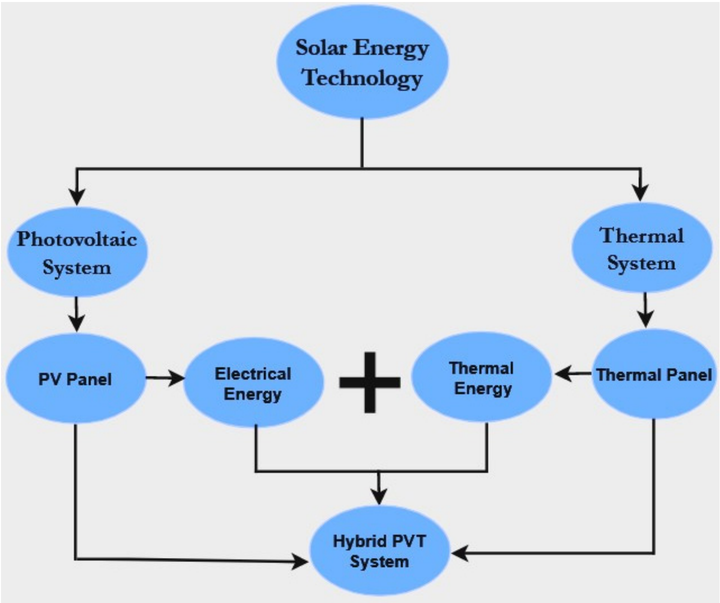

Figure 6. Hybrid PVT system concept.

It is important to indicate the cost of the main system to identify the PV system's low-cost properties. To calculate the electricity value in relation to the heat received from the collector, it is necessary to estimate the PVT system's efficiency. The hybrid system's overall efficiency surpasses that of any single PV system due to waste heat recovery [43]. PVT systems are still in the early stages of development, despite the fact that research into them began in the 1970s, and this system will be a productive and efficient substitute for individual photovoltaic systems because of their greater output power and possibly lower expenses. Considering the available spaces on the rooftops, R&D is concentrated on the integration of PV systems with buildings. The main objectives are to identify PVT systems that generate thermal energy and electricity at reasonable and cheap costs. This implies that the system's overall cost will be as low as achievable. This objective can be achieved by employing an optimal system with an appropriate vision, design, and quantified production for cost reduction. In addition to all of this, the system needs to be made to fit in with the architectural style of the buildings, creating attractive geometric shapes [44]. The following are PVT systems main advantages [2]:

- A distinct portion of the solar spectrum is used by both photovoltaic and thermal collectors.
- The visible light portion is used by the solar cell, and infrared waves are used by the collectors.
- Combining the two technologies in a tandem solar cell could lead to a more efficient use of the solar spectrum.
- By employing this system, the installation costs will be split between both systems and lower the overall cost compared to the separate systems, which will reduce the total costs, and this is the most significant benefit. Additionally, it requires less space for installation.
- The PVT system's additional advantage is that it reduces the building temperature during the summer by improving surface shading and building isolation. Finally, the

architecture of the buildings will be beautiful because of the use of PVT rather than two separate systems.

Based on the information provided above, PVT systems are important because they have the potential to produce higher electrical energy, including the compensation of thermal losses using other thermal applications.

The overall performance of the PVT system is determined by its total efficiency [45]:

$$\eta_{Total} = \eta_{Thermal} + \eta_{Electrical} \tag{1}$$

Thermal efficiency by considering PVT as a flat plate solar collector is:

$$\eta_{Thermal} = \frac{Q_{Useful-Heat}}{I_s \times A_{Collector}} \tag{2}$$

The system useful heat is evaluated as:

$$Q_{Useful-Heat} = \dot{m} C_p \Delta T \tag{3}$$

where $\dot{m}$ is the used fluid's mass flow rate, C_p is fluid's specific heat, ΔT is inlet and outlet temperature difference. In conventional form, the electrical output efficiency is computed as follows:

$$Q_{Electrical} = \frac{I \times V}{I_s \times A_{Collector}} \tag{4}$$

where, voltage V, current is I, I_s is the intensity of solar irradiation, $A_{Collector}$ is the area of PV panel. Further, the produced thermal energy in the PV module may be utilized, the varied electrical efficiency based on panel temperature is shown as:

$$\eta_{Electrical} = \eta_{ref}\left(1 - \beta\left(T_{PV} - T_{ref}\right)\right) \tag{5}$$

where, β is the coefficient of temperature, T_{PV} is the module temperature, T_{ref} is the reference temperature, η_{ref} is reference efficiency. These equations are used to calculate the efficiencies of the thermal and electrical of the panel. These equations became more complex with the advancement of mathematical and numerical modeling which includes more variables.

In the first part of this section on hybrid PVT systems and classifications, a general description, and the existing literature review are discussed. The construction diagram of the PVT system shows the design and parts associated with the PVT system. The combination of thermal and photovoltaic technology in the hybrid PVT system offers notable consequences for sustainable energy solutions. This description will help to better understand the constructive analysis of the PVT system. A developed PVT system block diagram is proposed, which will provide a clear idea to the researchers regarding the PVT system mechanism. Later on, the main advantages of PVT systems are also discussed, which will provide better energy management and encourage more devotion to the development of PVT systems. Finally, a mathematical model of the PVT system was also discussed, which helped to better understand and optimize the PVT system's overall performance.

2.1. PVT Classification

There are several existing ways to classify PVT systems. For the classifications, a numerous research study was conducted, and literature review was performed. The selected publications were analyzed and collected from the years 2010–2023. The following Figure 7 shows the yearly view of the selected articles for the classification purpose, which is shown in Table 1.

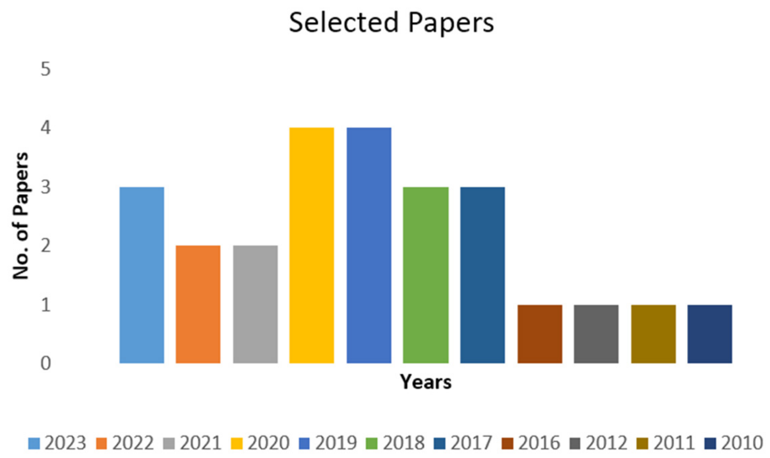

Figure 7. Studied papers yearly view for classifications.

Table 1. Classification of Hybrid PVT system.

Reference	Year	Classification	Types
[46]	2023	PVT Systems	• Air-based • Water-based • Bi fluid-based • Heat-pipe-based • PCM-based
[47]	2023	PVT Collectors	• Air-based collectors • Liquid-based collectors • Heat-pipe collectors • Dual air-water collectors • Building-integrated collectors • Concentrated collectors
[48]	2023	PVT System	• Absorber material • Absorber Configuration
[49]	2022	PVT Collector	• PV cell • Solar thermal collectors • Type of glazing • Working fluid
[50]	2022	PVT Collector	• PV Cell Type • Glazing • Heat Extraction Medium • Absorber • Collector
[51]	2021	PVT Collector	• Air-based PVT • Liquid-based PVT • Air and Liquid-based PVT • Concentrated PVT • PCM-based PVT
[52]	2021	PVT Systems	• Flat-plate PVT system • Concentrator type PVT system • Novel PVT system
[39]	2020	PVT Collectors	• PV Cell • Solar Thermal Collector • Working Fluid • Glazing • Thermal Absorber
[53]	2020	BIPVT	• Air base BIPVT • Water Base BIPVT • Hybrid BIPVT

Table 1. *Cont.*

Reference	Year	Classification	Types
[54]	2020	PVT Systems	• Air-based PVT • Water-based PVT • Air and water-based PVT • Nanofluid-based PVT • Concentrated PVT
[55]	2020	PVT System	• Conventional Systems i. Air ii. Water iii. Concentrator iv. Bi-fluid • Novel-based Systems i. Refrigerant ii. Nanofluid iii. PCM • Heat Pump
[56]	2019	PVT System	• Collector type • Coolant type • Material type
[57]	2019	PVT System	• Module type • Coolant type • PV material type
[58]	2019	PVT Collector	• Flat-plate PVT • Concentrator type PVT • Novel PVT
[59]	2019	PVT System	• Air PVT • Water PVT • Refrigerant PVT • Heat pipe PVT • PCM/PVT • Nanofluid PVT • Air and water PVT
[60]	2018	PVT Systems	• Medium of heat extraction • Type of heat extraction • Type of solar input • Systems configuration
[61]	2018	PVT System	• Collector design type • Type of PV • Working Fluid Type • Fluid flow type • Panel covered type
[62]	2018	PVT System	• Flat plate liquid • Flat plate air • Concentrator • Vacuum tube
[63]	2017	PVT Collectors	• Collector type • Coolant type • PV material type
[64]	2017	PVT System	• Conventional PVT systems • Novel PVT Systems
[65]	2017	PVT Collector	• PVT Water Collector • Combination of water and air • Air Collector

Table 1. *Cont.*

Reference	Year	Classification	Types
[66]	2016	PVT System	• Thermoelectric-based PVT • Air-based PVT • Water-based PVT • Air and water-based PVT • Refrigerant-based PVT • PCM-based PVT • Heat pipe-based PVT • Concentrated PVT
[67]	2012	PVT Collectors	• Liquid PVT collector • Air PVT collector • PVT concentrator
[68]	2011	PVT Collector	• AIR Collectors i. Unglazed ii. Glazed iii. Single pass iv. Double pass v. Channel flow • Water Collectors i. Unglazed ii. Glazed iii. Round tube absorber iv. Square/rectangular v. tube absorber vi. Sheet and tube • Channel flow
[69]	2010	PVT Products	• Liquid PVT collector • Air PVT collector • Ventilated PV with heat recovery • PVT concentrator

The above figure shows that most of the papers were from 2020 and 2019, and so on. In the recent years, like 2023–2021, we studied seven papers for analysis purposes based on the kinds and classifications of PVT systems. These papers discussed the PVT systems/collector's classification based on various parameters. After performing an extensive literature review, we structured the following table for the classification of hybrid PVT systems:

Table 1 shows several classification types described in several research papers. After analysis, it was found that the authors classified the PVT systems based on several criteria. For example, classification obtained based on heat extraction medium is shown in [46–48,51,53–55,59,62,65–67,69], classification based on the overall system's is discussed in [39,49,50,57,60,61,63,64], and classification based on the PVT system's design is shown in [52,56,58,68]. The overview of different criteria of classification discussed in the papers is shown in Figure 8.

The above figure shows all the classification criteria used in the investigated research papers. After analyzing this summary, it was determined that there are three major criteria considered: Heat Extraction Medium, the system's overall classification and the PVT system's design. The summary also shows that the maximum of thirteen papers among the twenty were discussed to obtain classification based on Heat Extraction medium and then eight on the System's overall classification. Finally, the four papers were classified based on the PVT system's design. The literature review implies the lack of a complete and efficient PVT classification system, as no classification method is provided or discussed in any of the literature that provides a complete and detailed analysis. By considering that, we proposed a better and upgraded classification system, which is shown in Figure 9 below.

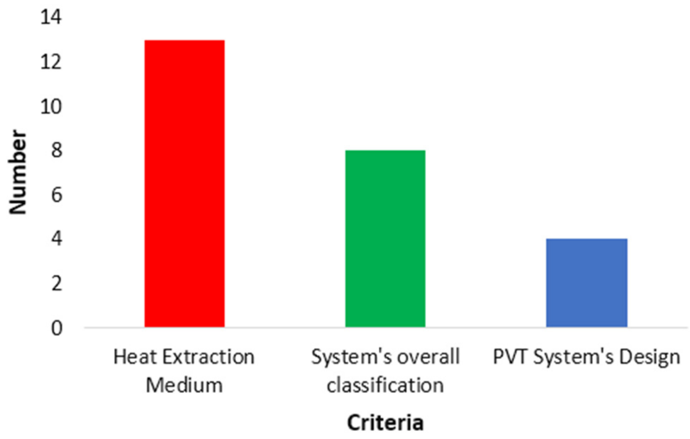

Figure 8. Criteria of PVT system's classification.

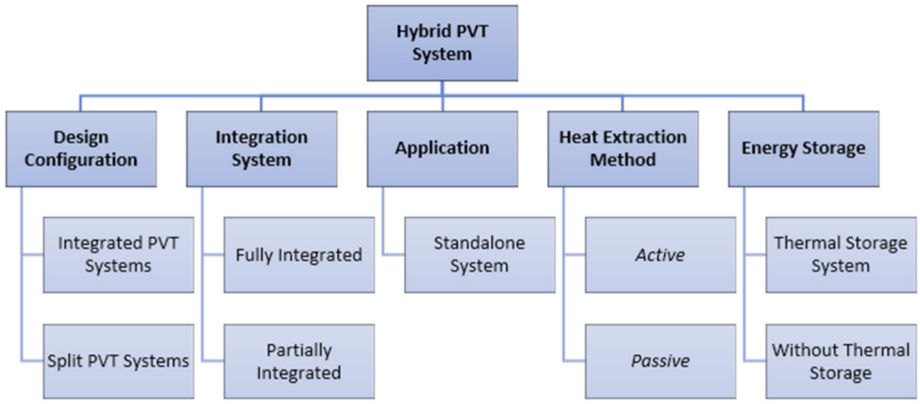

Figure 9. Classification of Hybrid PVT system.

2.2. Results

Our proposed classification of hybrid PVT system mainly consists of design configuration, integration system, application, heat extraction method, and energy storage. It also shows the subparts of this classification. It provides a complete overview of the hybrid PVT system. In this classification, the heat extraction method is the most important and extensive part. It consists of several other subparts, which are shown in the figure below.

The above Figure 10 describes the PVT system's classification based on possible heat extraction medium/method that could be used in the system. It is proposed two types of heat extraction method in the classification which is active and passive. In active heat extraction method, there are several types like heat exchangers mechanism, heat pump, active PCM, thermal energy storage, thermos electric generator, active air heating, direct fluid flow control, desiccant-based system, combined heat and power system, selective active coatings, and nanostructured materials. On the other hand, passive type includes natural convection, natural ventilation, radiative cooling, PCM cooling, thermal mass, natural evaporative cooling, thermal fins, and heat sinks.

This part discusses PVT classification and the chosen method, including criteria for classifying the hybrid PVT system. Firstly, it describes the research paper chosen by year, which shows the most recent literature review on classification. The significance of PVT classification and the chosen technique, with a particular emphasis on the classification criteria for hybrid PVT, will provide scope to the researcher in the designing and modeling of PVT system. The study's significance is found in its attempt to improve comprehension through current data, which serves as a basis for precise and pertinent classification standards. After analyzing numerous PVT types from recent research, a simplified and summarized classification technique is described. This effort seeks to simplify intricate data into a more manageable structure, offering an accessible and useful method for classifying hybrid PVT systems. Finally, an innovative and developed classification structure is proposed with an emphasis on heat extraction methods. The contribution improves comprehensiveness and makes it simpler to apply technologically updated PVT technologies found in recent investigations.

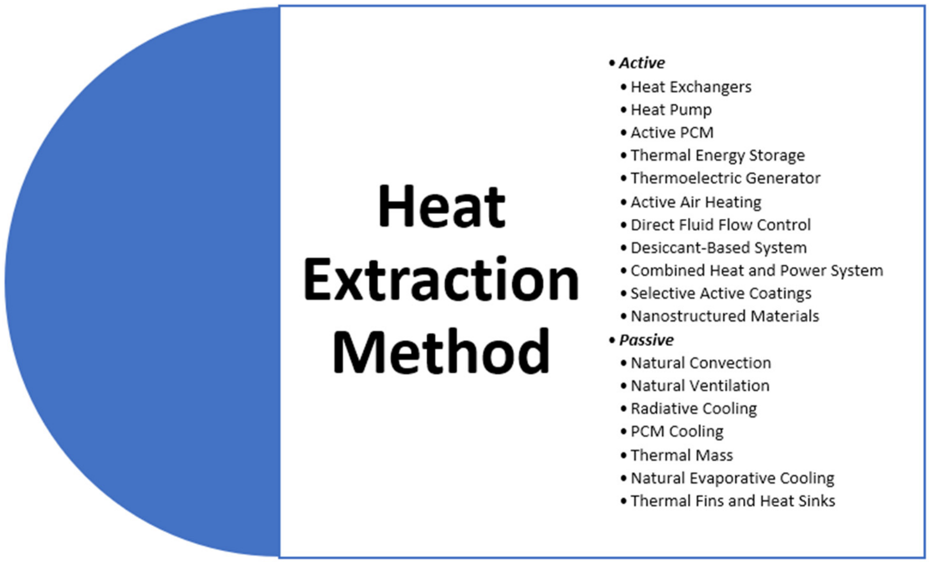

Figure 10. Heat Extraction Method classification in Hybrid PVT system.

3. Parameters and Optimization Analysis

Parameter analysis and optimization of hybrid PVT systems are inherent to performance evaluation. Many of the research papers on hybrid PVT systems discuss parametric and optimization systems to obtain better performance. A parametric study provides a deep understanding of the various parameters related to the performance of hybrid PVT [67]. Parameters associated with channel size, mass flow rates, and heat exchange resistance to both ambient and channel air flow are discussed in [68]. The performance of a PVT system based on various regimes of flow is discussed in [69]. The performance analysis of the PVT system includes the examination of a substantial paper from reputable publishers. An overview of the analyzed articles is shown in the figure below:

The above Figure 11 shows the yearly view of the selected articles for the analysis. It reflects that most of the paper is selected from the year 2023, which is eight, then 2019, and so on. Table 2 shows the summary of the performance analysis obtained after an extensive review of the above-mentioned research papers.

Figure 11. No. of studied articles by year.

Table 2. Parametric and Optimization analysis of Hybrid PVT system.

Reference	Year	Analysis Topic	Parameters
[67]	2023	Parametric	• Mass flow • Channel thickness • Air velocity • Wind speed
[47]	2023	Optimization	• Geometric parameters • Operating conditions
[68]	2023	Parametric	• Air temperature • Solar insolation • Wind speed • Micro-channel heat pipes • Packing factor • Glazing cover • Mass flow rate
[69]	2023	Parametric	• Design parameters • Different flow regimes
[70]	2023	Parametric	• Meteorological parameters • Temperature evolution
[71]	2023	Parametric	• Fluid and air velocities • Fluid channel diameter • Receiver side length • Thermal conductivity
[72]	2023	Parametric	• Temperature • Different fins shapes
[73]	2023	Parametric	• Climatic parameters • Geometric parameters
[74]	2022	Parametric	• Solar irradiance • Wind speed • Nanofluid type • Volume concentration • Flow rate • Dust • Humidity • Ambient temperature
[75]	2022	Optimization	• Geometric parameter
[76]	2021	Optimization	• Position • Ambient temperature • Irradiance • Humidity • Dust
[52]	2021	Optimization	• System design • Environmental conditions
[77]	2021	Parametric	• Design parameters • Boundary conditions
[53]	2021	Parametric	• Design parameters • Weather conditions
[78]	2021	Parametric	• Cell temperature • Solar irradiation • Incidence angle • Electrical losses
[79]	2020	Parametric	• Different parameters • Air temperature • System voltage/current

Table 2. *Cont.*

Reference	Year	Analysis Topic	Parameters
[1]	2020	Parametric	• PV cells • Thermal collector • Cooling type and efficiencies
[22]	2020	Optimization	• Packing factor • Air mass flow rate • Glazing • Wind velocity • Coolant temperature
[80]	2020	Parametric	• Irradiance • Ambient and module temperature • Wind speed • Humidity • Shading, dust • Design parameters
[81]	2020	Parametric	• System parameters
[82]	2020	Parametric	• Design parameters • Electrical parameters • Thermal parameters
[57]	2019	Optimization	• Design parameters
[58]	2019	Optimization	• Design parameters
[56]	2019	Optimization	• Design parameters
[83]	2019	Parametric	• Geometric parameters • Meteorological parameters • Thermal parameters
[84]	2019	Optimization	• Design parameters • Meteorological parameters • Incident parameters
[85]	2019	Parametric	• Design parameters • Electrical parameters
[58]	2018	Optimization	• Design parameters
[40]	2018	Optimization	• Design parameters
[86]	2018	Optimization	• Meteorological data • Electrical parameters
[87]	2018	Parametric	• Heat transfer • Thermal capacity
[61]	2017	Optimization	• Design parameters • Meteorological parameters
[60]	2017	Optimization	• Natural parameters • Design parameters
[2]	2017	Optimization	• Technological parameters • Location • Weather parameters • System configuration • Thermal parameters
[34]	2016	Parametric	• Density • Thermal conductivity • Heat capacity • Irradiance • Velocity
[88]	2016	Parametric	• Electrical parameters • Thermal parameters

Table 2. *Cont.*

Reference	Year	Analysis Topic	Parameters
[89]	2016	Parametric	• Solar irradiance • Ambient temperature • Phase change material
[90]	2015	Optimization	• Meteorological parameters • Solar radiation • Temperature • Heat transfer coefficient
[37]	2015	Parametric	• Global radiation • Wind speed • Temperature
[91]	2014	Parametric	• Design parameters • Mass flow rate
[92]	2013	Parametric	• Packing factor • Mass flow rate • Efficiency • PVT Materials
[93]	2013	Parametric	• Operating temperature • Design parameters
[66]	2010	Parametric	• Mas flow rate • PV/T dimensions • Air channel geometry
[94]	2010	Optimization	• Design parameters
[95]	2010	Parametric	• Design parameters

Table 2 shows the parameters and optimization properties mentioned in the recent literature. From the described Table 2, we summarized the obtained analysis as follows.

Figure 12 shows the classification of summarized topics described in the studied research papers. From this figure, it can be seen that most of the authors chose to depend on parametric analysis to evaluate the efficiency of hybrid PVT systems; on the other hand, many of them chose to evaluate parameters with the optimization method. Parametric analysis also varies from author to author. For example, many authors focused on only climatic parameters; others focused on design parameters [69] or meteorological parameters [70], and a few of them described both climatic and geometric parameters. Fluid flow with air velocities, including its shape, is studied in [71]. The author of [72] focused on temperature and the different fin shapes of the system.

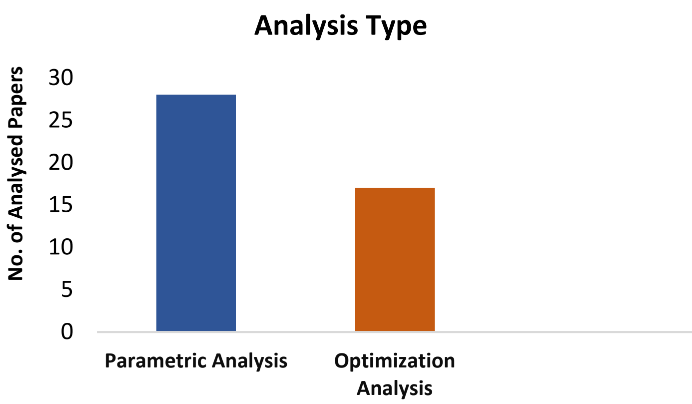

Figure 12. Classification of obtained analysis.

The author [74] focused on specific parameters for the evaluation purpose. Optimization based on geometric parameters is considered in [75]. In addition to climatic parameters, it is considered the position of the PVT system for the performance analysis [76]. Parametric analysis with design parameters and weather conditions is discussed in [53]. Incidence angle and electrical losses with climatic parameters are studied in [78]. Air temperature is another important parameter in the analysis of hybrid PVT system performance, which is discussed in [79]. For that purpose, many authors [1,22] considered active or passive colling for the efficiency increase. Design parameter optimization is given importance for the performance evaluation purpose in [56–58].

A photovoltaic thermal system has both electrical and thermal output, where thermal output is obtained using a heat transfer mechanism. In the parametric analysis case, heat transfer and thermal capacity are considered in [87]. The authors of [85] simply studied electrical and thermal parameters related to the PVT system. Phase change material (PCM) is used for heat extraction purposes, which are discussed in [89]. The packing factor and mass flow rate [90] of the heat extraction fluid are also important for the efficiency calculation. Design parameters [93–95] are analyzed in many papers, which shows an impact on the performance of the hybrid PVT system.

Results Analysis

The research review shows that researchers studied and analyzed a vast number of parameters for optimization of performance evaluations and efficiency analysis. After obtaining all this information, we summarize the following responsible parameters for parametric and optimization of hybrid PVT systems:

Figure 13 shows the proposed parameters for obtaining an efficient and optimized hybrid PVT system. We considered two types of analysis: based parametric analysis and optimization study. Among the significant parts of the parametric analysis are geometric parameters, geographical parameters, external/climatic parameters, meteorological parameters, and internal parameters. A short overview of these parameters is given in the next part. The parameter in the geometric part is described as:

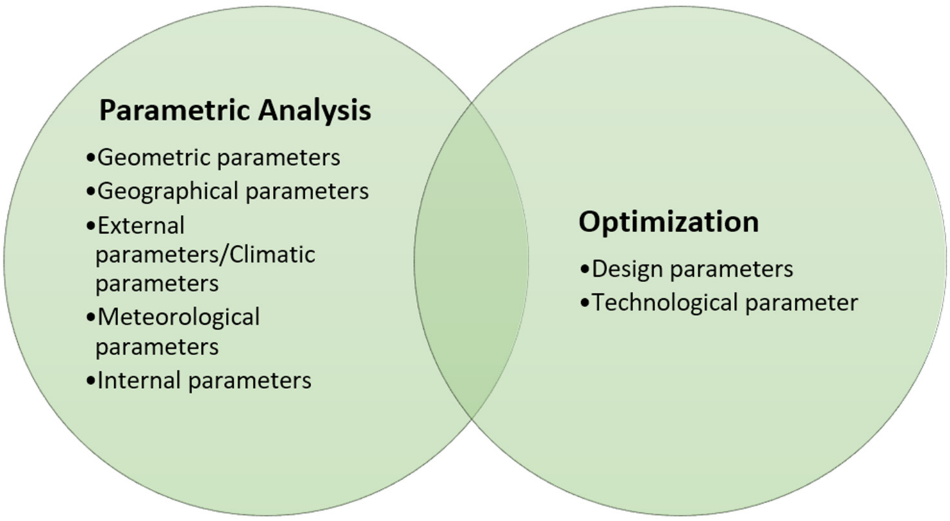

Figure 13. Proposed parameters for analysis and optimization.

Geometric parameters are the primary parameters considered for the construction of a hybrid PVT system, and they have an influence on the overall output. Mainly, we considered PVT panel shape, storage tank size, shape of the heat exchange, channel thickness, fin shapes, and air channel geometry as the geometric parameters which is shown in Figure 14.

Figure 15 shows the geographical parameters of the hybrid PVT system, which mainly consist of latitude and longitude, incidence angle, location, etc. These parameters are also responsible for the overall efficiency of the photovoltaic thermal system.

Climatic parameters are also known as external parameters, which are one of the most important parametric branches of the hybrid PVT system. The main parameters of this branch are solar irradiance, air temperature, air velocity, and wind speed are classified in the above Figure 16. Among these parameters, solar irradiance has the most significant impact on the photovoltaic thermal system's overall output.

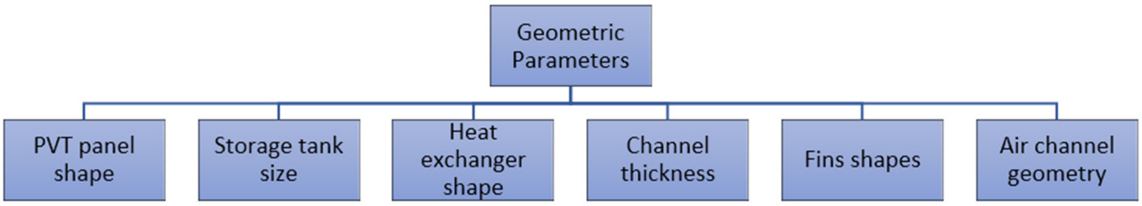

Figure 14. Geometric parameters of hybrid PVT system.

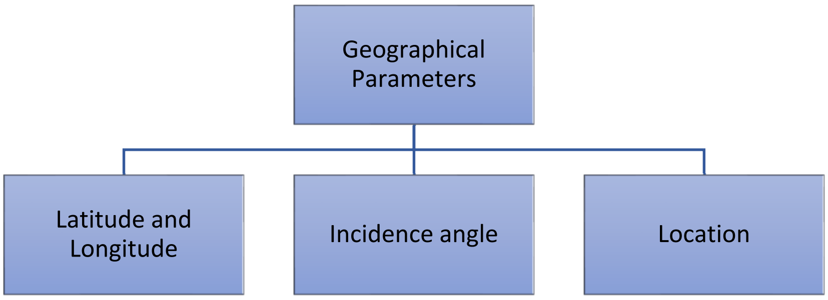

Figure 15. Geographical parameters of hybrid PVT system.

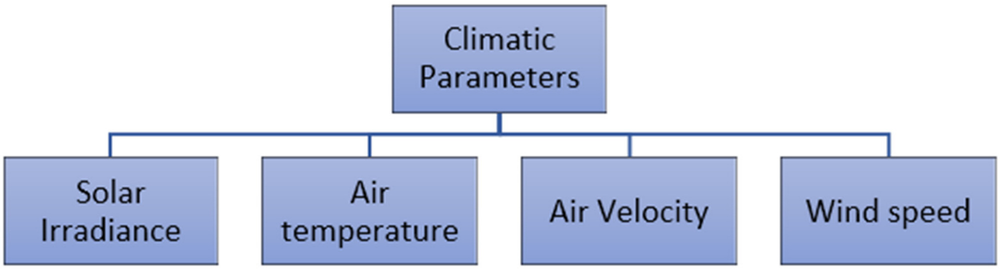

Figure 16. Climatic parameters of hybrid PVT system.

Meteorological parameters that have an effect on the efficiency of hybrid PVT systems are air mass, dust and pollution, humidity, rain, snow, cloud cover, and albedo are classified in the above Figure 17. These parameters typically influence the overall output of the system.

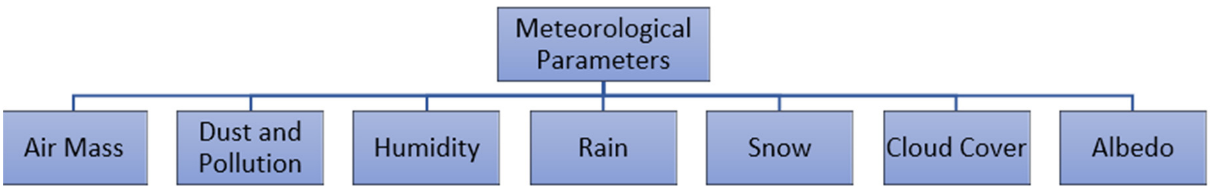

Figure 17. Meteorological parameters of hybrid PVT system.

We already discussed many of the parameters that have an impact on the performance of the hybrid PVT system. These parameters are almost the external parameters of the PVT system, but there are many parameters that have a huge influence on the overall efficiency of the energy output that are considered internal parameters.

Internal parameters of a hybrid PVT system is classified in the above Figure 18 consist of electrical characteristics or losses, thermal characteristics, mass flow rate, fluid types, packing factor, system voltage/current, thermal conductivity, and so on. Internal parameters also have an influence on the hybrid PVT system.

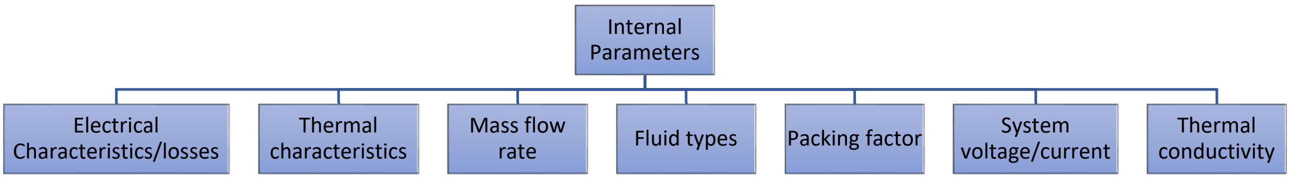

Figure 18. Internal parameters of hybrid PVT system.

In the above, we explained the parametric impact of a hybrid PVT system. Now we will consider the optimization parameter of a hybrid PVT system to understand the influence and efficiency relationship. Optimization parameters are divided into two main parts: design parameters and technological parameters are shown in the Figure 19.

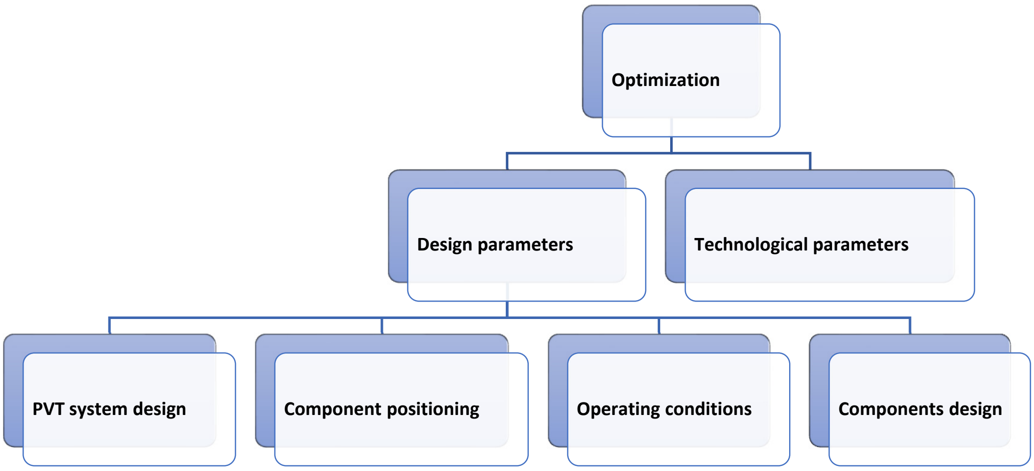

Figure 19. Optimization parameters of hybrid PVT system.

Design parameters are one of the main components of the hybrid PVT system. It consists of the design of PVT systems, the positioning of the components, the operating conditions, and the design of several important components.

This section describes significant optimization parameters that influence the PVT system's performance. Mainly, it will show the importance of PVT parameter dependency in analysis and optimization. Based on the analysis, the recent literature study describes that the performance of PVT relies on parametric and optimization studies. The classification summary proposed by the analysis will provide a clear picture of PVT performance and optimization parameters to the people, which will help them choose the appropriate parameters for the optimized design of the PVT system.

In this result analysis part, the proposed parameter model with parametric classification is discussed. It will offer an in-depth and realistic method for improving hybrid PVT systems. Through a comprehensive analysis of several variables, including geometric, geographical, meteorological, external/climatic, and internal aspects, the paper proposes a design and optimization roadmap for hybrid PVT systems. This strategy is essential for the implementation of practical PVT systems, as it may improve performance and overall efficiency under various environmental [96] circumstances.

The optimization part addresses optimizing the performance of PVT systems by taking into account technological and design factors. The importance of optimizing parameter studies in improving PVT performance for optimal system design has been emphasized in recent publications, and it is the motivation for focusing on and analyzing optimization parameters. This proposed classification will help in understanding and optimizing design and technical parameters for maximizing the PVT system's performance.

4. Discussion

This work studies, analyzes and proposes a review of hybrid PVT systems in the context of classification, parameters, efficiency, and performance evaluation. Existing research works related to photovoltaic, PVT, and thermal systems are also studied to have a clear concept in the area of solar energy engineering. This paper focuses mainly on the classification concept, methodologies for classifying PVT systems, and criteria considered to obtain this type of classification. The importance of the classification part is to propose a robust, efficient classification system so that it can mitigate the gap in the previous research. Additionally, to enhance the capacity of the researchers in the point of classification analysis. In another section, different internal and external parameters and optimization parameters of the hybrid PVT system are studied. At the end, an important and effective parametric model is proposed to enhance the efficiency and output of the solar hybrid PVT system. We discussed and analyzed the parameters related to both internal and external. Heat extraction medium is considered one of the most important elements of the hybrid PVT system. In the scope of our future research, further broad analysis will be conducted on the heat extraction medium.

5. Conclusions

An extensive literature review with deep analysis has been performed in this article, which will be extremely helpful to the researchers developing work in this area of solar energy engineering. Increased solar cell efficiency and recovering excessive heat are the main purposes of the introduction of hybrid PVT systems. Firstly, this paper discusses the types of PVT cells, their formation, and their efficiency with spectral analysis in the PVT panel. Additionally, an absorption model for several solar cells is also studied, which shows the better choice of the described cells. Then, the concept of a hybrid PVT system is described, explaining its advantages and disadvantages. The mathematical modeling of the PVT system is also discussed here. A brief review of the classifications of the PVT systems from various research papers is performed here. It shows the necessity of classifying PVT system based on the researchers focuses and needs, which implies a variety of options. After analyzing these papers, a new classification is proposed. The research classifications are divided into three main criteria. These criteria summarize the overall classifications described in the literature. The proposed classification will provide new and innovative information regarding the PVT system. We also studied and analyzed the impact and optimization parameters described in many research papers. It shows that researchers mentioned various internal and external parameters and optimization parameters in their research work. After a deep analysis, we obtained a model for both optimization and parametric analysis. This model shows a complete set of parameters involved in the performance analysis of a hybrid PVT system.

Based on the analysis obtained, several major and minor problems and challenges were also found. In the case of performance optimization and overall efficiency, the balance between electrical and thermal output is a major challenge to this research study. Additionally, determining the best operational parameters to increase energy output without compromising efficiency is also a challenge. In the course of this research, this problem can be minimized by using the proposed classification and parametric analysis. By considering modeling and simulation systems, it is found that the development of an exact mathematical model that can integrate with practical implementation is a big challenge, and resolving any differences between performance in the practical and theoretical models is also complicated. The mathematical model proposed in this work will provide the scope to start the development of an efficient model. Integration and compatibility of hybrid PVT systems are existing challenges. The integration of PVT systems with existing energy infrastructures is a major problem that also focuses on different types of solar cells and solar PVT panel/collector. This research provides the initiative to understand this gap and mitigates the challenges in terms of integration and compatibility.

In keeping with the objective of increasing solar cell efficiency and heat extraction, with a strong focus on the solar PVT system's enhanced efficiency analysis, this research is important. It promotes industry-wide standards to help the wider use of this technology by making it easier to integrate hybrid PVT systems into the current energy grids.

After analyzing this research, it is also possible to explore new research topics in this field. To achieve the objective of increasing efficiency, new types of PVT with new materials can be developed. For the purpose of smart grid integration, new technologies can be introduced to integrate with smart grids that will also allow for the recovery of a higher amount of excessive heat. Employing machine learning methods to optimize the PVT performance and better handling using real-time data, parameter effects can be explored.

With new scopes come new challenges. The challenges include grid robustness, environmental impact, storage methodologies, etc. In conclusion, the suggested research effort offers a basis for comprehending and developing hybrid PVT systems, and it provides recommendations for further study that concentrate on efficiency integration, policy support, and tackling newly identified issues in this sector. Finally, the proposed research work will provide an overview of the hybrid PVT system in relation to classification, parameters, optimization, and performance analysis.

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References

1. Al-Waeli, A.H.A.; Kazem, H.A.; Chaichan, M.T.; Sopian, K. A review of photovoltaic thermal systems: Achievements and applications. *Int. J. Energy Res.* **2020**, *45*, 1269–1308. [CrossRef]
2. Al-Waeli, A.H.A.; Sopian, K. Photovoltaic/Thermal (PV/T) systems: Status and future prospects. *Renew. Sustain. Energy Rev.* **2017**, *77*, 109–130. [CrossRef]
3. Zervos, A.; Lins, C.; Muth, J. *RE-Thinking 2050: A 100% Renewable Energy Vision for the European Union*; EREC: Brussels, Belgium, 2010.
4. Qureshi, U.; Baredar, P.; Kumar, A. Effect of weather conditions on the hybrid solar PV/T collector in variation of voltage and current. *Int. J. Res.* **2014**, *1*, 872–879.
5. Chaichan, M.T.; Kazem, H.A. *Generating Electricity Using Photovoltaic Solar Plants in Iraq*; Springer International Publishing AG: Cham, Switzerland, 2018.
6. International Energy Agency. *Sol. PV*. 2020. Available online: https://www.iea.org/reports/solar-pv (accessed on 25 June 2021).
7. Solar Power Europe. EU Market Outlook for Solar Power 2022–2026. Available online: https://api.solarpowereurope.org/uploads/5222_SPE_EMO_2022_full_report_ver_03_1_319d70ca42.pdf (accessed on 16 July 2023).
8. Ahmed, M.T.; Gonçalves, T.; Tlemçani, M. Single diode model parameters analysis of photovoltaic cell. In Proceedings of the 5th International Conference on Renewable Energy Research & Applications, Birmingham, UK, 20–23 November 2016.
9. Camargo, R.L.; Zink, R.; Dorner, W.; Stoeglehner, G. Spatio-temporal modeling of rooftop PV panels for improved technical potential assessment and electricity peak load off setting at the municipal scale. *Comput. Environ. Urban Syst.* **2015**, *52*, 58–69. [CrossRef]
10. Rodrigyuez, G.D. A utility perspective of the role of energy storage in the smart grid. In Proceedings of the Power and Energy Society General Meeting (IEEE), Minneapolis, MN, USA, 25–29 July 2010.
11. Dolara, A.; Leva, S.; Manzolini, G. Comparison of different physical models for PV power output prediction. *Sol. Energy* **2015**, *119*, 83–99. [CrossRef]
12. Huld, T.; Amillo, A.M.G. Estimating PV module performance over large geographical regions: The role of irradiance, air temperature, wind speed and solar spectrum. *Energies* **2015**, *8*, 5159–5181. [CrossRef]
13. Liou, H.M. Overview of the PV technology status and perspective in Taiwan. *Renew. Sustain. Energy* **2010**, *14*, 1202–1215. [CrossRef]

14. Schindler, F.; Michl, B.; Krenckel, P.; Riepe, S.; Benick, J.; Muller, R.; Richter, A.; Glunz, S.W.; Schubert, M.C. How to achieve efficiencies exceeding 22% with multi-crystalline n-type silicon solar cells. *Energy Procedia* **2017**, *124*, 777–780. [CrossRef]
15. Tiwari, G.N.; Mishra, R.K.; Solanki, S.C. Photovoltaic modules and their applications: A review on thermal modelling. *Appl. Energy* **2011**, *88*, 2287–2304. [CrossRef]
16. Debberma, M.; Sudhakar, K.; Baredar, P. Thermal modeling, exergy analysis, performance of BIPV and BIPVT: A review. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1276–1288. [CrossRef]
17. Xie, K.; Guo, M.; Liu, X.; Huang, H. Enhanced efficiencies in thin and semi-transparent dye-sensitized solar cells under low photon flux conditions using TiO2 nanotube photonic crystal. *J. Power Source* **2015**, *293*, 170–177. [CrossRef]
18. Shaikh, J.S.; Shaikh, N.S.; Shaikh, A.D.; Mali, S.S.; Kale, A.J.; Kanjanaboos, P.; Hong, C.K.; Kim, J.K.; Patil, P.S. Perovskite solar cells: In pursuit of efficiency and stability. *Mater. Des.* **2017**, *136*, 54–80. [CrossRef]
19. Leva, S.; Dolara, A.; Grimaccia, F.; Mussetta, M.; Ogliari, E. Analysis and validation of 24 h ahead neural network forecasting of PV output power. *Math Comput. Simul.* **2017**, *131*, 88–100. [CrossRef]
20. Katsumata, N.; Nakada, Y.; Minemoto, T.; Takakura, H. Estimation of irradiance and outdoor performance of PV modules by meteorological data. *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 199–202. [CrossRef]
21. Chaichan, M.T.; Kazem, H.A. Experimental analysis of solar intensity on PV in hot and humid weather conditions. *Int. J. Sci. Eng. Res.* **2016**, *7*, 91–96.
22. Diwania, S.; Agrawal, S.; Siddiqui, A.S.; Singh, S. Photovoltaic–thermal (PV/T) technology: A comprehensive review on applications and its advancement. *Int. J. Energy Environ. Eng.* **2020**, *11*, 33–54. [CrossRef]
23. Available online: https://www.fluxim.com/absorption-module (accessed on 7 June 2023).
24. Fudholi, A.; Sopian, K.; Yazdi, M.H.; Ruslan, M.H.; Ibrahim, A.; Kazem, H.A. Performance analysis of photovoltaic thermal (PVT) water collectors. *Energy Convers. Manag.* **2014**, *78*, 641–651. [CrossRef]
25. Sopian, K.; Alwaeli, A.H.A.; Kazem, H.A. Advanced photovoltaic thermal collectors. *J. Mech. Eng.* **2020**, *234*, 206–213. [CrossRef]
26. Ramos, C.A.F.; Alcaso, A.N.; Cardoso, A.J.M. Photovoltaic-thermal (PVT) technology: Review and case study. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 354.
27. Ahmed, M.T.; Rashel, M.R.; Janeiro, F.M.; Tlemçani, M. MATHEMATICAL MODELLING AND SIMULATION TECHNIQUES REVIEW FOR HYBRID PHTOVOLTAIC THERMAL SYSTEM. In Proceedings of the SYMCOMP 2021 Évora, Evora, Portugal, 25–26 March 2021.
28. Naves, A.X.; Barreneche, C.; Fernández, A.I.; Cabeza, L.F.; Haddad, A.N.; Boer, D. Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector: A review. *Sol. Energy* **2019**, *192*, 238–262. [CrossRef]
29. Molaei, M.J. The optical properties and solar energy conversion applications of carbon quantum dots: A review. *Sol. Energy* **2020**, *196*, 549–566. [CrossRef]
30. Yang, K.Y.; Lee, W.; Jeon, J.Y.; Ha, T.J.; Kim, Y.H. Controlling the visibility of embedded silicon solar cells in building-integrated photovoltaic windows using surface structure modification and metal-oxide back coating. *Sol. Energy* **2020**, *197*, 99–104. [CrossRef]
31. Trindade, A.; Cordeiro, L. Automated formal verification of stand-alone solar photovoltaic systems. *Sol. Energy* **2019**, *193*, 684–691. [CrossRef]
32. Joshi, S.; Dhoble, A.S. Photovoltaic—Thermal systems (PVT): Technology review and future trends. *Renew. Sustain. Energy Rev.* **2018**, *92*, 848–882. [CrossRef]
33. Wolf, M. Performance analyses of combined heating and photovoltaic power systems for residences. *Energy Convers.* **1976**, *16*, 79–90. [CrossRef]
34. Ahmed, M.T.; Rashel, M.R.; Ahmed, M.T. Tlemçani, M. A Study of Thermal Regulations and Efficiency Analysis in Hybrid PVT Panel. In Proceedings of the 6th International Conference on Numerical and Symbolic Computation Developments and Applications, Evora, Portugal, 30–31 March 2023.
35. Florschuetz, L.W. Extension of the hottel-whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. *Sol. Energy* **1979**, *22*, 361–366. [CrossRef]
36. Fine, J.P.; Dworkin, S.B.; Friedman, J. A methodology for predicting hybrid solar panel performance in different operating modes. *Renew. Energy* **2019**, *130*, 1198–1206. [CrossRef]
37. Khelifa, A.; Touafek, K.; Moussa, H.B.; Ismail, T. Analysis of a hybrid solar collector photovoltaic thermal (PVT). *Energy Procedia* **2015**, *74*, 835–843. [CrossRef]
38. Magrassi, F.; Rocco, E.; Barberis, S.; Gallo, M.; Del, B.A. Hybrid solar power system versus photovoltaic plant: A comparative analysis through a life cycle approach. *Renew. Energy* **2019**, *130*, 290–304. [CrossRef]
39. Herez, A.; El-Hage, H.H.; Lemenand, T.; Ramadan, M.; Khaled, M. Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems. *Sol. Energy* **2020**, *207*, 1321–1347. [CrossRef]
40. Abdelrazik, A.S.; Al-Sulaiman, F.A.; Saidur, R.; Ben-Mansour, R. A review on recent development for the design and packaging of hybrid photovoltaic/thermal (PVT) solar systems Renew. *Sustain. Energy Rev.* **2018**, *95*, 110–129. [CrossRef]
41. Al-Sabounchi, A.M.; Yalyali, S.A.; Al-Thani, H.A. Design and performance evaluation of a PV grid-connected system in hot weather conditions. *Renew. Energy* **2013**, *53*, 71–78. [CrossRef]
42. Gasparin, F.P.; Buhler, A.J.; Rampinelli, G.A.; Krenzinger, A. Statistical analysis of I–V curve parameters from PV modules. *Sol. Energy* **2016**, *131*, 30–38. [CrossRef]

43. Chow, T.T.; He, W.; Chan, A.L.S.; Fong, K.F.; Lin, Z.; Ji, J. Computer modeling and experimental validation of a building-integrated PV and water heating system. *Appl. Therm. Eng.* **2008**, *28*, 1356–1364. [CrossRef]
44. Bazilian, M.D.; Leerders, F.; Van Der Ree, B.G.C.; Prasad, D.P.V. Cogeneration in the built environment. *Sol. Energy* **2001**, *71*, 57–69. [CrossRef]
45. Ahmed, M.T.; Rashel, M.R.; Tlemçani, M. Parametric Study and Efficiency Analysis Hybrid PVT System. In Proceedings of the AMPSECA, Marrakech, Morocco, 25–26 May 2023.
46. Samykano, M. Hybrid Photovoltaic Thermal Systems: Present and Future Feasibilities for Industrial and Building Applications. *Buildings* **2023**, *13*, 1950. [CrossRef]
47. Herrando, M.; Wang, K.; Huang, G.; Otanicar, T.; Mousa, O.B.; Agathokleous, R.A.; Ding, Y.; Kalogirou, S.; Ekins-Daukes, N.; Taylor, R.A.; et al. A Review of Solar Hybrid Photovoltaic-Thermal (PV-T) Collectors and Systems. *Prog. Energy Combust. Sci.* **2023**, *97*, 101072. [CrossRef]
48. Va, T.; Sekhar, R. Hybrid Photovoltaic/Thermal (PVT) Collector Systems with Different Absorber Configurations for Thermal Management—A Review. *Energy Environ.* **2021**, *34*. [CrossRef]
49. Dewangan, D.; Ekka, J.P.; Arjunan, T.V. Solar photovoltaic thermal system: A comprehensive review on recent design and development, applications and future prospects in research. *Int. J. Ambient Energy* **2022**, *43*, 7247–7271. [CrossRef]
50. Abdin, Z.U. Modeling and Control of Hybrid PV Thermal Panels. Modeling and Simulation. Ph.D. Thesis, Université de Picardie Jules Verne, Amiens, France, 2022. NNT: 2022AMIE0057.
51. Zhou, B.; Pei, J.; Nasir, D.M.; Zhang, J. A review on solar pavement and photovoltaic/thermal (PV/T) system. *Transp. Res. Part D Transp. Environ.* **2021**, *93*, 102753. [CrossRef]
52. Bandaru, S.H.; Becerra, V.; Khanna, S.; Radulovic, J.; Hutchinson, D.; Khusainov, R. A Review of Photovoltaic Thermal (PVT) Technology for Residential Applications: Performance Indicators, Progress, and Opportunities. *Energies* **2021**, *14*, 3853. [CrossRef]
53. Rajoria, C.S.; Kumar, R.; Sharma, A.; Singh, D.; Suhag, S. Development of flat-plate building integrated photovoltaic/thermal (BIPV/T) system: A review. *Mater. Today Proc.* **2020**, *46*, 5342–5352. [CrossRef]
54. Noxpanco, M.G.; Wilkins, J.; Riffat, S. A Review of the Recent Development of Photovoltaic/Thermal (PV/T) Systems and Their Applications. *Future Cities Environ.* **2020**, *6*, 9. [CrossRef]
55. Sredendek, K.; Seme, S. A review of hybrid photovoltaic/thermal systems. *J. Energy Technol.* **2019**, *12*, 39–49.
56. Yuting, J.; Guruprasad, A.; Guiyin, F. Development and applications of photovoltaic–thermal systems: A review. *Renew. Sustain. Energy Rev.* **2019**, *102*, 249–265.
57. Abdullah, A.L.; Misha, S.; Tamaldin, N.; Rosli MA, M.; Sachit, F.A. Technology Progress on Photovoltaic Thermal (PVT) Systems with Flat-Plate Water Collector Designs: A Review. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2019**, *59*, 107–141.
58. Sachit, F.A.; Tamaldin, N.; Rosli, M.A.M.; Misha, S.; Abdullah, A.L. Current progress on flat-plate water collector design in photovoltaic thermal (PV/T) systems: A review. *J. Adv. Res. Dyn. Control Syst.* **2018**, *10*, 680–689.
59. Keizer, C.D.; Bottse, J.; Jong, M.D.; Folkerts, W. An Overview of PVT modules on the European Market and the Barriers and Opportunities for the Dutch Market. In Proceedings of the ISES EuroSun 2018 Conference, Rapperswil, Switzerland, 10–13 September 2018.
60. Babu, C. The role of thermoelectric generators in the hybrid PV/T systems: A review. *Energy Convers. Manag.* **2017**, *151*, 368–385. [CrossRef]
61. Sathe, T.M.; Dhoble, A.S. A review on recent advancements in photovoltaic thermal techniques. *Renew. Sustain. Energy Rev.* **2017**, *76*, 645–672. [CrossRef]
62. Lamnatou, C.; Chemisana, D. Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. *Renew. Energy* **2017**, *105*, 270–287. [CrossRef]
63. Al-waeli, A.H.; Sopian, K.B.; Kazem, H.A.; Chaichan, M.T. Photovoltaic Solar Thermal (PV/T) Collectors Past, Present and Future: A Review. *Int. J. Appl. Eng. Res.* **2016**, *11*, 10757–10765.
64. Tyagi, V.V.; Kaushik, S.C.; Tyagi, S.K. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1383–1398. [CrossRef]
65. Avezov, R.R.; Akhatov, J.; Avezova, N.R. A Review on Photovoltaic-Thermal (PV–T) Air and Water Collectors. *Appl. Sol. Energy* **2011**, *47*, 169–183. [CrossRef]
66. Hasan, M.A.; Sumathy, K. Photovoltaic thermal module concepts and their performance analysis: A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1845–1859. [CrossRef]
67. Ahliouati, M.; Rabie, E.O.; Kandoussi, K.; Boutaous, M.; Amal, L.; Louzazni, M.; Daya, A. Energetic and parametric studies of a basic hybrid collector (PV/T-Air) and a photovoltaic (PV) module for building applications: Performance analysis under El Jadida weather conditions. *Mater. Sci. Energy Technol.* **2023**, *6*, 267–281. [CrossRef]
68. Pathak, P.K.; Ghoshroy, D.; Yadav, A.K.; Padmanaban, S.; Blaabjerg, F.; Khan, B. A State-of-the-Art Review on Heat Extraction Methodologies of Photovoltaic/Thermal System. *IEEE Access* **2023**, *11*, 49738–49759. [CrossRef]
69. Azad, A.K.; Parvin, S. Photovoltaic thermal (PV/T) performance analysis for different flow regimes: A comparative numerical study. *Int. J. Thermofluids* **2023**, *18*, 1000319. [CrossRef]
70. Barbu, M.; Siroux, M.; Darie, G. Performance Analysis and Comparison of an Experimental Hybrid PV, PVT and Solar Thermal System Installed in a Preschool in Bucharest, Romania. *Energies* **2023**, *16*, 5321. [CrossRef]

71. Herez, A.; Jabe, H.; El-hage, H.H.; Lemenand, T.; Chahine, K.; Ramadan, M.; Khaled, M. Parabolic trough photovoltaic thermoelectric hybrid system: Simulation model, parametric analysis, and practical recommendations. *Int. J. Thermofluids* **2023**, *17*, 100309. [CrossRef]
72. Ajel, M.G.; Gedik, E.; Wahhab, H.A.A.; Shallal, B.A. Performance Analysis of an Open-Flow Photovoltaic/Thermal (PV/T) Solar Collector with Using a Different Fins Shapes. *Sustainability* **2023**, *15*, 3877. [CrossRef]
73. Farjad, M.; Soloveva, T.A. Performance Analysis of Solar Water Heating (SWH) and Photovoltaic-Thermal (PVT) Systems in Vladivostok, Russia. *JP J. Heat Mass Transf.* **2023**, *32*, 15–29. [CrossRef]
74. Madas, S.R.; Narayanan, R.; Gudimetla, P. A systematic review on furtherance of photovoltaic thermal panel technology. In Proceedings of the 3rd International Conference on Energy and Power (ICEP2021), Chiang Mai, Thailand, 18–20 November 2021.
75. Nascimento, V.F.; Yahyaoui, I.; Fiorotti, R.; Amorim, A.E.A.; Belisario, I.C.; Abreu, C.E.S.; Rocha, H.R.O.; Tadeo, F. Dimensioning and efficiency evaluation of a hybrid photovoltaic thermal system in a tropical climate region. *Sustain. Energy Grids Netw.* **2022**, *32*, 100954. [CrossRef]
76. Yousif, J.H. Prediction and evaluation of photovoltaic-thermal energy systems production using artificial neural network and experimental dataset. *Therm. Eng.* **2021**, *27*, 101297. [CrossRef]
77. Amal, H.; Hicham, E.H.; Hierry, L.; Mohamad, R.; Mahmoud, K. Parabolic trough photovoltaic/thermal hybrid system: Thermal modeling and parametric analysis. *Renew. Energy Elsevier* **2021**, *165*, 224–236.
78. Ventura, C.; Tina, G.M.; Gagliano, A.; Aneli, S. Enhanced models for the evaluation of electrical efficiency of PV/T modules. *Sol. Energy* **2021**, *224*, 531–544. [CrossRef]
79. Hossain, R.; Ahmed, A.J.; Islam, S.M.K.N.; Saha, N.; Debnath, P.; Kouzani, A.Z.; Mahmud, M.A.P. New Design of Solar Photovoltaic and Thermal Hybrid System for Performance Improvement of Solar Photovoltaic. *Int. J. Photoenergy* **2020**, *2020*, 8825489. [CrossRef]
80. Dwivedi, P.; Sudhakar, K.; Soni, A.; Solomin, E.; Kirpichinikova, I. Advanced cooling techniques of P.V. modules: A state of art. *Case Stud. Therm. Eng.* **2020**, *21*, 100674. [CrossRef]
81. Khordehgah, N.; Zabnienska-Gora, A.; Jouhara, H. Energy Performance Analysis of a PV/T System Coupled with Domestic Hot Water System. *ChemEngineering* **2020**, *4*, 22. [CrossRef]
82. Abdul-Ganiyu, S.; Quansah, D.A.; Ramde, W.W.; Seidu, R.; Adaramola, M.S. Investigation of Solar Photovoltaic-Thermal (PVT) and Solar Photovoltaic (PV) Performance: A Case Study in Ghana. *Energies* **2020**, *13*, 2701. [CrossRef]
83. Barbu, M.; Darie, G.; Siroux, M. Analysis of a Residential Photovoltaic-Thermal (PVT) System in Two Similar Climate Conditions. *Energies* **2019**, *12*, 3595. [CrossRef]
84. Antony, A.; Wang, Y.D.; Roskilly, A.P. A detailed optimisation of solar photovoltaic/thermal systems and its application. *Energy Procedia* **2019**, *158*, 1141–1148. [CrossRef]
85. Abdullah, A.L.; Misha, S.; Tamaldin, N.; Rosli, M.A.M.; Sachit, F.A. Hybrid Photovoltaic Thermal PVT Solar Systems Simulation via Simulink/Matlab. *CFD Lett.* **2019**, *4*, 64–78.
86. Fuentes, M.; Vivar, M.; Casa, J.D.L.; Aguilera, J. An experimental comparison between commercial hybrid PV-T and simple PV systems intended for BIPV. *Renew. Sustain. Energy Rev.* **2018**, *93*, 110–120. [CrossRef]
87. Nasir, F.H.M.; Husaini, Y. MATLAB Simulation of Photovoltaic and Photovoltaic/Thermal Systems Performance. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *341*, 012019. [CrossRef]
88. Hasanuzzaman, M.; Malek, A.B.M.A.; Islam, M.M.; Pandey, A.K.; Rahim, N.A. Global advancement of cooling technologies for PV systems: A review. *Sol. Energy* **2016**, *137*, 25–45. [CrossRef]
89. Sargunanathan, S.; Elango, A.; Mohideen, S.T. Performance enhancement of solar photovoltaic cells using effective cooling methods: A review. *Renew. Sustain. Energy Rev.* **2016**, *64*, 382–393. [CrossRef]
90. Oussama, R.; Houcine, D.; Abdelmajid, J. A numerical investigation of a photovoltaic thermal (PV/T) collector. *Renew. Energy* **2015**, *77*, 43–50.
91. Khelifa, A.; Touafek, K.; Moussa, H.B.; Tabet, I. A numerical modeling of hybrid photovoltaic/thermal (PV/T) collector. *Sol. Energy* **2016**, *135*, 169–176. [CrossRef]
92. Moradia, M.; Ebadian, M.A.; Lin, C.-X. A review of PV/T technologies: Effects of control parameters. *Int. J. Heat Mass Transf.* **2013**, *64*, 483–500. [CrossRef]
93. Bahaidarah, H.; Subhan, A.; Gandhidasan, P.; Rehman, S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. *Energy* **2013**, *59*, 445–453. [CrossRef]
94. Chow, T.T. A review on photovoltaic/thermal hybrid solar technology. *Appl. Energy* **2010**, *87*, 365–379. [CrossRef]
95. Tiwari, A.; Sodha, M.S. Performance evaluation of hybrid PV/thermal water/air heating system: A parametric study. *Renew. Energy* **2006**, *31*, 2460–2474. [CrossRef]
96. Islam, M.; Rashel, M.R.; Ahmed, M.T.; Islam, A.K.M.; Tlemçani, M. Artificial Intelligence in Photovoltaic Fault Identification and Diagnosis: A Systematic Review. *Energies* **2023**, *16*, 7417. [CrossRef]