

Novel Designs of Photovoltaic Thermal (PV/T) Systems



K. Sopian, Ali H. A. Alwaeli, Hussein A. Kazem

Abstract: Advanced concepts of hybrid photovoltaic thermal (PV/T) collectors are proposed to improve electrical efficiency and utilize the waste heat as thermal energy. The use of air, water, and combinations of the two are considered traditional techniques. The complexity is raised when using advanced state-of-the-art systems to improve the overall efficiency of PV/T such as employing nanofluids, nano-Phase Change Material (PCM), heat pump and jet impingement. This paper presents a review of novel designs which are proposed in the literature to enhance the performance of PV/T collectors and from it the evaluation criteria is derived. The comparison between different designs could be based on having same pumping power, size, or designs; depending on the element intended for the comparison. The designs also vary according to the bias assigned; whether to improve electrical performance more, or thermal performance. The common aspects observed in the literature are investigations of mass flow rate, impact of solar irradiance, and design parameters such as pipe material, configuration and diameters.

Keywords: Nanofluids; PCM; nano-PCM; jet impingement; heat pump

I. INTRODUCTION

PV modules are sold commercially provided with rated power output, efficiency and other electrical characteristics at standard test conditions (STC). These conditions are defined as testing under solar irradiance of 1000 W/m² which is equivalent to 1 sun, ambient temperature of 25 °C and pressure of 1.5 AM. However, during operation in outdoor conditions the performance of the PV experience variations which are associated with weather conditions and solar cell manufacturing [1-2]. The increase of the heat in solar cell causes a drop in the open circuit voltage which ultimately causes power reduction [3]. This is demonstrated in Figure 1 which shows power degradation of multiple PV systems across time. Hence, manufacturers provide the temperature coefficient of the maximum produced power of the PV to illustrate the amount of loss which is caused by an increase of 1 °C of cell temperature

For example, the temperature coefficient of the (JKM315P-72 295-315 Watt) type PV [4] is -0.41%/°C above STC. In some works, it is reported that a reduction in efficiency of up to 5% occurs when the cell temperature increases 10 °C [5]. Hence, the importance of introducing cooling mechanisms to improve the performance of PV modules. Passive cooling technique such as use of fins or phase change material is useful and low in operation and maintenance costs. A heat sink was implanted for PV heat dissipation by Cuce et al. [6]. The authors conducted a steady-state heat transfer analysis for the system to formulate the design of the heat sink in terms of dimensions. A 20% increase in the PV maximum power output was observed by the authors for implementing the heat sink. On the other hand, Chandrasekar et al. [7] investigated the use of passive cooling system with simplified design and implemented cotton wick structures to reduce temperature of the PV modules. The investigation was also extended to test PV performance under cooling and non-cooling modes; using water and nanofluids for cooling. Numerical investigations were carried out by Stritih et al. [8] using TRNSYS software to study the impact of placing a tank filled with phase change material (PCM) to the back of PV module. The aim is to improve the electrical efficiency by providing thermal regulation through use of PCM material. Validation was made through outdoor experiments. The efficiency was found to increase from 1.1 to 2.8% as a result of passive cooling by PCM, and for simulation of 1 year, the system generation is found higher by 7.3% for the location of installation [8].

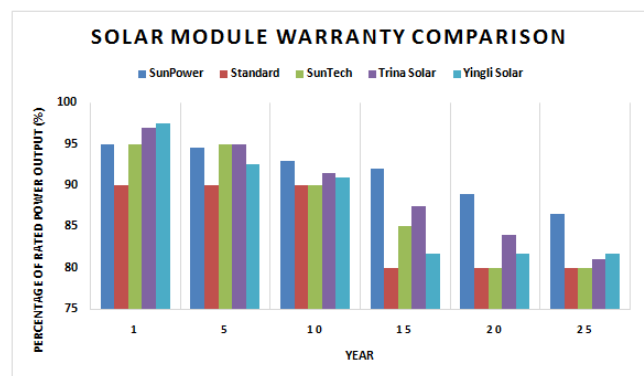


Fig. 1 Degradation of multiple PV products across the years in terms of power output

Although for the simplicity of having passive cooling, active cooling offers different features. Active PV/T systems are useful for simultaneously producing electrical and thermal energy.

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The PV/T hybrid collector is commonly comprised of a

PV module and a thermal absorber attached to it, with a working fluid flowing within. The type of working fluid can and have been used to classify the different types of PV/T's.

Hybrid PV/T systems produce higher energy than separate systems of PV and solar thermal and hence this technology has massive potential for commercialization and transforming the solar energy market. The design of the thermal absorber varies according to the intended configuration (e.g. direct-flow, parallel-flow, serpentine, etc.) and different absorber shapes (rectangular, square, circular, etc.), dimensions (e.g. thickness, diameter, etc.), material (copper, aluminum, steel, etc.). Certainly, highly thermally conductive material must be placed in between the two to ensure; minimizing air gaps, and improving heat transfer (e.g. silicon oil). The type of working fluid and set mass flow rate are critical for enhanced heat transfer, which is demonstrated in the literature.

The role of the pipe is to absorb the heat either directly from the PV plane, or from the absorber sheet. The heat is transferred into the working fluid, which flows at a set flow rate. The areas which are left out will remain heated, and perhaps minimal temperature distribution across the PV is achieved. The occurrence of hot spots is another issue that requires to be treated through cooling, etc.

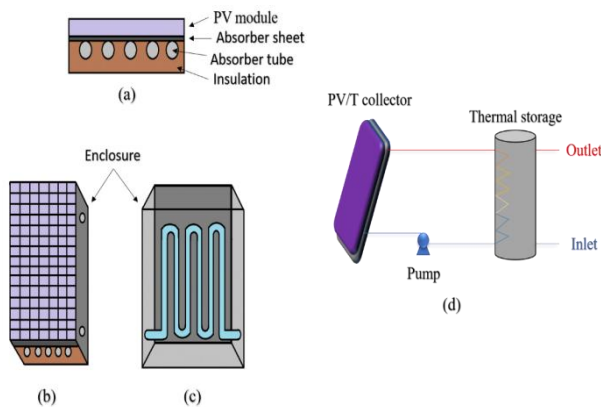


Fig. 2 Typical PV/T collector (a) cross-sectional side view (b) 3-D view of collector (c) 3-D view from the inside of PV/T enclosure and (d) schematic drawing of PV/T system

The components, illustrated in Figure 2, used to assemble a typical PV/T are PV module, an absorber, tubes (either part of the absorber or separated from it) and an enclosure which confines all elements, as depicted in figures 2.b and 2.c. Moreover, Figure 2.c shows the tube configuration within enclosure. While Figure 2d shows components outside of the collector, such as pump, pipes, thermal storage, etc. The concept of PV/T is further illustrated in Figure 3, which shows how solar irradiance is converted to thermal and electrical energies, both of which can be calculated along with device efficiency. The efficiencies are described in equations for solar thermal, photovoltaic and the overall PV/T efficiency [9-11].

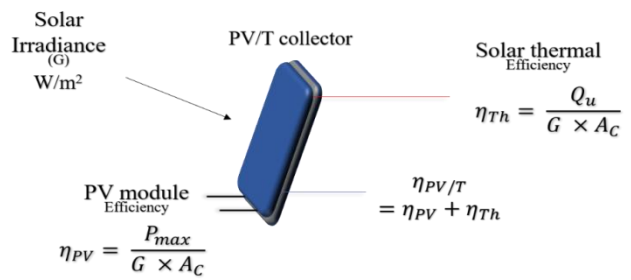


Fig. 3 Efficiency equations of PV/T

The heat gain is considered the thermal output of solar thermal and is represented by Q_u , while output of PV module is P_{max} which is multiplication of V_{mpp} and I_{mpp} [10]. The outputs could feed thermal and electrical needs, or conversion to feed auxiliary from electrical output to maximize thermal output and vice versa.

II. LITERATURE REVIEW

The taxonomy of the study is provided in Figure 4, which shows two classifications for the PV/T's under review, which are working fluid and novel designs of PV/T systems. The working fluids are sub-categorized into air, water and combinations of the two. While, novel fluids are made of nanofluids and refrigerants. The novel designs to be described are jet impingement with CPC, jet impingement using nanofluids, nanofluid with PCM medium, and nanofluids with nano-PCM medium.

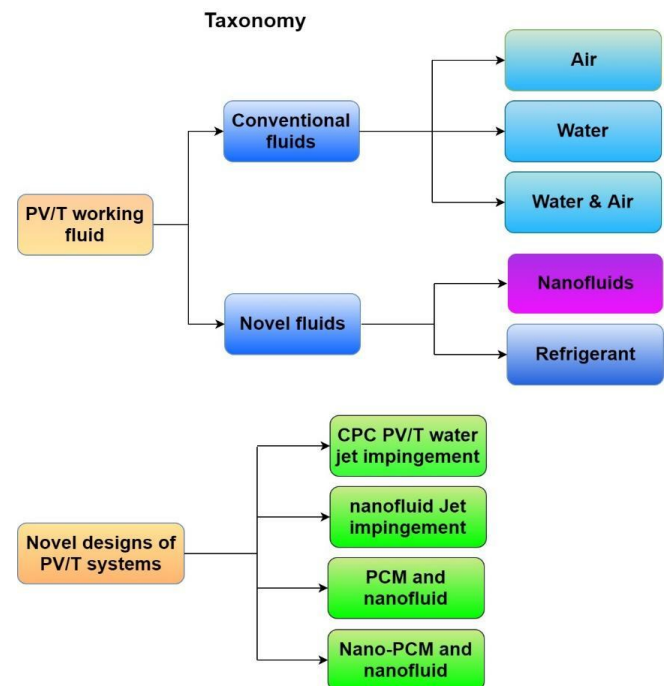


Fig. 4 Methodology of literature review flowchart

Conventional PV/T systems

Air-based PV/T systems are useful for heating air in residential and industrial settings for a mid to low temperature range. The research and development are aimed to increase the overall PV/T efficiency for active-cooling mode, while maintain the low-costs related to this technology.

Typical air-based PV/T collectors exhibit single or double air-passage channels, while air-based PV/T collectors use sheet-and-tube absorber, round tube absorber, etc.

Hu et al. [12] investigated the outdoor performance of an ETFE cushion roof integrated with PV/T system by assessing its energy. The investigation was aimed for performance of PV/T under winter and summer conditions. On the other hand, water-based PV/T's are more efficient in cooling and have better thermal efficiency. Although issues of costs, leakage and possible freezing in cold climates are possible. Moreover, the structural parameters of ETFE cushion roof and the solar energy utilization for these systems were investigated. The authors claim the system produces average total and net electricity of 54.5 Wh and 42.9 Wh which indicates its high potential for autonomy. Further studies can be made for study [13] to include aspects such as Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA). Moreover, given the high temperatures which occur inside the ETFE cushion roof, it is reasonable to assume high thermal energy can be produced. However, possibility for thermal stress on PV should be investigated. Although 1 year of testing was completed for this study [13] further testing to achieve long-term evaluation of PV/T performance is highly useful to understand the level of electrical energy reduction due to PV material degradation.

Ahn et al. [13] analyzed performance characteristics of PV/T assisted Heat Recovery Ventilation using air as working fluid for building integrated applications. The HRV system exhibited a heat transfer efficiency of 80%. The purpose of the study was to assess the performance of Building-Integrated PV/T with air as working fluid to assist residential HRV systems. Hence, two modes were used to investigate the performance of HRV which are: PV/T mode and OA mode. The former used the outlet warm air from PV/T as inlet to HRV, while the latter used outdoor air by feeding it directly. The two systems were assessed through monitoring the enthalpy for either modes, as well as performance evaluation of the PV/T itself. The findings reveal better performance by PV/T assisted HRV systems to their conventional counterparts. However, the authors did not study the added costs associated with material and installation for the lifetime of the project. Certainly, higher performance is an advantage for PV/T assisted HRV systems, yet it is preferable to demonstrate the cost differences as well.

Alzaabi et al. [14] study the efficiency of a water-cooled PV system in UAE in contrast to a non-cooled type. The findings of the water-based PV/T and conventional PV were compared to expected outcome through computer simulation, using SimuLink software. The study shows clear deviation between cooled-PV output (in W) and non-cooled-PV output (in W). Minor deviation was found between the SimuLink model results and actual PV (of PV/T) results. Although the authors did not present further elaboration on the SimuLink model, nor its implementation. In addition, the model did not account for cooling of PV module.

Lu et al. [15] Compared three types of PV/T [PVT-1, PVT-2 and PVT-3] in terms of daily efficiency, where each with its own configuration. The study used both experimental method and numerical CFD simulation. The three types proposed by the authors [15] are: conventional

air-gap PV/T, new-air-gap PV/T and zero-air-gap PV/T, respectively. All types are water-based PV/T's with thermal collector of sheet and tube type. The solar cells are stuck on the solar thermal collector in the first type (PVT-1), while they are fixed on the bottom of the glass cover for the second type (PVT-2). Certainly, the study shows highest overall efficiency is achieved when using PVT-1, while highest electrical efficiency was achieved for PVT-3. Hence, this study shows the difference of these configurations in terms of performance, however it is left to the consumer to decide; given that some consumers may prefer electrical efficiency to overall efficiency.

Liang et al. [16] tested the water-type PV/T which is filled with graphite by comparing it to conventional PV module. The authors tested elements such as temperature of backplane, inlet fluid, outlet fluid and tank. In addition, evaluation of PV/T performance was made by finding the thermal, electrical and primary energy-saving efficiencies. A submersible pump with a hydraulic head of 5 meters was used to provide required mass flow rate. The authors [16] followed the ANSI/ASHRAE Standard 93 for the testing for solar collector using simulator. Although comparison was made to typical PV system in terms of achieved efficiency, it is also preferable to calculate the energy of the proposed system over the testing period.

A combination of water and air as working fluids for cooling of PV modules is found to cause further increase in overall efficiency depending on the type of design and combination. Certain issues such as complexity of design are bound to occur with this type of PV/T. Jarimi et al. [17] used a serpentine-shaped copper pipe to cool a monocrystalline PV using both water and single pass air channel. The bi-fluid collector was compared to individual water, air and no-cooling types. The authors [17] provide electrical energy efficiency and power for all proposed configurations. Typical PV modules exhibits lowest produced overall energy efficiency. However, highest was attributed to air and water -based PV/T. The same difference was observed for the electrical efficiency. The study presents a thermal model for the proposed collectors and uses two methods for validations: the first through using manufacture's data sheets (NOCT data) and the second using real data from other studies to validate the model.

Novel working fluids

Further development in working fluids is observed in investigations of refrigerant based PV/T, which are commonly employed for assisting heat pump systems. Heat pump systems are composed of evaporator unit, condenser unit, compressor unit and expansion valve. The heat enters through evaporator and exits through condenser. A refrigerant is a heat transfer medium that circulates through these components.

Tsai et al. [18] employed a refrigerant-based PV/T for the assistance of a heat pipe water heating system. The system was composed of PV/T evaporator, compressor, expansion valve and condenser. While, a Lab View based measurement system was implemented for the experiments.

The PV/T consisted of laminated PV, copper tube, thermal insulation and coated steel, where PV cells were sandwiched between ETFT and PET that were directly laminated in a steel-coating. Furthermore, the study provides a model and simulation for the system presented. Moreover, experiments were made to validate the findings.

Nanofluids are fluids composed of nanoparticles mixed with working fluids. The type of nanomaterial, size, shape and quality of mixing are all relevant topics of discussion and considerations for effective design of nanofluid-based PV/T systems. Khanjari et al. [19] simulated the performance of PV/T collectors which employ nanofluids using CFD to investigate the impact of nanofluids. The types of nanofluids used were Alumina-water and Ag-water. The study considered aspects such as nanoparticle volumetric ratio and heat transfer coefficient. The results of the numerical model by Khanjari et al. [19] were validated by comparing the findings with other studies in the literature. The authors found that increase of fluid inlet velocity led to reduction in outlet fluid temperature. The same was observed for the absorber plate temperature. However, the rate of reduction was found higher Alumina-water nanofluids than AG-water nanofluids, with same volumetric ratio. Authors claim [19] increase of electrical efficiency and decrease of thermal efficiency in response to increase of fluid velocity. Hence, a drop in overall energy efficiency. While, electrical, thermal and overall energy efficiencies were observed to increase with increase of volume fraction, to 0.14. Ag-water nanofluid lead to higher thermal and overall efficiency rise, while Alumina-water nanofluid led to higher electrical efficiency rise.

The one-step method of nanofluid preparation was used by Aberoumand [20] to produce an Ag/water nanofluid and use it as coolant for a PV/T collector. Evaluation of both energy and energy was made to examine the PV/T performance. The Electrical explosion of wire (EEW) was used due to its relative cheap cost and environmental friendliness. The main contribution is conducting the experiments for laminar, transient, and turbulent flow regimens. Comparison between the proposed system and water-based PV/T was done based on power production. However, further work needs to be done to compare PV/T with nanofluid and PV/T with water by using equal pumping power criteria.

Novel concepts of PV/T systems

The studies published on advanced PV/T systems have different elements of novelty which could be through utilizing methods of enhancing the heat transfer or use of engineered working fluids. Hence, its elements such as

concentrators and reflectors are introduced to the design, in addition to higher efficiency material.

Sardarabadi et al. [21] performed experiments to test the performance of a hybrid nanofluid based PV/T which uses PCM as medium, embedding the cooling pipes, in outdoor conditions of Iran. The nanofluid used is Silica-nanofluid (SiO₂). The outlet temperature, energy and energy efficiency were examined to evaluate the novel system in terms of performance, showing improvement over conventional designs of PV/T collectors. Another development to the system was performed by Al-Waeli et al. [22] by employing nano-material into the PCM layer. The authors justify this by the low thermal conductivity of PCM. The performance of nano-PCM based PV/T using nanofluid coolant under tropical climate of Malaysia. The author claims addition of nanoparticles to PCM layer leads to improved thermal regulation and heat recovery for the PV/T system. Moreover, leads to enhanced electrical and thermal efficiency overall the experiments period. However, the authors [22] highlight the need for continuing to operate the pumps for cooling after sunset to remove heat trapped in nano-PCM layer. Other aspects that must be added are energy calculations for charging and discharging period of nano-PCM.

Jaaz et al. [23] used a concentrator CPC-type to increase the solar irradiance landing on the PV module and introduced cooling using Jet impingement with water as coolant. The system was experimentally tested in outdoor conditions of Malaysia. Another setup of a jet impingement PV/T without CPC and with nanofluid as coolant was done by Hasan et al. [23]. However, the experiments were carried out indoors, using a jet with 36 nozzles. The main difference between the two studies is the use of nanofluids and the experiments being conducted outdoors for Jaaz et al. [23] and indoors for Hasan et al. [24]. Both studies presented novel methods and reported high energy efficiency. The same system produced by Jaaz et al. [23] could use nanofluid instead of water as base fluid. Although much complexity and costs are added to manufacture and operate the PV/T system, it is important to view the improvements. Further LCA and LCCA studies could be made for the presented systems [23-24]. Finally, Du et al. [25] used MWCNT-paraffin as phase change material for a PV/T system. The system used MWCNT-WEG 50 nanofluid as coolant. The results show that around 40% of generated electricity was achieved between 12 and 4 PM local time. The evaluation was based on energy performance and equivalent electrical-thermal power of the system. The results show that the highest thermal and electrical performance was around 292.1 W/m². Table 1 provides a brief summary of features emphasizing type of working fluid, efficiency (electrical and thermal -PV/T, design and operating parameters.

Table. 1 Features in PV/T systems from some of the studies

Ref.	Type of fluid	Mass flow rate	Electrical power or efficiency	Thermal power or efficiency
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Hu et al. [12]	Cushion roof Integrated photovoltaic/Thermal system (CIPV/T system)	Air	-	7.7% 28%
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Liang et al. [16]	Sheet and tube (PV/T)	Water	0.012 kg/s.m ²	7.2%	36%
Khanjari et al. [19]	Sheet and tube (PV/T)	Nanofluid	0.022 kg/s.m ²	13.2%	55%
Aberoumand [20]	Sheet and tube (PV/T)	Nanofluid	0.034 - 0.116 kg/s	10.5%	70%
Jaaz et al. [23]	Jet impingement (PV/T)	Water	0.25 kg/s	≈ 12.5%	≈ 81.5%
Hasan et al. [24]	Jet impingement (PV/T)	Nanofluid	0.167 kg/s	12.75%	85%
Alwaeli et al. [22]	Absorber tank (filled with nano-PCM)	Nanofluid	0.17 kg/s	13.7%	72%
Du et al. [25]	Absorber tank (filled with nano-PCM)	Nanofluid	0.0017- 0.02 kg/s	▲ ~20%	▲ ~130%

(≈) refers to the value is approximate; observed through a figure

(▲) refers that the parameter was enhanced by the value

The table above shows precisely the impact when implementing nanofluids on the efficiency of the thermal aspect of the system, although the comparison is unrealistic given the differences in design, operating conditions and environmental conditions as well. The range of mass flow rates varies through the literature between 0.012 kg/s to 0.17 kg/s. The highest electrical efficiency was observed when cooling rate achieved was higher than temperature rise in the cell.

III. THEORETICAL ANALYSIS

Almost all original studies consist of theoretical analysis. The theoretical aspect is simply a mathematical description of the physical concepts associated with presented technology. For instance, PV electrical conversion efficiency can be described through equation, as illustrated in Figure 3. Theoretical analysis is usually performed to layout mathematical bases for numerical analysis. Jarimi et al. [17] performed a theoretical analysis considering the heat conduction term in the x-direction of PV cells for a sheet and tube PV/T collector. Due to complexity of the system, authors [17] employed finite difference method and constructed temperature nodes. Certainly, assumption is generally made to simplify the theoretical analysis. For instance, the serpentine-shaped copper pipe was assumed a long-straight tube. Along the y-direction, the solar collector was segmented into segment M which is sub-segments into m. In addition, authors [17] constructed temperature nodes in the x-z plane, while nodes are positioned in the x-y plane. The accuracy of the numerical or theoretical findings are dependent on the accuracy the mathematical model's describe the physical aspects of the proposed system, hence its necessity.

IV. NUMERICAL AND EXPERIMENTAL STUDIES

Numerical analysis of PV/T performance is quite useful to determine the best parameters and behavior associated with the proposed configuration and/or design. This technique allows for saving both time and money which are associated with manufacturing and installing the proposed PV/T as well as testing it. Hence, numerical studies are conducted to find the optimum performance parameters and behavior of the proposed PV/T. It is important to validate those studies by producing a prototype for experimental purposes. The experiments should include different types of sensing elements for temperature (such as k-type

thermocouples), wind speed (anemometer), solar irradiance (pyranometer), voltage and current (multimeters, LIV testers, etc.). However, it is noteworthy to mention that due to PV/T being a relatively new technology, there is still no prominence for PV/T numerical software. Hence, different software is used for numerical studies. CAD and Solid Works are generally implemented to draw the conceptual design and export it to software like ANSYS Fluent (CFD software) for thermal simulation. The numerical method by Lu et al. [15] was used to determine the thermal behavior of the proposed PV/T collectors (PVT-1, PVT-2 and PVT-3) via CFD software. The authors [15] used ANSYS Fluent 14.0 for the simulation. The CFD model was made considering the heat conduction, heat convection and thermal radiation. Furthermore, the authors [15] utilized a surface-to-surface (S2S) model to calculate the solar irradiance. The fluid within the tubes was assumed laminar and incompressible due to the collector being like thermosyphon where the velocity of water is quite low. Moreover, the numerical meshing process included creating 1,000,000 meshed cells.

The experimental data was used to validate the numerical findings, specifically comparing the water temperature rise in the tank. The comparison is shown for the July and August. The numerical method was also used to assess the PV's covering factor (β) influence on PV/T. This was done by assuming four different values for the covering factor. The authors claim that PVT-2 was more sensitive than other types to the covering factor; glass temperature (of PVT-2) increases with increase of covering factor, unlike glass temperature of PVT-1 and PVT-3, which decreased slightly. SimuLink software is used to model and analyze the performance of PV modules. Khanjari et al. [19] conducted a comprehensive CFD study for the proposed system. Performing grid-independence study which resulted in selecting a mesh with 882,722 elements. Furthermore, the authors used the first and second laws of thermodynamics to establish energy and energy analysis, respectively. On the other hand, Alzaabi et al. [14] used SimuLink to compare its findings for PV module performance to that of experimental, or actual, PV (of PV/T) performance. The authors report only minor deviation in the findings. However, the PV module in SimuLink only shows PV module performance (without-cooling) as in a typical PV module.

Tsai et al. [18] used MATLAB/Simulink environment to build their proposed model and considered reciprocal energy exchange which occurs between PV/T evaporator and the Heat Pump Water Heating (WPWH) system. The model was made considering PV effect (converting irradiance into electricity), thermal transportation (PV/T and environment) and heat recovery (evaporating refrigerant within coil of evaporation). Hence the model combines PV/T electricity and thermodynamics as well as HPWH system.

V. CRITICAL REVIEW

Extensive research has been conducted in the area of PV/T with respect to validating the importance of this technology and exploring the various designs and operating modes it can be installed under. The potential for increased reliability and effective adoption, of PV/T in harnessing solar energy for residential, commercial and industrial purposes, is significant. However, this technology remains relatively under development and several points have been observed in this review that needs to be addressed in future studies. These points cover both technical and economic side views and are listed for both thermal and electrical aspects of the PV/T technology.

Thermal aspect:

1. Nanofluids based-PV/T systems are compared with water-based PV/T systems in terms of energy and power production. However, comparison should be made on bases of equal pumping power. Certainly, this should also be made for different types of absorbers as well. Different pressure drops and power loss due to further pumping requirement are associated with different designs and working fluids. Having the pumping power equalized shows how much efficient the proposed systems are.

2. What are the suitable methods in disposing the temperature which arise in cooling water when used for continues cycles of cooling in tropical areas? Moreover, some studies does not consider cooling element or reducing the hot water produced for cooling-PV or at least using it for an application. It is necessary to view the temperature which reaches the end-consumer or intended thermal application, as well.

3. In many studies, extreme examples to assess the performance of PV/T are taken such as summer and winter, or simply days with high and days with low solar irradiance. However, given the constant variation in weather, especially in tropical climates, is it acceptable to carry out the experiments under clear sky? Or evaluation novel PV/T systems in extreme weather only?

4. Nano-PCM and nanofluids are used in novel PV/T systems. However, authors must consider aspects such as long-term performance evaluation, as well as testing of latent heat with more accurate methods. Moreover, presenting experimental aspects for testing the nano-PCM, for instance how to test the temperature if nano-PCM is placed in a tank. Furthermore, how many cycles can nano-PCM's operated in and remains to be useful.

5. Larger area is needed to accompany jet-impingement based PV/T collectors for the tanks employed to cover them. How can these systems work cascade in series? Moreover,

what are the considerations made for heat losses of these fluids across the tank to maintain thermal efficiency?

6. Many research studies focus on comparing nanofluid-based PV/T systems to water-based PV/T systems according to only equal Reynolds number basis; however other criteria such as equal pump power should be considered.

7. PV/T performance is mainly assessed using total efficiency; however, this is not enough to truly judge the capabilities of PV/T systems accurately. Hence, it is necessary to measure how much of that energy is useful through energy analysis.

VI. CONCLUSIONS

In conclusion, this review offers an insight into trends in research and development of advanced PV/T systems. Many features can be introduced to PV/T systems such as use of concentrators, passive cooling structures and combination of heat transfer enhancing material. Due to the diverse components associated with these systems, it is clear that further investigation into impact of weather, mainly solar irradiance and temperature, are crucial to further understand the key elements of making this technology the future of solar. The following points have been observed from the literature:

1. Majority of investigations of design parameters such as pipe dimensions, configuration and material are made numerically, later validated experimentally. This is clearly to avoid the costs of having to construct many experimental setups which are both labor intensive and cost inefficient. The optimum design from a numerical point of view is then fabricated into an experimental setup to test the validity of prediction. Certainly, variations due to uncertainty in measurements and manufacturing quality of the prototype create some disparity in the findings. However, if within acceptable range and with similar curve shape then the findings are acceptable.

2. The increase of solar irradiance leads to higher efficiency if a good cooling rate is achieved through the PV/T collector. Cooling of PV module requires enhanced heat transfer, which is achieved by increasing area of contact between PV and absorber, improving material (i.e. using highly thermal conductive material) and using optimum mass flow rate.

3. The use of PV/T means that PV modules and solar thermal collectors can be utilized in the same space, which makes the system excellent for residential applications; as area is a limitation for public consumers. Hence, systems like building integrated PV/Ts are favorable to supply user with water heat and improved PV electricity generation. However, aspects such as added weight and area perhaps maintenance costs must be accounted and compared to separate systems.

The following points should be considered for future research in PV/T review, design, optimization and performance evaluation:

1. The back surface of the PV module could be nano coated to increase the heat transfer to the absorber attached to it.

2. To investigate the effectiveness of jet impingement using a thermosyphon scheme in cooling of PV module.
3. To compare between utility of focusing on cooling of PV system, or simultaneous heat generation.
4. There is an innate need to conduct long-term performance testing of these systems in order to establish a database which can provide definitive answers to the industry; for commercialization.
5. There is a need for creating a PV/T standard for testing, installation and performance evaluation.
6. The CPC PV/T system with jet impingement can be investigated utilizing nanofluids as coolants.

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DECLARATION OF CONFLICTING INTERESTS

“The Author(s) declare(s) that there is no conflict of interest.”

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