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Review

PV/Thermal as Promising Technologies in Buildings: A Comprehensive Review on Exergy Analysis

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Abstract: Solar Photovoltaic (PV) systems are degraded in terms of efficiency by increment in their temperature. To keep away from efficiency degradation regarding the temperature increase, various thermal management techniques have been introduced to keep the temperature low. Besides improvement in electrical efficiency, the overall efficiency can be enhanced by using the extracted thermal energy from the cell. The extracted heat in these systems, known as PV/Thermal (PV/T), can be applied for some purposes including water or air heating. This article reviews the works on the PV/T systems exergy analysis and discusses their findings. Based on the findings of the reviewed works, different factors such as the system configuration, used components and elements, and working conditions affect the exergy efficiency of these systems. As an example, use of coolants with improved thermal features, i.e., nanofluids, can cause improvement in the exergy efficiency. In addition to the nanofluid, making use of the thermal energy storage unit can further enhance the exergy efficiency. Furthermore, it has been observed that the materials of nanostructures can be another element that influences the enhancement of exergy efficiency. Moreover, the usage of some components such as glazing can lead to avoidance of thermal energy loss that would be beneficial from an exergy point of view. Finally, according to the reviewed works and knowledge of the authors, some suggestions are represented for future works in this field.

Keywords: PV/thermal; solar energy; exergy efficiency; solar radiation

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1. Introduction

The population growth and development of industrial activities appeared as two determining factors that lead to an upward trend in global electricity consumption, rising from 14,158 TWh in 2000 to more than 25,027 TWh in 2019 (as revealed in Figure 1) [1]. During this period, coal and natural gas had the lion's share of the electricity generation as energy sources, respectively. The blame is put on fossil fuels as they have a greater part of power generation and consequently cause huge amounts of greenhouse gas emissions. Moreover, due to the non-renewable essence of fossil fuels, it is not reasonable to depend on electricity generation from these energy sources. Thus, overcoming the issues caused by the consumption of fossil fuels calls for the usage of other substitutes. Recently, there has been much focus on replacing clean energy technologies including wind turbines, solar Photovoltaic (PV), and thermal, geothermal power plants, and hydropower with power plants working with fossil fuels [2–4]. Seeking an appropriate alternative as a clean power generation unit, PV cells can be a good choice as they possess features such as being able to be used on various scales, usefulness for off-grid and outlying areas, solar energy which is reachable in every part of the world and the newly occurred progresses in these technologies. With regard to Figure 2, the electricity generated by PV cells has gone up from almost 800 GWh in 2000 to approximately 680,952 GWh in 2019 and based on the predictions it will grow steadily from 2019 onward.

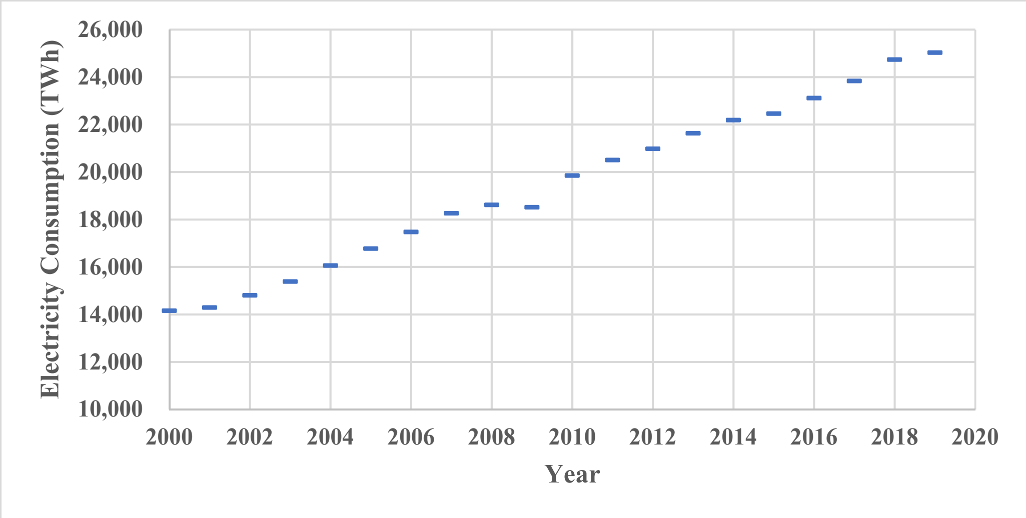

Figure 1. Electricity consumption in the world between 2000 and 2019 in the world [1].

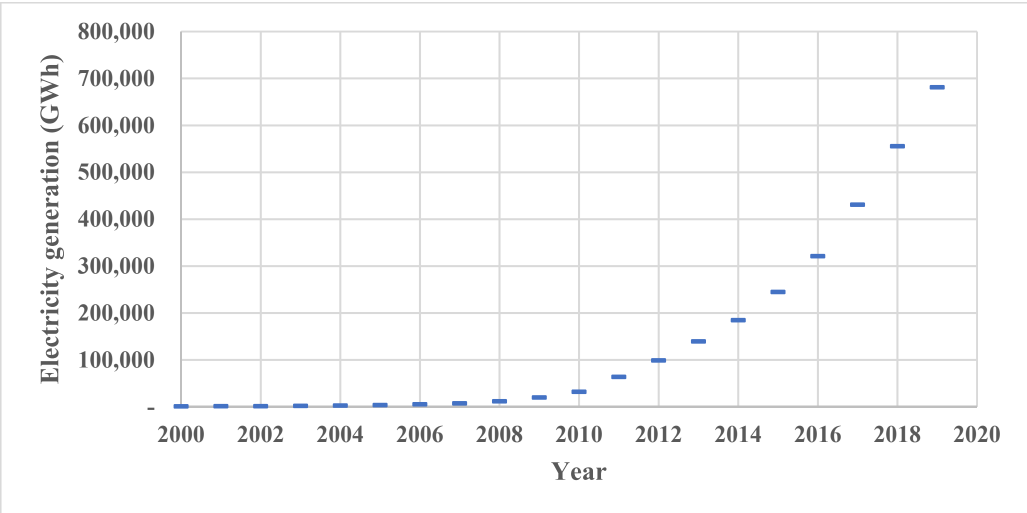

Figure 2. Electricity generation by PV cells between 2000 and 2019 in the world [1].

Although coal and natural gas have been two of the most popular energy sources for heating [1], the utilization of renewable energies is taking the place of these non-renewable energies. These renewable energies can be applicable for other purposes besides power generation such as desalination, heating, and cooling. Figure 3 reveals the process of heating generation with the help of geothermal and solar thermal systems in recent decades. The process of heating production is mostly based on the biofuels and geothermal rather than solar systems. However, features such as applicability for different scales and low or zero emission are among the most important privileges of solar systems. Also, heat production can take place by using solar energy with thermal energy content of solar radiations. Due to the global concern about greenhouse gas emission, solar energy is an appropriate replacement as its consumption leads to a drop in fossil fuel usage. Regarding the utilization of solar energy for producing heat, technologies such as heat pumps and solar collectors are applicable. The heating generated by solar energy is used for either space or water heating.

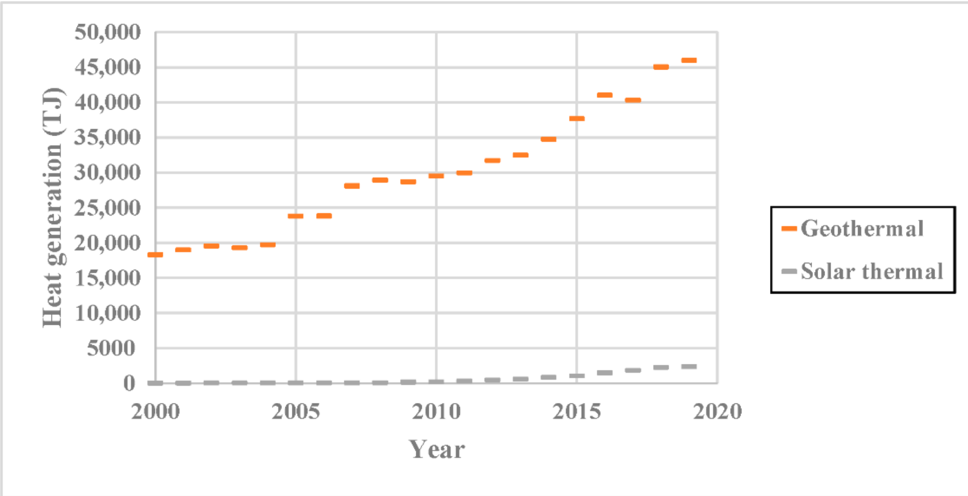

Figure 3. Heat generation by solar thermal and geothermal systems between 2000 and 2019 in the world [1].

PV cell's performance depends on their temperature and its efficiency and output decrease with increment in the temperature [5,6]. Consequently, managing the thermal status of the cells is crucial aiming to improve the output. Studies have shown that applying some cooling methods for their thermal management can significantly increase the electrical output [7]. To manage the temperature of PV cells, the methods applied are using air and liquid flow, Phase Change Material (PCM) and heat pipes [8–10]. The process of cooling the cells, provides some thermal energy that can be used for other intentions. These systems called PV/Thermal (PV/T), are dual-purpose as they are applied for either heat production or power generation [11]. Thus, the mentioned systems are so popular in comparison with other solar systems used and they can be among the most efficient ones, as well [12]. Also, PV/Thermal systems take over the stand-alone cells (in case they lack additional components) in terms of efficiency improvement, as they have advantages such as thermal management and extraction of thermal energy that is employed for other determinations. Depending on the applied components and materials for thermal management of the cells in PV/T systems, different configurations can be obtained. The coolants that can be used in these systems are water, air or a mixture of two fluids which can be both natural and forced circulation [13]. The determining factors of PV/T systems performance are components features, operating status, configuration, etc. [14]. Based on the Vaishak and Bhale [15] investigations on cell backsheet material, the material utilized in the PV/T system is declared to affect the system output and performance. Also, Maadi et al. [16] have proved the positive thermal and electrical effects of applying conical-leaf inserts in the tubes of the coolant of PV/T systems. Yuan et al. [17] compared two PV/T configurations one with water pipe and the other with micro channel heat pipe array and discovered that the system with water pipe had better performance in comparison with the other system. With regard to the Abdallah et al. [18] investigations, Al_2O_3/water nanofluid can be an appropriate substitute for water in PV/T systems as it enhances the performance of the system. Kang et al. [19] analyzed a dual-inlet air cooled PV/T system and observed that by increment in the angle between the bottom plate and solar panel, thermal efficiency of the system can be improved. In another work [20], a dual-fluid PV/T system with nanofluid and air was investigated and compared with the system using water and air. Higher energy output was observed in condition of using the nanofluid and the maximum efficiency was around 85%. In addition to the technical point of view, these systems have been investigated economically. For instance, Net Present Value (NPV) of PV/T system with electrical and thermal storage was investigated for different locations in Sri Lanka by considering the capacity of solar panel and found that increment in the capacity of the panel, rise of NPV reduces for all of the considered regions [21]. In another work [22], PV and PV/T systems were compared economically by considering projected payback period and found that this value for the mentioned systems was 21.2 years and 15.4 years, respectively. PV/T system can be integrated with other clean energy systems such as fuel cell. Integration of PV/T systems with other technologies can provide higher overall efficiency. For instance, Zafar and Dincer [23] analyzed a combined PV/T-fuel cell system and found that making use of the thermal energy released from fuel cell can increase both energy and exergy efficiencies of the system.

The majority of the researches conducted on PV/T systems are focused on energy efficiency and the methods applied for boosting the system performance. By applying exergy analysis on the energy systems, potential for performance improvement can be distinguished and the defects of the systems can be found. There is a necessity for more review studies on PV/T system exergy analysis as the ones conducted [24,25], lack up-to-date information, new configurations and attitudes brought up in the recent studies. Thus, this article reviews the PV/T systems with various configurations to fill the main gaps in previous review studies with focus on exergy concept. Furthermore, the recently published studies are the main part of the current research to fulfill the demand for being upgraded. However, the findings of the research and their key points are viewed in the next part of the article.

2. PV/T Systems in Buildings

Given the applicability of PV/T systems in providing both heat and electricity in a clean way, they can be applied as a desirable technology in buildings [26,27]. Making use of these technologies or coupling them with the conventional heating systems applied in the buildings, would result in remarkable decrement in the emission of greenhouse gases in residential sectors and is a practical way to have green buildings. In addition to heating and electrification, these systems are usable for cooling in the buildings [28]. Use of PV/T systems in buildings have been discussed in several studies; however, some of the most important and interesting ones are considered here as literature review. For example, Gora et al. [29] analyzed utilization of PV/T system in a single-family building in London. They found that despite the heating system with just PV/T, without any additional heat source, does not allow to have comfort temperature of 20 °C in winter, it is able to significantly decrease air system heat requirement in the autumn and spring. Buker et al. [30] investigated utilization of building integrated PV/T system in Nottingham, UK. For their case study, overall system annual energy saving was around 10.3 MWh/year and the power generation cost was 0.0078 €/ kWh. Farshchimonfared et al. [31] implemented optimization on a building-linked PV/T system to find the optimal values of the depth of cooling channel, mass flow rate of coolant and distribution duct diameter. They found that optimal depth increases as the collector length to wdith ratio and area increase. Effect of collector geometry on the output of these systems, integrated with a building, was considered in another work and it was concluded that larger collector depth could lead to better overall energy output delivery; however, the temperature increment was lower in this condition [32].

PV/T systems are integrable with other technologies to be applied in buildings. For example, Sotehi et al. [33] presented a system based on the integration of PV/T system and solar still. They discovered that total coverage of yearly electricity and thermal demand is possible by the provided system. Applying solar energy for providing domestic hot water, by using the proposed system, causes remarkable reduction in total energy requirement. In addition, around 2.97 times increment in production of the solar still was observed in case of preheating the brine prior to its injection. Shao et al. [34] proposed a hybrid configuration, direct-expansion roof-PV/T heat pump system. They discovered that the efficiency (electrical) does not have significant variations in winter and summer while the system thermal and overall efficiency was more in summer. To sum up, it can be denoted that PV/T systems would be attractive for utilization in residential sector and their performance depends on different elements including the geometrical features, configuration, components and operating conditions.

3. Exergy Analysis of PV/T Systems

Similar to other solar systems, performance of PV/T technology is influenced by several factors. Some of the main elements that are involved in the output of solar systems are shown in Figure 4.

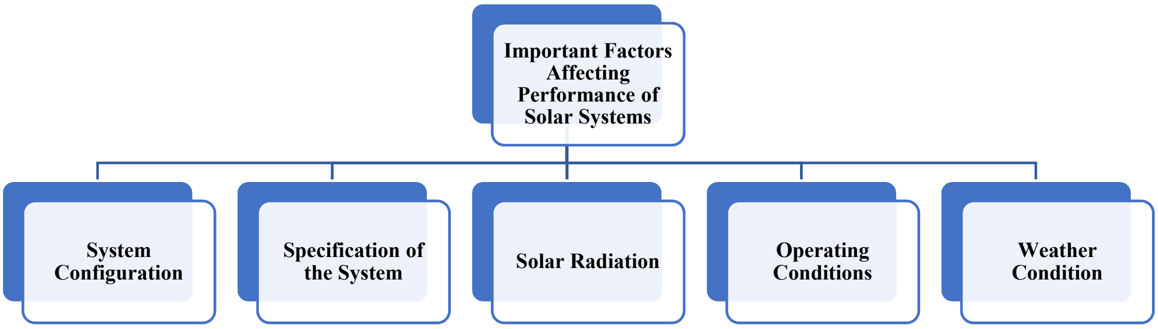

Figure 4. Important factors influencing the performance of solar systems.

Out of the various configurations of PV/T systems, there is one traditional type, shown in Figure 5 that applies flow as PV coolant. These dual-purpose systems, that generate electricity and power appear as more efficient systems compared with individual cell ones as they possess a high-performance thermal management which enables the absorbance of heat from cells by working fluid.

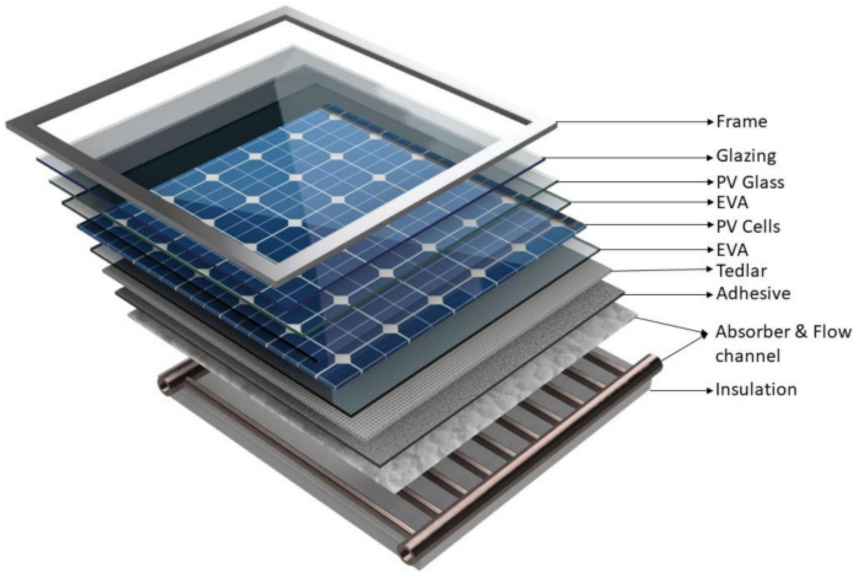

Figure 5. Detailed parts of a conventional PV/T system [35].

A system can benefit from exergy concept and its analysis by providing a good revenue for itself and by finding the demolitions occurring in different parts through applying the exergy analysis and using the possibilities and chances to improve the system performance. When the system and its surrounding reach equilibrium, the amount of work performed is characterized as exergy [36]. Based on Figure 6, N, U, V, S, T, p and μ are characterized as mole of various chemical components, energy, volume, entropy, temperature, pressure and the chemical potential of components, respectively. The exergy concept has been widely used in various energy systems such as heat exchangers [37], power plants [38] and many other renewable energy systems [39,40]. Also, the analysis on PV/T systems [41,42] is performed by the exergy concept used by various scholars. Considering a simple PV/T system utilizing fluid flow as coolant, shown in Figure 7, according to Ref. [43], overall exergy inlet can be determined as follows:

$$\sum \dot{Ex}_i = \dot{Ex}_{i,th,PV} + \dot{Ex}_{i,el,PV} \quad (1)$$

where, $\dot{ex}_{i,th,PV}$ is the thermal exergy inlet of the module and is calculated as follows:

$$\dot{Ex}_{i,th,PV} = \dot{m}_f.c_{pf}.\left[(T_{av,i,PV} - T_0) - T_0.ln\frac{T_{av,i,PV}}{T_0}\right] \quad (2)$$

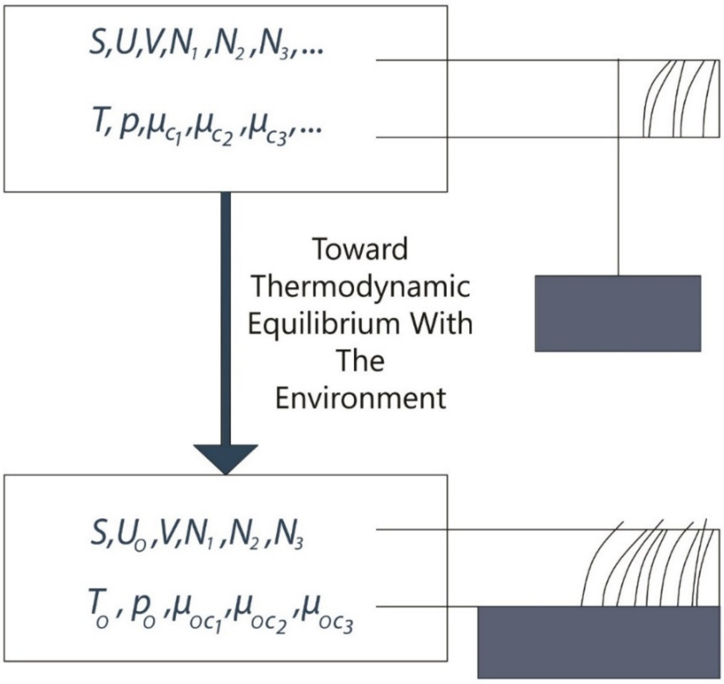

Figure 6. Exergy definition of a system [36].

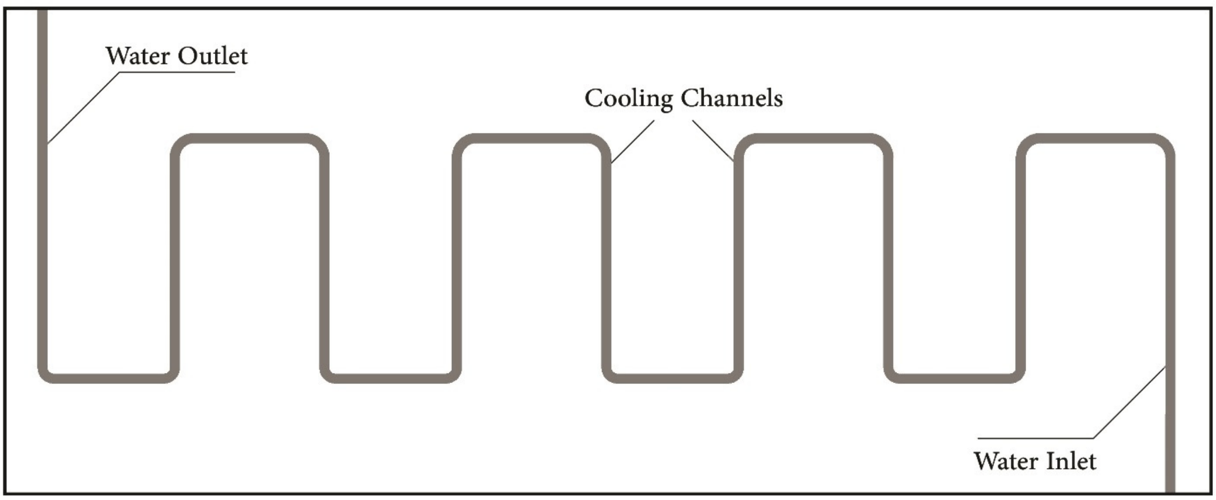

Figure 7. Schematic of a water-cooled PV module [43].

$T_{av,i,PV}$ is the average temperature of fluid at the inlet and is calculated as follows:

$$T_{av,i,PV} = \frac{T_{fs} - T_{out,\ Pv}}{2} \quad (3)$$

where T_{fs} is fluid supply temperature and $T_{out,PV}$ refers to the PV module outlet fluid temperature. Electrical exergy of the system is determined as follows:

$$\dot{Ex}_{out,el,PV} = A_{PV}.I.\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}.\left(\frac{T_a}{T_s}\right)^4\right] \quad (4)$$

where A is the area of the cell, I is the solar radiation and T_s and T_0 refer to temperature of the sun surface (5777 K) and ambient temperature, respectively.

System outlet exergy is calculated by applying Equation (5) as follows:

$$\sum \dot{Ex}_{out} = \dot{Ex}_{out,th,PV} + \dot{Ex}_{out,el,PV} \quad (5)$$

The applied terms in the above equations are determined as follows:

$$\dot{Ex}_{out,th,PV} = \dot{m}_f.C_{pf}.\left[(T_{out,PV} - T_0) - T_0.ln\frac{T_{out,PV}}{T_0}\right] \quad (6)$$

$$\dot{Ex}_{out,el,PV} = A_{PV}.\beta.I.\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}.\left(\frac{T_a}{T_s}\right)^4\right] \quad (7)$$

where β is the electrical efficiency of the cell.

Qingyang et al. [44] compared the exergy of PV, solar thermal and PV/T. Based on their results and with regard to the meteorological features of Hong Kong as the research case study, in respect of energy efficiency and energy gain, solar thermal system ranked first while considering the exergy efficiency, PV was ahead. However, PV/T was introduced as systems possessing the highest efficiency. Also, based on the previous studies, PV/T systems can meet the expectations with regards to the exergy efficiency more than the individual PV modules [45]. Based on the investigations of Huang et al. [46], comparing a PV/T system that applies air collector with an individual PV module with regards to electrical exergy efficiency, exergy performance of the latter was flat at 4.83%. However, in case of high air mass flow rate, the cell overtook the individual module in terms of electrical exergy efficiency. However, the individual cell had a better electrical performance at low mass flow rates due to the shielding in PV/T system causing a decrement in the heat dissipation, losing the radiation of air interlayer between the cell and glass cover and the application of back insulation layer used for decreasing the convective heat transfer.

Various factors are taken into consideration in researches conducted on PV/T systems exergy analysis. For instance, in a comparison made by Hazami et al. [47] between passive and active modes of the PV/T system, water mass flow was used as a factor to distinguish the more efficient one. The passive mode lacked the water mass flow. Consequently, the active mode had an electric exergy improvement of 19.35% due to the application of water mass flow of 0.083 kg/s. Furthermore, thermal exergy is another factor which is significantly higher in the active modes of these systems. Generally, the PV/T systems exergy efficiency is regulated by various elements [42]. For instance, Wu et al. [48], compared and analyzed the effect of different factors including the thermal exergy efficiency, electrical exergy efficiency, solar irradiance, mass flow rate and height of channel on overall exergy efficiency. They came to the conclusion that, thermal exergy efficiency is more effective on the overall exergy efficiency in comparison to the electrical exergy efficiency. Furthermore, it was found that an increase in solar irradiance causes reduction in exergy efficiency while there is an optimal value for channel height and mass flow rate.

In addition to the mentioned elements that were limited to the system features, some environmental and time related factors such as location and season (or month of the year) were investigated by Joshi and Tiwari [49], as parameters acting on the exergy output of PV/T systems. The survey was carried out in various regions of India in different months of the year. Based on the results, In Bangalore, the system had higher monthly exergy in winter (remarkably in January) compared with summer. In Mumbai, the monthly exergy went up to its maximum value in March and the values in winter were higher than that of the summer. The results were completely different in Srinagar as, the system reached its maximum exergy in May. In another research implemented by Jahromi et al. [50], in which the exergy analysis were applied for a PV/T system utilizing a combination of water and Ethylene Glycol (EG) as the working fluid of the system, solar radiation was characterized as a significant factor acting on the efficiency of the whole system including the PV cell and thermal unit. It is worth noting that, the survey was conducted in three different regions of Iran. With regard to the results, in all the case studies of the research, the system reached higher overall exergy efficiency in winter compared with summer. Furthermore, adding extra components to PV/T systems, can prompt boosting in the system performance. For instance, Hossain et al. [51] investigated the relation between different flow rates of water and exergy efficiency. Thus, PCM was used in a double-faced PV/T system with serpentine flow and was encompassed in anti-leakage aluminum foil packets. The PCM was utilized as a coverage for coolant channels aiming to maintain the thermal storage. The flow rates of water were arranged between 0.5 to 4 lit/min with the aim of finding the optimal condition. The optimum flow rate to achieve the highest exergy efficiency was 0.5 lit/min which was equal to 12.19%, and the maximum exergy efficiency of PV was observed at 7.09%.

The PV/T system overall performance is affected by its operating fluid [52,53]. In order to boost the output of the PV/T system through heat transfer, nanofluids can be beneficial [54], as they can transfer the heat more properly due to their progressive features [55–57]. Aberoumand et al. [58] declared a higher exergy efficiency is caused in PV/T systems by using Ag/water nanofluid with various flow rates instead of water. Increased mass flow rates and concentrations of Ag/water nanofluids are their main distinguishments that improve the efficiency. Compared with a PV system that uses water instead of an improved cooling system, utilization of nanofluid with 4% wt concentration and turbulent flow can create a 50% and 30% increment in system exergy efficiency, respectively. Adun et al. [59] analyzed a PV/T system utilizing a ternary nanofluid, Al_2O_3-ZnO-Fe_3O_4/water, and found that the mixture ratio of the particle influences the system performance. Furthermore, the exergy analysis revealed that solar irradiance pattern is observed in the system total exergy efficiency. In addition to the mixture ratio and concentration, other specifications of the applied nanofluid can influence the PV/T system performance [60]. As an example, applying various methods such as one-step and two-step ones for preparing the nanofluids and also the type of nanostructure material used can differentiate the PV/T systems' exergy efficiency as they affect the nanofluids, as well. Regarding the mentioned approaches, Parsa et al. [61] used one-step and two-step approaches in order to prepare Ag/water nanofluid in three concentrations of 1%, 3% and 5% and the results revealed, one-step method contributed to a higher exergy efficiency for PV/T system compared with the cases of using the two-step methods. Regarding the effects of nanostructure materials on PV/T system performance, findings of Sangeetha et al. [62] demonstrated that among all the three nanofluids that they applied including the Al_2O_3/water, MWCNT/water and TiO_2/water being fixed at the volume ratio of 0.3%, using the MWCNT/water nanofluid and Al_2O_3/water and TiO_2/water afterward lead to the highest exergy efficiency. Various exergy efficiencies are revealed in PV/T systems based on the applied nanofluids. As an example, in one of the studies [63], after the utilization of Al_2O_3/water, ZnO/water, Al_2O_3-ZnO/water and Al_2O_3-ZnO-Fe_3O_4/water nanofluids, it was the Al_2O_3-ZnO-Fe_3O_4/water followed by Al_2O_3-ZnO/water that maximized the exergy efficiency of the system, as revealed in Figure 8. Furthermore, Sopian et al. [64] evaluated the impact of factors such as material and configuration on electrical exergy of PV/T systems. There were four various cases of PV/T with water, PV/T with water and PCM tank, PCM with nanofluid and nano-PCM tank and conventional PV module in their analysis which among all of the analyzed cases, systems applying the PV/T with nanofluid and nano-PCM had the maximum electrical exergy. Furthermore, based on the analysis, in case of the PV, PV/T with water, PV/T with water and PCM and PV/T with nanofluid and nano-PCM, the mean electrical exergy efficiency was 8.84%, 10.53%, 11.83%, and 12.05%, respectively.

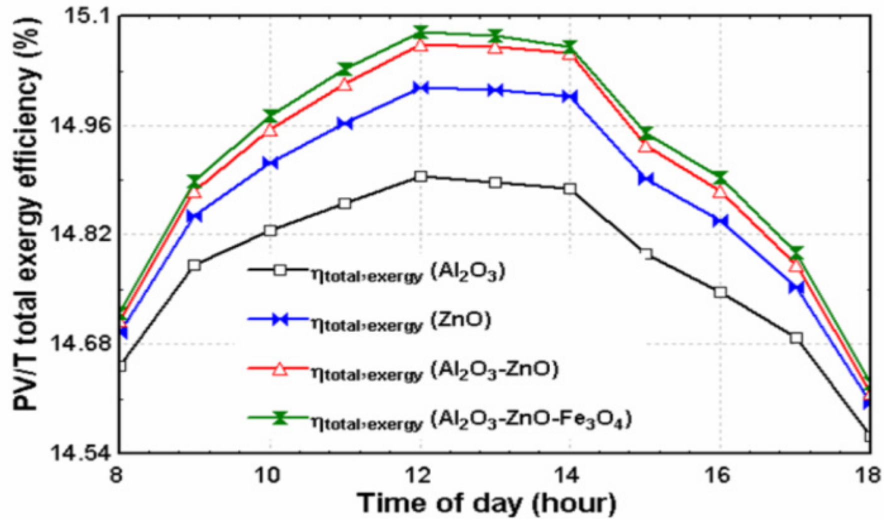

Figure 8. Effect of various nanofluids on the exergy efficiency of PV/T system [63].

According to the results of the researches, the configuration of the system and component is considered as one of the main factors that can positively influence the PV/T system [65]. For instance, among the two configurations analyzed by Dubey et al. [66], one of the configurations lead to higher exergy gain that had air flow below the plate of the absorber in contrast with the second case in which PV modules covered the air collector and the air flow was above the plate of the absorber. Based on the Lahoucine et al. [67] investigations of the height of the rectangular cooling channel, the exergy efficiency alters inversely with the height of the channel. Eisapour et al. [68], investigated the electrical and thermal exergy efficiencies by applying various coolant configurations altered by using different non-uniform wavy tubes including A: straight, B: constant wavy, and C: descending wavy, and D: ascending wavy. Furthermore, the heat transfer fluids utilized in their research were pure water, two various types of nanofluids (Ag/water and SiC/water), Micro-encapsulated Phase Change Materials (MPCM-28 and MPCM-37) slurry and hybrid fluids (MPCM nano-slurry). Based on the results of this survey, among all the configurations, case D created the highest electrical and thermal exergy efficiency and after that cases B, C and A were rated as the maximum, respectively. Based on the observations of various fluids used in PV/T system, MPCM-28 SiC nano-slurry fluid leads to the highest electrical exergy while by applying the MPCM-37 slurry fluid, the system reaches its maximum exergy efficiency. Generally, nanoparticles with lower density and higher thermal conductivity were a preference. However, higher heat capacity and latent heat of fusion were more appropriate for the PCM. In another work [69], exergy analysis was performed on a PV/T system on the basis of ethanol phase change self-circulation technology by considering both glazed and unglazed systems. They observed that the entropy generation of a glazed system was lower than the unglazed one which was interpreted by loss of heat transfer and fluid friction. In some other studies [70], contrary results have been observed and it has been noticed that unglazed conditions can lead to higher exergy efficiency compared with glazed under specific operating conditions. The utilization of concentrators is another approach that can enhance the PV/T systems performance. According to the research implemented by Zuhur et al. [71], there was an increase in exergy efficiency from 11% to 16% by using concentrator. Another research [72], introduces a new configuration of PV/T system applying plasmonic nanofluid and silica aerogel glazing. As revealed in Figure 9, in the mentioned system, the extra amounts of thermal energy being absorbed through nanofluid which flows below the cell owing to the photoelectricity conversion. Subsequently, the preheated fluid flows in the photo-thermal channel that is located on the top of the cell in order to absorb a portion of the photons that could not be properly utilized by the cell. Furthermore, an optical filer based on plasmonic nanofluid is designed and used in order to absorb the low and high-energy photons of the solar spectrum. The function of the glazing was insulating the cell from channels and causing a decrement in the heat lost by the system. In this configuration, exergetic efficiency was 13.3% up at a solar concentration of 10 which was higher than what was achieved by common PV/T systems.

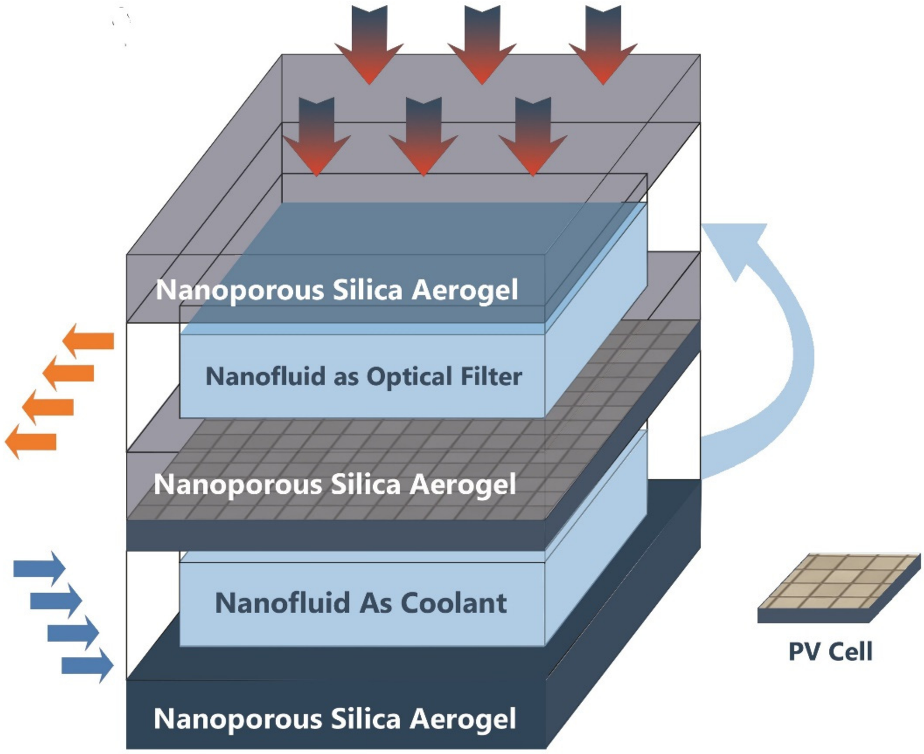

Figure 9. Schematic PV/T system with nanofluid and glazing [72].

As indicated, exergy analysis provides profound insight into the systems. In this regard, the findings from exergy analysis can be applied to optimization of systems. As an example, Sobhnamayan et al. [73] used the exergy concept for a PV/T system optimization. They considered exergy balance for various units of a PV/T system and obtained expressions that provide exergy of the components. In addition, they performed a correction on the obtained expression to reach a modified equation. Subsequently, they developed a computer simulation program that enables them to determine electrical and thermal parameters and found the results in proper agreement with the data obtained in the experiments. Finally, a Genetic Algorithm (GA) was applied for optimizing the exergy efficiency of the system. Independent variables in their work were inlet water velocity and diameter of the pipes. In the case of optimization, the highest exergy efficiency was 11.36%.

Similar to the other energy systems, PV/T can be integrated with other technologies in order to have higher reliability, overall performance, etc. [74,75]. Exergy analysis would be a proper tool to investigate these systems more deeply. In a study by Ogbonnaya et al. [76], four systems including PV-battery (1), PV/T-battery (2), PV-battery, electrolyzer(EL)-fuel cell (FC) (3) and PV/T-battery, EL-FC (4) were considered for exergy analysis. A comparison of the system revealed that the exergy efficiency of system 2 was upgraded by around 5.4% compared with system 1 while system 3 exergy was degraded by 4.1% compared with system 1 and the exergy efficiency of system 4 was decreased by 7.72% over system 2. On the basis of these findings, the highest exergy efficiency was obtained in case of using system 2, indicating its maximum ability to harness monthly solar exergy. In another work [77], exergy analysis was applied to a PV/T system integrated with an electrolyzer. They found that depending on the climate conditions, the exergy efficiency of the system varied in range of 1.9–5.3% and it can be improved by an increment in the number of PV/T in parallel connection. Moreover, they observed that increase in the cooling flow rate can cause increment in the energy efficiency while there was no considerable influence on the exergy efficiency.

In Table 1, the findings of the exergy analysis of PV/T systems are summarized.

Table 1. Summary of the research on exergy analysis of PV/T systems.

Reference	System	Findings
Huang et al. [46]	PV/T with air	High mass flow rates of air caused higher efficiency (electrical) of PV/T compared with individual PV modules.
Wu et al. [48]	PV/T with water	For this configuration, cooling channel above the PV, effect of thermal exergy efficiency on the overall exergy efficiency was more remarkable compared with electrical exergy efficiency.
Aberoumand et al. [58]	PV/T with water and nanofluid	Improvement in the exergy efficiency was more notable in cases of higher concentrations and mass flow rates.
Adun et al. [59]	PV/T with ternary nanofluid	Solar irradiance pattern was seen in the total exergy.
Parsa et al. [61]	PV/T with nanofluid	Using the nanofluids obtained from one-step method caused higher exergy efficiency compared with the nanofluid prepared by two-step approach.
Hazami et al. [47]	PV/T with water	Electric exergy of the system in active mode was around 19.35% higher than in passive mode.
Joshi and Tiwari [49]	PV/T with air	Maximum monthly exergy of the system was dependent on the city.
Jahromi et al. [50]	PV/T with water/EG mixture	Exergy efficiency of the system was higher in winter (with lower ambient temperature) compared with summer (with higher ambient temperature).
Hossain et al. [51]	PV/T with PCM packets	Maximum exergy efficiencies of the PV/T system in optimal condition and PV were 12.19% and 7.09%, respectively.
Sangeetha et al. [62]	PV/T with nanofluids	Using MWCNT/water nanofluids provided higher exergy efficiency compared with TiO_2/water and Al_2O_3/water.
Adun et al. [63]	PV/T system with different nanofluids	The highest exergy efficiency belonged to Al_2O_3-ZnO-Fe_3O_4/water that was followed by Al_2O_3-ZnO/water.
Sopian et al. [64]	PV/T with water, PV/T with water and PCM, PV/T with nanofluid and nano-PCM	The highest average electrical exergy efficiency belonged to the PV/T with nanofluid and nano-PCM.
Dubey et al. [66]	PV/T with air	Air flow below the absorber plate provided higher exergy gain compared with the case of flow above the plate.
Lahoucine et al. [67]	PV/T with water and nanofluid	Increment in cooling channel height causes reduction in exergy efficiency.
Eisapour et al. [68]	PV/T with different fluids	Using wavy channels with modified configuration (ascending) leads to the highest electrical exergy among the tested configurations.
Gao et al. [69]	PV/T with ethanol phase change self-circulation technology	Entropy generation in case of glazed system was lower than unglazed case.
Chow et al. [70]	PV/T with water	Under some working conditions, exergy efficiency of unglazed system can be better than glazed system.
Zuhur et al. [71]	PV/T with concentrator	Applying concentrator increased the exergy efficiency.
Du et al. [72]	PV/T with nanofluid and glazing	Enhancement of 13.3% in exergetic efficiency was observed compared with traditional system.

Table 1. *Cont.*

Reference	System	Findings
Sobhnamayan et al. [73]	PV/T with water	Optimization was performed on the system based on exergy concept.
Ogbonnaya et al. [76]	PV-battery, PV/T-battery, PV-battery-electrolyzer-fuel cell, PV-T-battery- electrolyzer-fuel cell	The highest exergy efficiency among these systems belonged to PV/T-battery.
Caglar et al. [77]	PV/T with electrolyzer	Increase in coolant flow rate can improve energy efficiency while there was no considerable impact on the exergy efficiency.

4. Suggestions for Future Research

Despite all the informative research on exergy analysis of different PV/T systems represented in previous sections, there are still some vital considerations and recommendations for future studies aiming to investigate this subject. For instance, there should be some sensitivity analysis that determines to what extent the exergy efficiency is dependent on different parameters. In this regard, different factors such as solar radiation, ambient temperature, mass flow rate of coolants or the concentration of nanoparticles (in the case of using nanofluids) can be used to obtain their impact on the exergy efficiency of PV/T systems and find their level of importance. According to the findings of the reviewed works, represented in the previous section, making use of fluids with modified properties such as nanofluids can be useful in terms of improving the exergy efficiency. In this regard, different nanofluids including conventional and hybrid types can be applied in PV/T systems. Utilization of the nanofluids containing carbon nanotubes, due to their significant thermal conductivity, would be beneficial to enhancing the exergy efficiency. Effects of different factors affecting the specifications of the nanofluids such as concentration, synthesis method, base materials, a., on the exergy efficiency could be investigated in the upcoming studies. Furthermore, some other novel fluids such as the ones containing encapsulated PCMs, as shown significant performance in thermal devices such as heat pipes [78], can be used in PV/T systems. In addition to the abovementioned ideas, it would be attractive to apply exergy analysis to the PV/T systems with different configurations and components. For instance, the exergy concept can be used for the PV/T systems including both fluids as coolant, and PCM for thermal management and energy storage. Moreover, it would be an attainable idea to implement exergy analysis on the PV/T systems composed of nano-incorporated PCMs due to their ability in enhancing the performance of solar systems [79]. Another suggestion for the upcoming works is applying exergy analysis to the hybrid systems composed of PV/T systems and other renewable energy technologies such as fuel cells. Furthermore, it is recommended to apply different optimization approaches, including the novel ones obtained by combining different techniques, to optimize PV/T systems based on the exergy concept. In this regard, the performance of different optimization approaches can be compared to find the most appropriate ones. Finally, it is suggested to develop some models based on intelligent techniques such as artificial neural networks to easily determine the exergy efficiency of PV/T systems by using the defined inputs.

5. Conclusions

This research represents the findings and exergy analysis of various PV/T systems obtained from other studies. Thus, the considerable conclusions are briefly brought up here:

- Various factors such as the weather condition, operating variables and system features can determine the exergy efficiency of PV/T systems.
- According to the system configuration, the overall exergy can be highly affected by the thermal or electrical exergy.
- Enhancement of energy and exergy efficiencies can be fulfilled by nanofluids.

- Although, nanofluids are able to improve the ratio of exergy efficiency, their performance relies on some factors such as the type of applied nanofluid, concentration and flow rate.
- Using nano-PCM and nanofluid simultaneously, can lead to an improvement in exergy efficiency of a PV/T system compared with using them individually.
- Architectural alterations in a system such as applying wavy coolant channels, can improve the system exergy output.
- To boost the exergy of the system, it would be beneficial to use extra components such as a concentrator.
- Aiming to optimize the PV/T systems, the exergy concept can be beneficial.

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