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A REVIEW OF HYBRID PHOTOVOLTAIC/ THERMAL SYSTEMS

PREGLED HIBRIDNIH TERMOELEKTRIČNIH SISTEMOV

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Abstract

The primary objective of this paper is to review state-of-the-art hybrid photovoltaic/thermal systems and their performance analysis. The paper is designed to facilitate the comparison and evaluation of results obtained by other authors. The review was carried out for different types and designs of photovoltaic/thermal modules in indoor and outdoor conditions, as well as for different cooling types and materials.

Povzetek

Cilj prispevka je pregled stanja hibridnih termoelektričnih sistemov in njihove učinkovitosti delovanja. Struktura prispevka je tematsko zasnovana tako, da olajša primerjavo in ovrednotenje rezultatov med drugimi študijami. Pregled je izveden za različne tipe in oblike termoelektričnih modulov, ter za različne vrste hlajenja in uporabljenih materialov.

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1 INTRODUCTION

Life depends primarily on energy and its consumption. Due to population growth, the electrification of transport and many other aspects, the development of new technologies for extracting energy from renewable sources is of utmost importance. The share of renewables in total final energy consumption (TFEC) grew by an estimated 0.25%, to around 19% of TFEC by 2017. The world needs to increase the share of renewable energy in TFEC from 19% to 65% by 2050, *[1]*. The share of photovoltaic systems (PV) increased dramatically over the previous decade, and their total installed capacity exceeded the sum of all other renewables. The efficiency of PV modules depends mainly on the density of solar radiation, G, and the temperature of PV module T. Hybrid photovoltaic/thermal systems have been developed that simultaneously increase the efficiency of the PV module and use excess heat in heating applications.

Given that PV/T modules produce more energy per unit area than PV and thermal modules separately, these systems are particularly suitable for applications where the available surface area is limited *[2]* and will play an essential role in the near future. Over the past thirty years, a great deal of research has been carried out by researchers on the concept of module type, coolant type and materials suitable for PV/T systems. Therefore, the next three chapters will briefly outline the findings and current use of PV/T systems, which has been already done by other authors of PV/T review papers. Figure 1 shows a simplified schematic of the PV/T module connected to a water storage tank.

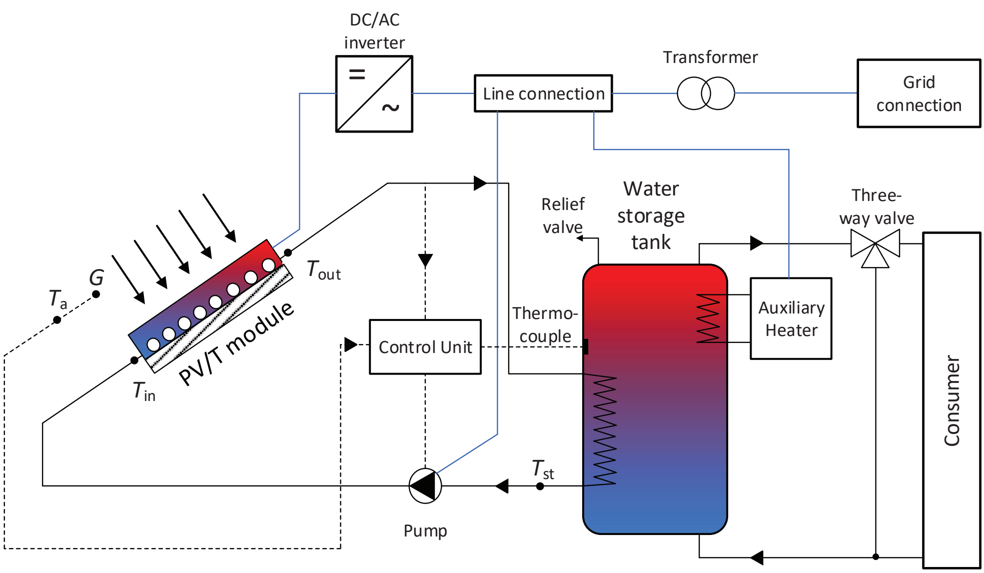

Figure 1: *A simplified scheme of PV/T system.*

2 HYBRID PHOTOVOLTAIC/THERMAL SYSTEM

Hybrid PV/T systems simultaneously convert solar energy into electrical and thermal energy. Excess heat that reduces the electrical efficiency of the PV module is discharged via the coolant to the heat storage tank. The PV/T system is divided into module type, coolant type, and PV material type, presented in Figure 2. The PV/T system can be optimized by setting the operating point at which the module will simultaneously produce more electrical energy and enough thermal energy. The operation is monitored by a unit that controls the mass flow rate of the coolant, via the inlet and outlet temperatures of the PV/T module.

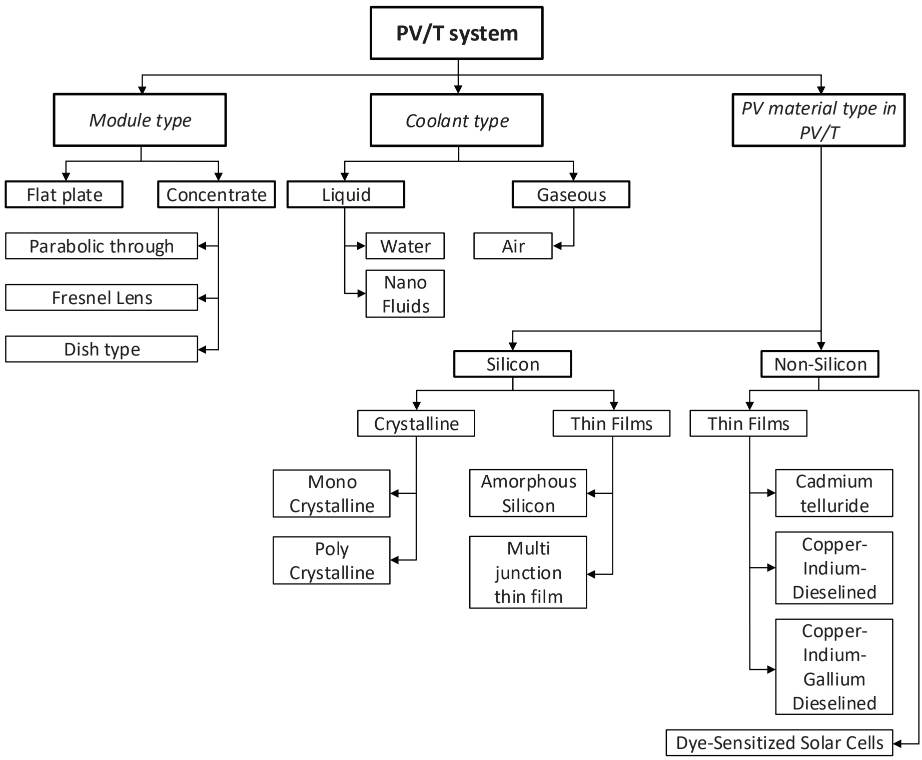

Figure 2: *Schematic division of PV/T modules (redrawn from [3]).*

3 MODULE TYPE

3.1 Concentrating PV/T modules

According to the concentration ratio (CR), the concentrating PV or PV/T systems can be divided into low-concentrating systems and high-concentrating systems with an additional tracking system. Under high concentration ratios, for instance, a multidisc concentrator with 150 concentration ratios, the PV system has a severe cooling problem, *[4]*. Jaaz et al., *[5]*, presents a performance analysis of a PV/T module using water jet impingement and compound parabolic concentrator (CPC). Since the electrical efficiency and output power are directly correlated with the mass flow rate, the system can be improved by using jet impingement of water to decrease the temperature of the PV module. The results show that electrical efficiency was improved by 7% when using CPC and jet impingement cooling, while the output power was improved by 36% when using jet impingement cooling with CPC, and 20% without CPC. In his second study, *[6]*, the results of power output and electrical efficiency were very similar, while thermal efficiency improved to 81%. Singh et al., *[7]*, performed an enhanced experimental study on concentrating PV/T air collector with fresnel lenses and CPC, based on previously applied studies and methodologies. The results showed that the highest electrical and thermal efficiencies of the concentrating PV/T collector were found to be 12.9% and 50%, while a total combined efficiency was 80%. The average solar radiation, mass flow rate, and geometric concentration ratio were 750 W/m^2, 0.03 kg/s, and 1.78, respectively.

3.2 Flat-plate PV/T modules

Flat-plate PV/T modules first appeared in 1978, *[8]*, and represent the most commercially successful type of PV/T modules. Flat-plate PV/T collectors can be divided according to the type of the used working fluid: water type, *[9-17]*, air type, *[18-20]*, and water/air type, *[21]*. Das et al., *[22]*, presents a review on the design and development of flat plate hybrid PV/T systems. According to the full review of the literature, the authors found that the sheet-and-tube is the most dominant thermal absorber fabrication technique when heat transfer fluid is a liquid, that the phase change material (PCM) based PV/T modules has immense potential to be integrated into building facades, and that the graphite infused PCM significantly enhances the electrical efficiency of PV module.

4 COOLANT TYPE

4.1 Water PV/T modules

The most useful working fluid in PV/T systems is undoubtedly water, as it has a higher thermal conductivity, heat-carrying capacity, and heat transfer rate than air, and thus provides more uniform cooling of the PV module. In addition to the working fluid, the design of the sheet-and-tube, which is usually installed on the back of the PV/T module, is also extremely important. Abdulameer et al., *[9]*, investigated the performance of two different types of sheet-and-tube PV/T module (serpin-direct and serpentine sheet-and-tube design), changing the mass flow rate. The results showed that the serpin-direct sheet-and-tube design achieved better electrical efficiency (by 0.4%), with a mass flow of 0.1 kg/s and solar radiation of 900 W/m^2. In summary, the mass flow rate plays an essential role in the design of PV/T modules. Nowzari, *[11]*, numerically investigated the performance of six different configurations of sheet-and-tube design on the PV module, with heat flux and output temperature representing the output parameters. The first four models represent a channel of different thicknesses mounted on the front or back of the PV module, while the last two models represent a channel with fins of different thicknesses mounted on the back of the PV module. The results showed that the first model with a front-mounted water channel had the highest amount of heat flux and, therefore, backside of a monocrystalline silicon PV module. As previous studies have shown, mass flow is critical as it changes the outlet temperature of the water from the sheet-and-tube collector and, consequently, the thermal efficiency of the PV/T module. However, since mass flow is also related to electrical efficiency (faster cooling), it is necessary to determine the optimal mass flow rate of the system to achieve relatively high thermal and electrical efficiency at the same time. Therefore, the study, *[12]*, investigates the optimum mass flow rate of a PV/T system, while also taking into account the most optimal slope and volume of water in the system. In addition, the results of the experiment showed that the PV/T module produces an excellent performance at a range of 0.10–0.15 kg/s mass flow rate, as well as, 100 l water volume and 25° inclination angle. Figure 3 presents the schematics of the various PV/T water/air modules; a) air-flow before PV module and water flow in the tube (commercial type of water cooling), b) air/water flow (separated) before PV module, c) air/water flow (combined) before PV module and d) air/water flow (separated) before PV module and air/water flow (combined) behind PV module.

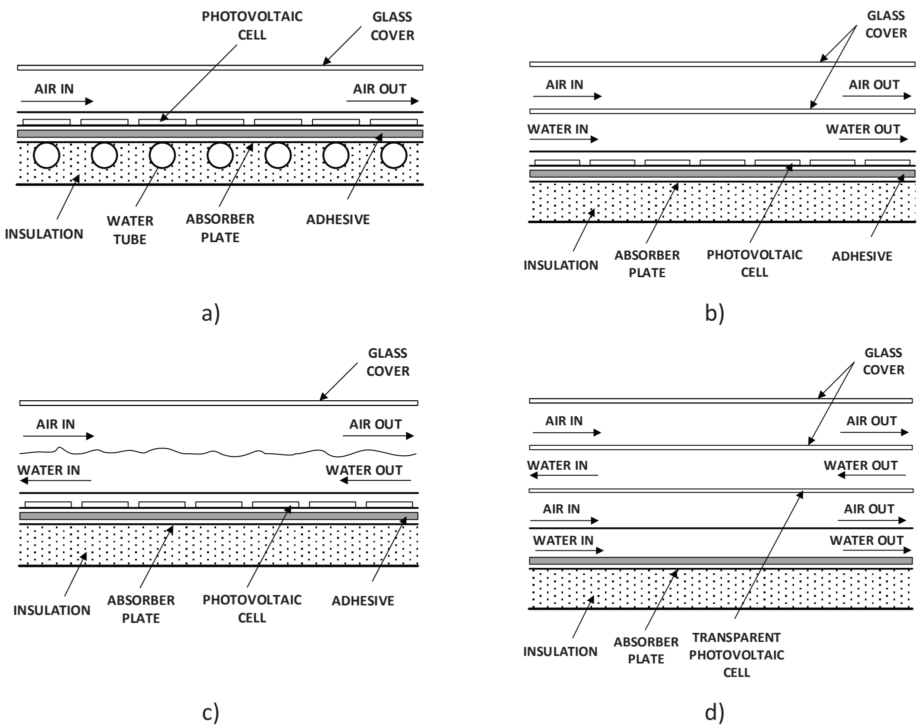

Figure 3: *Schematics of the various PV-T air/water modules (redrawn from [1]): a) airflow before PV module and water flow in the tube (commercial type of water cooling), b) air/water flow (separated) before PV module, c) air/water flow (combined) before PV module and d) air/water flow (separated) before PV module and air/water flow (combined) behind PV module.*

In addition to the described systems, there are also interesting features, such as adding iron filings between sheet-and-tube water module and absorbing plate to increase the heat transfer between the working fluid and PV module, *[13]*. An experimental study presented by Huo, *[13]*, shows that the temperature of the PV module is effectively reduced by filling iron chip (from 3.5 to 6.5 ° C), thus increasing the electrical efficiency to 19.8%. Cen et al., *[14]*, presents an experimental study on a direct water heating PV/T technology as a self-powered, off-grid, solar system. The PV/T system demonstrated the ability to provide hot water (approx. 80 °C) for a family of four, as well as providing excess electricity for household applications (average solar radiation of 4.5 kWh/m^2), with electrical and thermal efficiency of 13.4 and 53.4 %, respectively. Seme et al., *[23]*, present a research study of various designs of sheet-and-tube PV/T water modules and measurements of the flat-plate PV/T water module of the German manufacturer WIOSUN. The PV/T system is presented in Figure 4 and consists of a flat-plate PV/T water module, heat pump (evaporator/compressor/condenser) and convector. On its primary side, a flat-plate PV/T module uses solar glycol as a working fluid, while the secondary side uses water. Figures 5 and 6 present the output power and efficiency of the PV module as a function of the temperature of the PV module T and solar radiation G. The results show that cooling the PV/T module to 10 °C improves the output power and efficiency by approximately 10% and 2%, respectively.

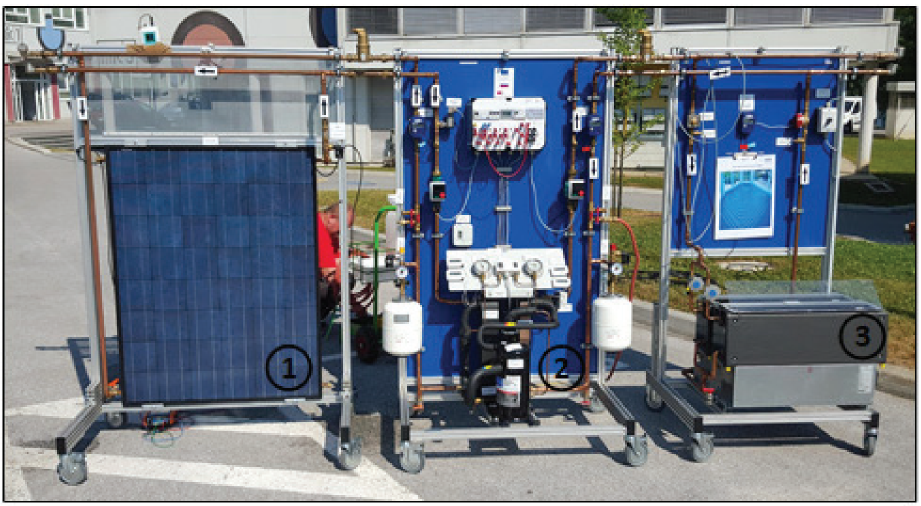

Figure 4: *PV/T system of a German manufacturer WIOSUN: 1. Silicon poly-crystalline PV/T water module, 2. heat pump (evaporator/compressor/condenser), 3. Convector, [23].*

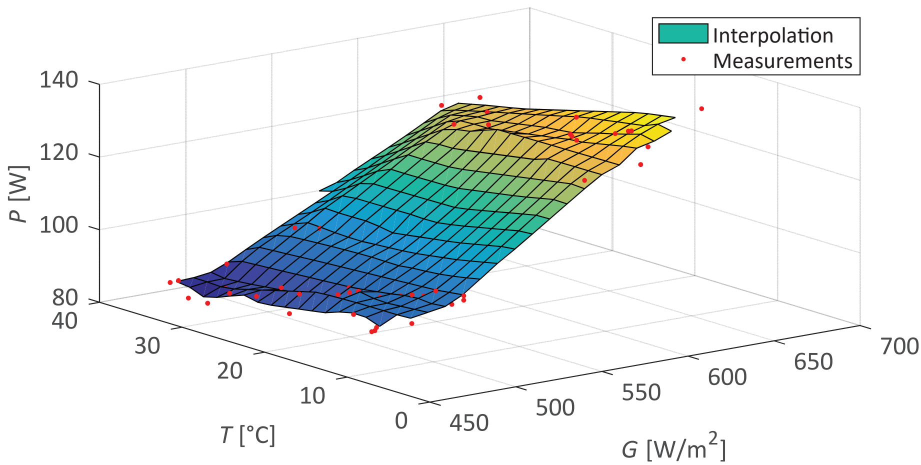

***Figure 5:** The output power P, as a function of the temperature of the PV module T and solar radiation G (results used from [23]).*

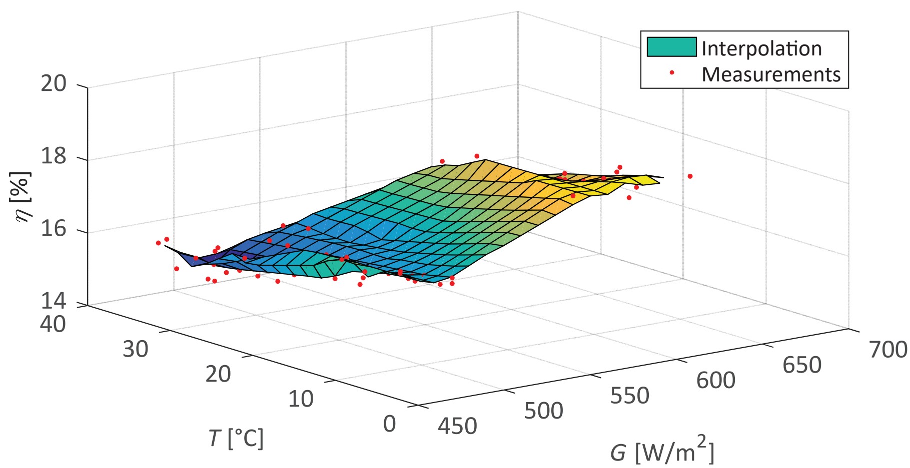

***Figure 6:** The efficiency of the PV module, as a function of the temperature of the PV module T and solar radiation G (results used from [23]).*

4.2 Air PV/T modules

In addition to the disadvantages, the air PV/T module also has enormous advantages over the water PV/T module: simplicity in construction, low operational cost and suitability for integration into buildings, *[24]*. Furthermore, it is suitable for implementation in areas with lower temperatures. Saygin et al., *[19]*, present an experimental study of a modified PV/T air module, with air entering the module through a gap in the middle of the glass cover.

Measurements were taken for 3 different distances (3, 5 and 7 cm) of the glass cover from the PV module, at different tilt angles and mass flow rates. The highest thermal efficiency was obtained at a distance of 3 cm between the glass cover and the PV module, while the electrical efficiency was obtained at a distance of 5 cm. Hussain et al., *[20]*, present a review paper of design development and performance evaluation of PV/T air modules, highlighting recent developments of PV/T modules and studies that present the integration of photovoltaic/thermal air (BIPV/T) systems into buildings. Figure 7 presents the schematics of the various PV/T air modules; a) airflow before PV module, b) airflow behind PV module, c) and d) before and behind PV module.

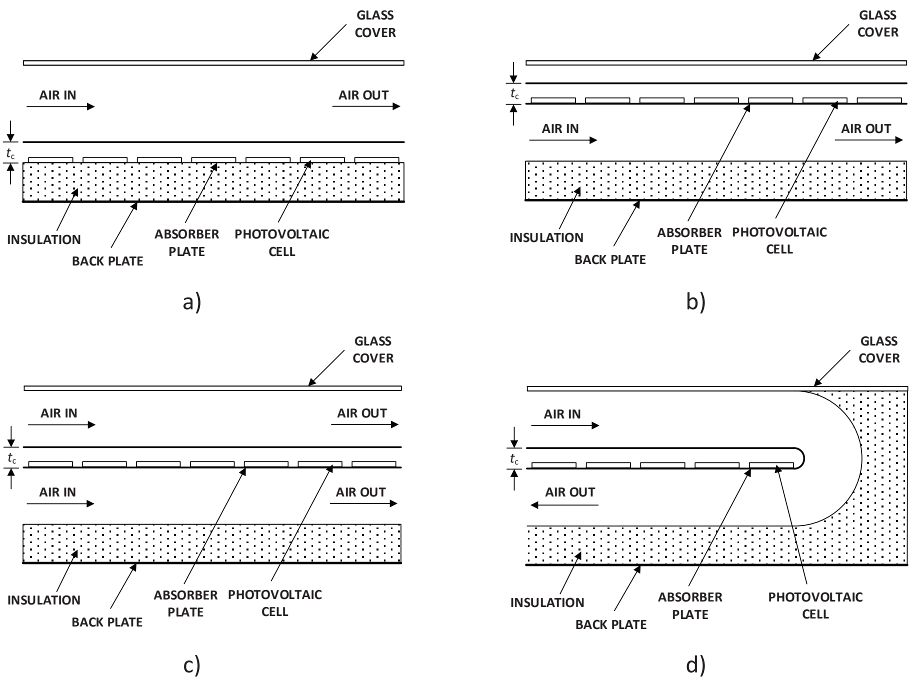

Figure 7: *Schematics of the various PV/T air modules (redrawn from [25]): a) airflow before PV module, b) airflow behind PV module, c) and d) before and behind PV module.*

5 CONCLUSION

This paper aims to present state-of-the-art hybrid PV/T systems; it describes the basic methodology, advantages and disadvantages of individual technologies and coolants. The results of studies presented by other authors have shown that the commercialization of PV/T systems is not growing as fast as individual photovoltaic or thermal systems. Given that PV/T modules represent greater potential due to high efficiency per unit area, it can be expected that the development will increase and thus reduce the production and installation costs in the near future. In further development, nanoparticles will play an important role as they have even problem of the sedimentation of nanoparticles in case of PV/T system failure (consequence: reduction of thermal conductivity).

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Nomenclature

(Symbols)	(Symbol meaning)
BIPV/T	building integrated photovoltaic/thermal
CPC	compound parabolic concentrator
CR	concentration ratio
G	solar radiation
PCM	phase change material
PV	photovoltaic
PV/T	photovoltaic/thermal
T	temperature
T_a	ambient temperature
TFEC	total final energy consumption
T_{in}	inlet temperature
T_{out}	outlet temperature
T_{st}	temperature from energy storage tank