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A review of solar photovoltaic systems cooling technologies

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ABSTRACT

Cooling the operating surface is a key operational factor to take into consideration to achieve higher efficiency when operating solar photovoltaic systems. Proper cooling can improve the electrical efficiency, and decrease the rate of cell degradation with time, resulting in maximisation of the life span of photovoltaic modules. The excessive heat removed by the cooling system can be used in domestic, commercial or industrial applications.

This paper presents a review of various methods that can be used to minimize the negative impacts of the increased temperature while making an attempt to enhance the efficiency of photovoltaic solar panels operating beyond the recommended temperature of the Standard Test Conditions (STC). Different cooling technologies are reviewed, namely Floating tracking concentrating cooling system (FTCC); Hybrid solar Photovoltaic/ Thermal system cooled by water spraying; Hybrid solar Photovoltaic/ Thermoelectric PV/TE system cooled by heat sink; Hybrid solar Photovoltaic/Thermal (PV/T) cooled by forced water circulation; Improving the performance of solar panels through the use of phase-change materials; Solar panel with water immersion cooling technique; Solar PV panel cooled by transparent coating (photonic crystal cooling); Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation, and Solar panel with Thermoelectric cooling.

Several research papers are reviewed and classified based on their focus, contribution and the type of technology used to achieve the cooling of photovoltaic panels. The discussion of the results has been done based on the advantages, disadvantages, area of application as well as techno-economic character of each technology reviewed.

The purpose of this review is to provide an understanding for each of the above-mentioned technologies to reduce the surface temperature of the PV module. The study will focus on the surface temperature reduction array bound by each of the cooling technologies. The performance of each cooling technology will also be highlighted. In addition to this study, this review will include a discussion comparing the performance of each cooling technology. The outcomes of this study are detailed in the conclusion section.

This paper has revealed that any adequate technology selected to cool photovoltaic panels should be used to keep the operating surface temperature low and stable, be simple and reliable and, if possible, enable the use of extracted thermal heat to enhance the overall conversion efficiency. The presented detailed review can be used by engineers working on theory, design and/or application of photovoltaic systems.

1. Introduction

One of the most widespread technologies of renewable energy generation is the use of photovoltaic (PV) systems which convert sunlight to into usable electrical energy [1,2]. This type of renewable energy technology which is pollutant free during operation, diminishes global warming issues, lowers operational cost, and offers minimal maintenance and highest power density compared to the other renewable energy technologies, highlights the advantages of solar photovoltaic (PV) energy [3,4]. Apart from the several advantages displayed by the PV technology, this conversion system does have some general problems, such as hail, dust and surface operating temperature which can negatively affect the efficiency of the conversion system [5]. Exogenous climatic parameters such as wind speed, ambient temperature, relative humidity, accumulated dust and solar radiation are the most common natural factors which influence the surface temperature of a PV module [6]. Every 1 °C surface temperature rise of the PV module causes a reduction in efficiency of 0.5% [7]. Therefore, due to the temperature rise, not all of the solar energy absorbed by the photovoltaic cells is converted into electrical energy. To satisfy the law of conservation of energy, the remaining solar energy is converted into heat. The consequences of this wasted heat bring about a reduction in

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the overall conversion efficiency.

Efficiency improvements in solar energy conversion systems must be made in order for this renewable energy technology to be a viable solution. To make it a viable solution, there is a need to find different means of solving this temperature problem, which must result in an increase of the overall conversion efficiency.

Very few authors have tried to put together and conduct an extensive review of different technologies that can be used to cool the operating surface of solar panels with the aim of increasing the overall efficiency of the solar conversion system.

The authors of the paper cited in reference [8] have briefly discussed various solar PV panel cooling technologies. However, only a few technologies were introduced while the main focus of the paper was on the testing and performance of a developed Ground-Coupled Central Panel Cooling System (GC-CPCS).

In reference [9], the authors presented an overview of various methods that can be employed for cooling photovoltaic cells. However, when looking closely, it can be seen that the focus of the paper was only on examining the passive, forced air and liquid forced convection cooling methods applied to different solar concentrator systems.

Unlike the above-mentioned review studies, this paper provides a comprehensive review of how different technologies can be used to minimize the negative effects of increased temperature, while trying to improve the performance of a PV panel operating beyond the recommended temperature of the Standard Test Conditions (STC). For this purpose, an extensive number of research papers from different authors are used to achieve the objectives of the current study. Different tools (schematic diagrams, pictures, tables and figures) are used to enhance the content and to offer an effective and simple presentation.

The following technologies will be discussed and analysed in this work:

- Floating tracking concentrating cooling system (FTCC)
- Hybrid solar Photovoltaic/Thermal system cooled by water spraying
- Hybrid solar Photovoltaic/Thermoelectric (PV/TE) system cooled by heat sink
- Hybrid solar Photovoltaic/Thermal (PV/T) cooled by forced water circulation
- Improving the performance of solar panels through the use of phase-change materials
- Solar panel with water immersion cooling technique
- Solar PV panel cooled by transparent coating (photonic crystal cooling)
- Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
- Solar panel with Thermoelectric cooling

The paper is organized as follows: in Section 2, the basic operational principle of a PV cell is presented. The problem caused by an increase of temperature is clearly explained using graphs and equations. In Section 3, the different cooling technologies are described based on their operational principle using a suitable visual representation. In Section 4, an extensive tabular list of reviewed works is provided. Information such as the authors, research focus, review contribution and the technology used to address the temperature problem, can be obtained from this table. A discussion of this paper's main findings on the different technologies reviewed are available in Section 5, and the last section is the conclusion.

2. Description of a solar photovoltaic system operation

When a PV cell is exposed to solar radiation, the photon is absorbed by the P-N junction, which creates a potential difference across the junction. The charge-carriers start to flow and the resulting photocurrent is denoted as I_{PV}, which is paralleled by a P-N junction diode.

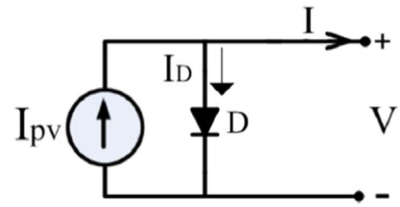

Fig. 1. Equivalent circuit of a PV cell [10].

Investigating the performance of a PV cell shows that the surface operating temperature plays a crucial part during the PV energy conversion process. High ambient temperatures and high PV panel surface operating temperatures cause overheating of the PV panel, which reduces the efficiency radically [11].

Fig. 1 shows that the preferred operating temperature ranges between 0 °C and 75 °C. The P-V characteristics are the relation between the output power and the output voltage, while the solar irradiance, E, and module temperature, Tm, are kept constant.

The effect of temperature on the solar panel's electrical efficiency can be analysed using the following equation:

$$\eta_{PV} = \eta_{T_R}[1 - \beta_R(T_C - T_R) + \gamma \log_{10} I_{PV}] \quad (1)$$

where: η_{PV} is the PV module efficiency measured at reference cell temperature; T_R (25 °C). β_R is the temperature coefficient for cell efficiency (typically 0.004–0.005/°C) [13]; I_{PV} is the average hourly irradiation incident on the PV module at nominal operating temperature; NT. T_C is the PV module temperature, and Υ is the radiation-intensity coefficient for cell efficiency, which is mostly assumed to be zero [14,15], reducing the equation to:

$$\eta_{PV} = \eta_{T_R}[1 - \beta_R(T_C - T_R)] \quad (2)$$

By adding and subtracting the ambient temperature, T_A, to and from the two temperature terms respectively, the following expression is obtained [13]:

$$\eta_{PV} = \eta_{T_R}[1 - 0.9\beta\left(\frac{I_{PV}}{I_{PV,NT}}\right)(T_{C,NT} - T_{A,NT}) - \beta(TA - TC)] \quad (3)$$

where: $T_{C,NT}$ (typically 45 °C) and $T_{A,NT}$ (typically 20 °C) are the cell and ambient temperatures, respectively. When using Eq. (3), it can be clearly seen that when $T_{A,NT}$ increases, the efficiency decreases.

3. Technologies used to increase the efficiency of the PV by solving the temperature problem

In this section the general operational principle of the different technologies that can be used to minimize the effect of the increased temperature, while attempting to improve the performance of a PV panel operating beyond the recommended temperature of the Standard Test Conditions (STC), will be explained technically in order to understand the relevant researches from different authors gathered, reviewed and summarized in Section 4 as well as the discussion in Section 5.

3.1. Floating tracking concentrating cooling (FTCC)

One method to achieve optimal output power of a PV module, makes use artificial basins for installing PV floating plants. These floating plants consist of a platform with PV modules, a set of reflectors and a solar tracking system. Cooling of the PV module is achieved via water sprinklers. Reflectors are used to concentrate the solar radiation to increase the energy harvesting. The floating platform allows for a one-axis tracking system for the positioning of reflectors and also for increasing the solar radiation on the PV modules. These plants are called FTCC, the acronym of Floating, Tracking, Concentrating and Cooling. Fig. 2 shows an FTCC system with its main components, where the following numbering represents:

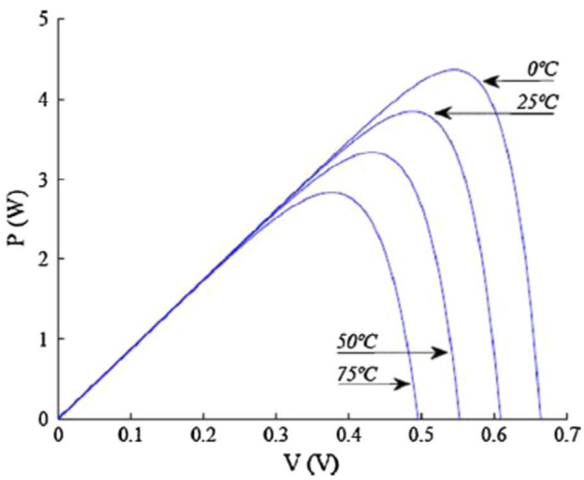

Fig. 2. The ideal P-V characteristics of a solar cell [12].

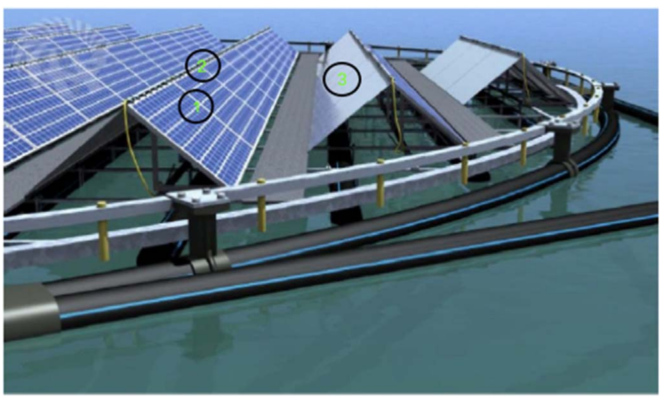

Fig. 3. Floating tracking concentrating cooling (FTCC) [16].

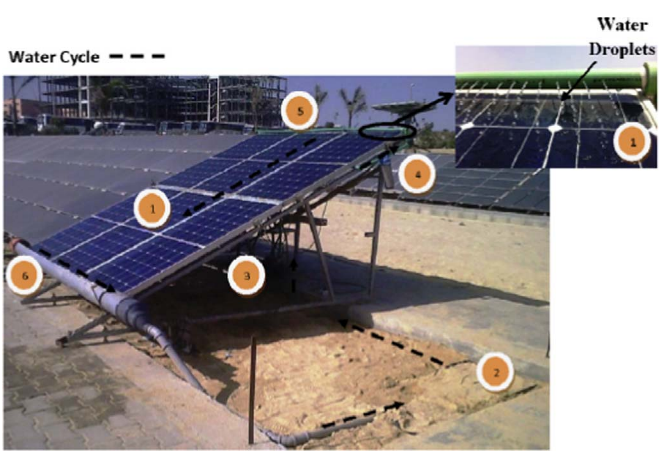

Fig. 4. Hybrid solar Photovoltaic/Thermal PV/T system cooled by water spraying [10].

(1) PV modules.
(2) Sprinklers
(3) Solar reflectors

3.2. Hybrid solar Photovoltaic/Thermal (PV/T) system cooled by water spraying

In this system, a centrifugal pump is used to force water flow through the spraying nozzles from the tank via a suction pipe. The suction pipe consists of a non-return valve and strainer to avoid the sucking in of large particles and to protect the centrifugal pump. Beyond the strainer water is transferred to the spraying nozzles with

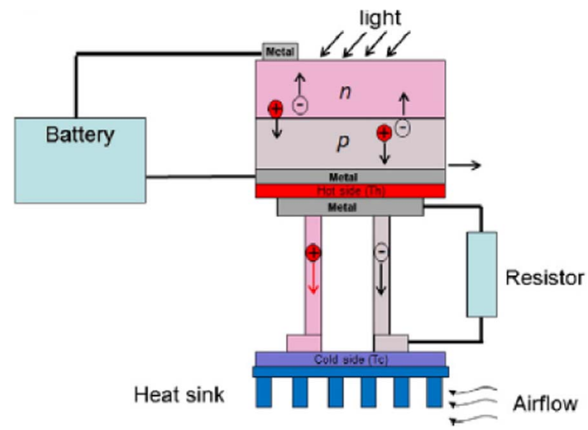

Fig. 5. Hybrid PV/TE system with heat sink [18].

Fig. 6. Hybrid solar Photovoltaic/Thermal (PV/T) cooled by forced water circulation [20].

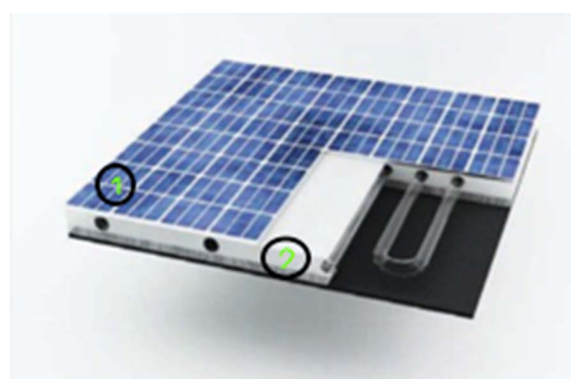

Fig. 7. PV panel with Phase-change materials [22].

the intention to cool the PV module via an industrial transparent water filter. A hybrid Photovoltaic/Thermal (PV/T) system, as seen in the figure below, consists of PV modules and a cooling system. The cooling agent, i.e. water, is sprayed on the surface area of the PV panel by using a fan [10]. When spraying water on the surface of the PV module, the temperature decreases and the electrical efficiency increases (Fig. 3).

The numbers on the figure above represent the following components:

(1) PV modules
(2) Aluminium water tank
(3) Centrifugal pump
(4) Industrial transparent water filter

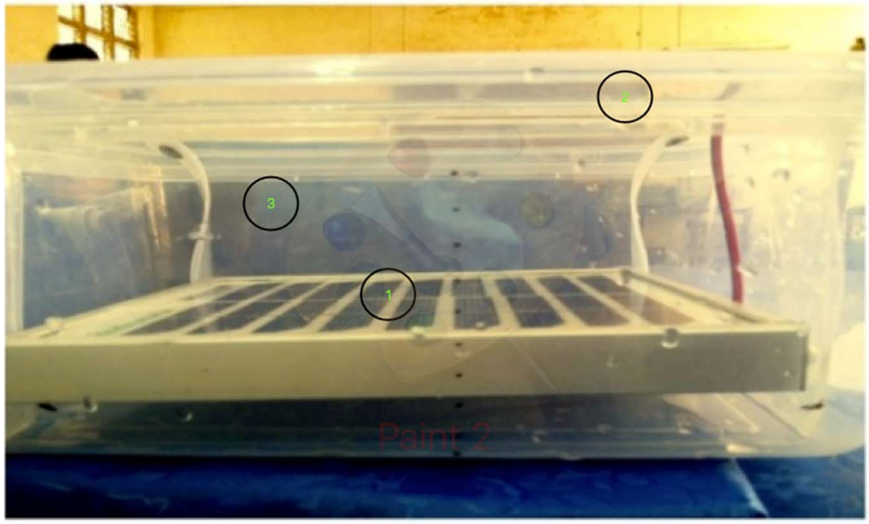

Fig. 8. Water immersion cooling technique applied to PV panel [23].

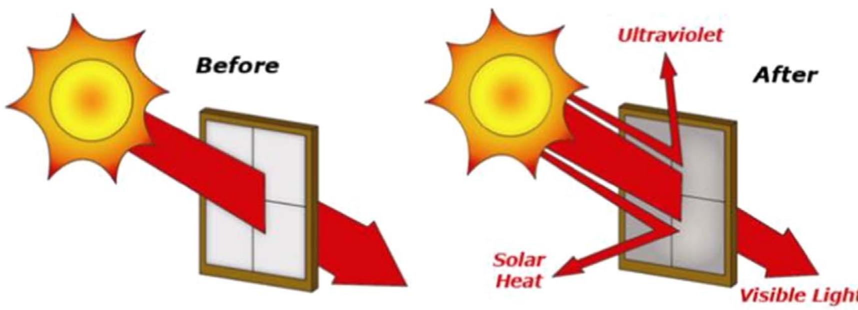

Fig. 9. PV panel cooled by transparent coating (photonic crystal cooling) [25].

Fig. 10. Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation [26].

(5) Water spraying nozzles
(6) Drain pipe for water collection

3.3. Hybrid solar Photovoltaic/Thermoelectric (PV/TE) system cooled by heat sink

Advancements have been made in PV conversion systems, by combining them with a thermoelectric module (TE) and heat sink as seen in Fig. 4 [17]. The TE module is used to absorb heat from the surface of the PV module, which is generated by thermalization loss of photons containing high energy and transmission loss of photons containing low energy. The thermoelectric module is placed at the centre of the back part of the PV module. One thermal resistor is placed on top of the TE module and other thermal resistors in the remaining surrounding areas of the TE module. When exposing the PV/TE system to solar radiation, the temperature increases with time. There is a small temperature difference between the thermal resistor on the top and the thermal resistors placed below, due to the diffusion of charge carriers within the thermoelectric materials when the top and bottom surfaces have a temperature variance. The collected power from the PV module is dissipated into the resistor and stored in a battery. The heat sink is used for heat dissipation of the PV module, which cools down the surface of the PV module [18] (Fig. 5).

3.4. Hybrid solar Photovoltaic/Thermal (PV/T) cooled by forced water circulation

With the aim of increasing the PV systems' efficiency, a hybrid Photovoltaic/Thermal (PV/T) system generates electrical energy and thermal energy simultaneously [19]. The system consists of a PV module and thermal collecting pipes, which are mounted to the back part of the PV module, as seen in Fig. 6 [20]. Rectangular collecting pipes are used to improve the contact area between the PV module and the thermal collecting pipes. Water is used as the circulating fluid, which flows through the paralleled thermal collecting pipes via a DC pump, which can be powered by the PV module or other sources. When the hybrid system is exposed to solar radiation, waste heat is transferred to the circulating water flowing through the thermal

Table 1
Highlights of selected studies on cooling of PV modules in terms of technology/Contribution.

Authors	Highlights/Contribution	Technology
Carlotti M, Ruggeri G, Bellina F. and Pucci A. [28]	● Investigation improving optical efficiency of solar concentrators was made. ● PMMA layers increased light concentration effectively.	FTCC
Vishwanathan B, Reinders A.H.M.E, de Boer D.K.G, Desmet L, Ras A.J.M, Zahn F.H. and Debije M.G. [29]	● Performance comparison between flat and cylindrically bent PMMA light guide sheets was done. ● Results showed cylindrically bent PMMA to be superior.	FTCC
Shaltout M.A.M, Ghettas A. and Sabry M. [30]	● Performance of PV module combined with V-trough concentrator was evaluated. ● V-trough concentrators showed increased efficiency in hot desert climate.	FTCC
Andrade L.A, Barrozo M.A.S. and Vieira L.G.M. [31]	● Study on dynamic heating in solar dish concentrators was done. ● Results show validity to provide high thermal energy demands.	FTCC
Parel T.S, Pistolas C, Danos L. and Markvart T. [32]	● Model developed showing angular distribution light escaping from luminescent solar concentrator (LSC) edge. ● Can be applied to PV modules, which enhances efficiency.	FTCC
Wu Y, Connelly K, Liu Y, Gu X, Gao Y. and Chen G.Z. [33]	● Smart solar concentrators lightweight, low cost and generate electricity. ● 3-D tracing technique used to analyse optimal optical performance, where results show output power increased.	FTCC
Rabl A. [34]	● Acceptance angle, sensitivity to mirror errors, reflector area and average reflections of parabolic concentrators were evaluated. ● Advantageous for high thermal applications.	FTCC
Correia S.F.H, Lima P.P, Andre P.S, Ferreira M.R.S. and Carlos L.A.D. [35]	● High efficiency LSC for flexible wave-guiding photovoltaics proposed showing optimal optical and power conversion efficiency. ● Cost-effectiveness and negligibility of self-absorption and transfer losses validated.	FTCC
Akbarzadeh A. and Wadowski T. [36]	● Cooling PV module can increase output power by around 50%. ● Results show PV panel does not allow PV panel surface temperature to go beyond 46 °C.	Sprinkler
Alonso Garcia M.C. and Balenzategui J.L. [37]	● Nominal Operation Cell Temperature (NOCT) effective method to estimate PV module performance. ● Applied to different types of PV modules to estimate temperature and performance [38].	Sprinkler
Dubey S. and Tiwari G.N. [38]	● Model derived for PV/flat plate solar collector. ● Results show an increase in thermal efficiency.	Sprinkler
Hashim H., Bomphrey J.J. and Min G. [39]	● Model derived for geometry optimisation of thermoelectric modules. ● Simulation results show an increase in electrical efficiency.	Hybrid PV/TE
Popovici C.G., Hudisteanu S.V., Mateescu T.D. and Chereches N.C. [40]	● Angle between ribs and base plate of heat sink modified to evaluate performance. ● Cooling method reduced PV surface temperature by 10 °C.	Hybrid PV/TE
Verma V., Kane A., and Singh B. [41]	● Dynamic model developed to simulate thermal and electrical characteristics of TEM material. ● Simulation results show maximum energy harvesting where hybrid system endured dynamic perturbation and solar radiation.	Hybrid PV/TE
Ali H., Yilbas B.S., and Al-Sulaiman F.A. [42]	● Performance of pin shaped thermoelectric generator is analysed. ● Simulation results show increased output power of PV module when air flow is utilised more efficiently.	Hybrid PV/TE
Soprani S., Haertel J.H.K., Lazarov B.S., Sigmund O. and Engelbrecht K. [43]	● Model developed for hybrid PV/thermoelectric modules integrated with heat sink specific design constraints. ● Simulation and experimental results indicate good compatibility with one another.	Hybrid PV/TE
Kalogirou S.A. and Tripanagnostopoulos Y. [44]	● Models tested and evaluated according to their electrical and thermal efficiencies. ● Increased electrical and thermal efficiency, and economic viability improved.	Hybrid PV/T
Ali H.H., Ahmed M. and Abdel-Gaied S.M. [45]	● Investigated how convection heat transfer and fluid flow affect PV module efficiency. ● Model results show different Reynolds number values in laminar flow with both optimum plate thickness and length increase heat transfer.	Hybrid PV/T
Wu S.Y., Zhang Q.L., Xiao L., Guo F.H. [46]	● Model developed to predict thermal-electrical performance of heat pipe. ● Results show overall thermal, electrical and exergy efficiencies increased to 63.65%, 8.45% and 10.26%.	Hybrid PV/T
Michael J.J., Iniyan S., Goic R. [47]	● Flat plate solar collector used to increase PV module efficiency.	Hybrid PV/T

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Table 1 *(continued)*

Authors	Highlights/Contribution	Technology
Hu M., Zheng R., Pei G., Wang Y., Li J. and Ji J. [48]	● An investigation is done on the different solar flat plate collector PV/T, efficiencies, advantages and disadvantages. ● Wickless heat pipe compared with wire-meshed heat pipe. ● Thermal efficiency on wickless heat pipe and wire-meshed heat pipe was 52.8% and 51.5%, respectively.	Hybrid PV/T
Jouhara H., Szulgowska-Zgrzywa M., Sayegh M.A., Milko J., Danielewicz J., Nannou T.K. and Lester S.P. [49]	● Experiments done on hybrid PV/T systems to analyse hot water to consumer. ● Results show systems able to supply 60% of consumer's hot water needs on cloudy days and 100% on sunny days.	Hybrid PV/T
Ntsaluba S., Zhu B. and Xia X. [50]	● Model developed to maximize the energy extracted from solar collectors by optimizing flow rate. ● 7.82% increased extracted energy, where thermal efficiency decreased between 5.54% and 7.34% using connecting pipes.	Hybrid PV/T
Tang X., Quan Z. and Zhao Y. [51]	● Micro-heat pipe array used for PV panel cooling, by making use of evaporator and condenser for heat transfer. ● Experiments show air cooling increased electrical efficiency by 2.6% and water cooling by 3%, which indicates water cooling to be superior.	Hybrid PV/T
Sotehi O., Chaker A., Maalouf C. [52]	● Hybrid PV/T solar collector for net zero energy buildings proposed. ● Results indicate produced solar electricity is high and covers hot water needs, air conditioning, lighting and household appliances.	Hybrid PV/T
Aste N., Leonforte F. and Del Podro C. [53]	● Water glazed PV/T system, where roll-bond flat plate absorber is used. ● Model developed to evaluate performance of PV/T collectors, where results validated enhancements in electrical efficiency.	Hybrid PV/T
Kroi A., Prabst A., Hamberger S., Spinnler M., Tripanagnostopoulos Y. and Sattelmayer T. [54]	● Seawater-proof hybrid PV/T solar collector developed and applied to reverse osmosis (RO) desalination plant. ● Seawater utilised to cool PV modules, where results show increased electrical efficiency.	Hybrid PV/T
Tonui J.K. and Tripanagnostopoulos Y. [55]	● PV/T solar collector cooled via natural airflow, where two methods improving heat transfer are evaluated. ● Thin metal sheet suspended at middle or fins attached to back part of PV panel, where modelling and outdoor test show good agreement.	Hybrid PV/T
Tonui J.K. and Tripanagnostopoulos Y. [56]	● PV/T system cooled by forced/natural air circulation with suspended metallic sheets or fins attached to back part of PV panel. ● Compared with typical PV/T air cooling system, where results show increased electrical and thermal outputs.	Hybrid PV/T
Tripanagnostopoulos Y, Yianoulis P. and Patrikios D. [57]	● Hybrid PV/T system, where water circulates through connecting pipes with fins attached to back part of PV module. ● Electrical performance improved.	Hybrid PV/T
Tripanagnostopoulos Y. [58]	● Hybrid action extraction system developed, which cools PV panel either by air or water. ● Experiment results show increased efficiency and cost-effectiveness.	Hybrid PV/T
Tripanagnostopoulos Y, Nousia T, Souliotis M. and Yianoulis P. [59]	● Hybrid PV/T solar collector cooled. ● Outdoor tests performed to evaluate, where results show electrical efficiency improved.	Hybrid PV/T
Tripanagnostopoulos Y. [60]	● Flat absorber, static parabolic absorber and Fresnel lens compared. ● Design and application aspects discussed, where results show electrical efficiency increased.	Hybrid PV/T
Rahul S.R. and Hariharan R. [61]	● PV/T collector integrated with blower passing air to back part of PV panel to increase efficiency and reduce surface temperature. ● Results show electrical efficiency increase and surface temperature reduced.	Hybrid PV/T
Hosseini R, Hosseini N. and Khorasanizadeh H. [62]	● PV system cooled by thin film of water using another system to transfer heat to water. ● Results show electrical efficiency improved.	Hybrid PV/T
Tan W.C., Chong K.K. and Tan M.H. [63]	● Multiple-channel heat sink for CPV cells. ● 91.4 °C cell temperature and 0.6 m/s flow rate optimized conversion efficiency to 31.8% and net power to 4064 W.	Hybrid PV/T
Huang M.J, Eames P.C. and Norton B. [63]	● 2-D finite volume heat transfer model developed for building-integrated PV/phase-change materials. ● The simulation and experimental results indicate an increase in efficiency.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Huang M.J, Eames P.C. and Norton B. [64]	● Internal fins for bulk PCM thermal conductivity compared with datum single flat aluminium plate used in buildings. ● Internal fins reduced PV/PCM system temperature by 30 °C	Phase-change materials (PCM) used to decrease the operating temperature of solar panels

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Table 1 *(continued)*

Authors	Highlights/Contribution	Technology
	compared to single flat aluminium plate.	
da Cunha J.P. and Eames P. [65]	● PCM phase transition temperatures between 0 and 250 °C presented. ● Organic compounds and salt hydrates effective below 100 °C, where eutectic mixtures vary from 100 to 250 °C.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Liu L., Su D., Tang Y. and Fang G. [66]	● Thermal conductivity enhancement of phase-change materials for thermal energy storage presented [67]. ● Models developed to improve PCM thermal conductivity and discussed for in-depth investigation.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Wang T., Wang S., Luo R., Zhu C., Akiyama T. and Zhang Z. [68]	● Microencapsulation of phase-change materials with binary cores and calcium carbonate shells for thermal energy storage proposed. ● Results show binary cores ranges between 55.7% and 59.4%. When heated to 400 °C mass loss of microcapsules between 5% and 28%. ● The conductive calcium carbonate shell enhances PV efficiency.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Hachem F., Abdulhay B., Ramadan M., El Hage H., El Rab M.G. and Khaled M [69]	● Pure and combined PCM enhances electrical performance of PV panel, where transient energy balance presented to analyse thermal behaviour. ● Combined PCM increased electrical efficiency by an average of 5.8%.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Hasan A., Sarwar J., Alnoman H. and Abdelbaqi S. [70]	● Yearly energy performance of paraffin based PV/PCM system presented. ● Model developed to predict melting and solidification fractions, where electrical energy yield improved by 5.9% and cost-effectiveness increased.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Sardarabadi M., Passandideh-Fard M., Maghrebi M.J. and Ghazikhani M [71]	● Experiments done on ZnO/water nanofluid (0.2 wt%) and paraffin wax. ● PVT with PCM/Nanofluid increased thermal energy output by 48%.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Chandel S.S. and Agarwal T [72]	● Research must be focused on inorganic PCM and only economically viable in high insolation throughout the year. ● Due to high system costs and only a 5% electrical efficiency increase, further research must be done.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Su D., Jia Y., Alva G., Liu L and Fang G [73]	● Dynamic model developed to do comparative performance analysis of PV/PCM. ● Upper phase-change material ensured improved performance.	Phase-change materials (PCM) used to decrease the operating temperature of solar panels
Chinamhora T., Cheng G., Tham Y. and Irshad W. [74]	● Performance of PV panel analysed when submerged in water at various depths. ● Results show surface temperature reduced effectively, which enhances electrical efficiency tremendously.	PV panel with water immersion cooling
Zhu L., Boehm R.F., Wang Y., Halford C. and Sun Y. [75]	● De-ionised water used as immersion fluid to cool PV cells in two-axis dish concentrator tracking system presented. ● Results show CPV module cooled to 45 °C at a 920 W/m^2 irradiance, 17 °C ambient temperature and 30 °C water inlet temperature.	PV panel with water immersion cooling
Abrahamyan Y.A., Serago V.I., Aroutiounian V.M., Stafeev V.I., Karamian G.G., Martoyan G.A. and Mouradyan A.A. [76]	● Efficiency of solar cells immersed in isotropic liquid dielectric, where analysis was done on current/voltage characteristics and fill factor. ● Efficiency increased by 40–69% of reference value.	PV panel with water immersion cooling
Wang Y., Fang Z., Zhu L., Huang Q., Zhang Y. and Zhang Z. [77]	● PV cells immersed in liquids evaluated performance under simulated sunlight, where non-polar silicon oil showed best performance. ● PV cells submerged in liquid improve performance thereof.	PV panel with water immersion cooling
Rosa-Clot M., Rosa-Clot P., Tina G.M. and Scandura P.F. [78]	● Performance of PV panel submerged in water evaluated at different submersion depths. ● Results show lower electrical efficiency when submerged in deeper water.	PV panel with water immersion cooling
Han X., Wang Y. and Zhu L. [79]	● De-ionized (DI) water, isopropyl alcohol (IPA), ethyl acetate, and dimethyl silicon oil chosen as submerging liquids. ● 3-D model developed where results show direct-immersion cooling keeps PV cells at low temperature, improving electrical efficiency.	PV panel with water immersion cooling
Sun Y., Wang Y, Zhu L, Yin B., Xiang H. and Huang Q. [80]	● Direct liquid-immersion cooling of concentrator PV cells, where dimethyl silicon oil is used as immersing fluid. ● Results show temperature controllable from 20 °C to 31 °C at 920 W/m^2 irradiance and Reynolds number varying between 13,602 and 2720.	PV panel with water immersion cooling
Xiang H., Wang Y., Zhu L, Han X., Sun Y. and Zhao Z. [81]	● Two structural models developed and tested under actual weather conditions. ● Heat transfer performance of two structural models at axial and lateral direction in agreement with simulations.	PV panel with water immersion cooling
Arpin A. K., Losego M.D., Cloud A.N., Ning H., Mallek J., Sergeant N.	● 3-D metallic photonic crystals modified to be within	PV panel cooled by transparent

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Table 1 *(continued)*

Authors	Highlights/Contribution	Technology
P., Zhu L., Yu Z., Kalanyan B¸, Parsons G.N., Girolami G.S., Abelson J.R., Fan S. and Braun P.V. [82]	emission spectrum for useful solar thermo-photovoltaics. ● High quality tungsten photonic crystals maintain stability to 1400 °C.	coating (photonic crystal cooling)
Zhu L, Raman A., Wang K.X., Anoma M.A. and Fan S. [83]	● Micro-photonic design approaching ideal performance scheme used to cool PV panel via radiative cooling. ● Results show micro-photonic design effectively cools PV cells.	PV panel cooled by transparent coating (photonic crystal cooling)
Cao C., Li H., Feng G., Zhang R. and Huang K. [84]	● PV/T system is applied to air source heat pump (ASHP) heating systems in cold climatic conditions. ● BTRNSYS transient simulation software used, where results show outlet temperature reaches 76.6 °C, which improves heating efficiency.	Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
Tiwari A., Sodha M.S., Chandra A and Joshi J.C. [85]	● Performance of PV module integrated with air duct evaluated by developing a model to determine overall efficiency. ● Results show good compatibility with developed model, which indicates increased overall efficiency reached.	Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
Mojumder J.C., Ong H.C., Chong W.T., Izadyar N. and Shamshirband S. [86]	● Extreme learning machine (ELM) applied to PV/T air cooled system. ● ELM model compared with genetic programming and artificial neural networks models, where results show ELM model to be most accurate.	Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
Kasaeian A., Khanjari Y., Golzari S., Mahian O and Wongwises S [87]	● Investigate effects of forced convection on thermal and electrical efficiencies of PV/T system. ● Reducing depth of channel and Reynolds number increases thermal efficiency, but has no considerable effect on electrical efficiency. ● Thermal efficiency ranges from 15% to 31% while electrical efficiency ranges from 12% to 12.4%.	Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
Saygin H., Nowzari R., Mirzaei N., and Aldabbagh L.B.Y [88]	● Model developed to determine effect on thermal and electrical performances when PV module position changed inside collector. ● Maximum thermal and electrical performance measured when distance between PV module and cover is 3 cm and 5 cm, respectively. ● Analysis of variance used to compare electrical efficiency of PV/T system with standard PV system, where hybrid system is superior.	Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
Senthil Kumar R., Puya Priyadharshini N. and Natarajan E [89]	● Heat rejected by heat sink used for domestic applications [90]. ● Geometric model developed and compared with experimental results, showing good compatibility.	Hybrid PV/TC
Borkar D.S., Prayagi S.V. and Gotmare J [91]	● Hybrid PV/TC system presented to increase overall efficiency by keeping temperature constant within limits. ● Model developed to evaluate performance, where results show overall efficiency improvement.	Hybrid PV/TC
Benghanem M, Al-Mashraqi A.A. and Daffalla K.O. [92]	● TEC module used to cool PV panel in hot climatic areas. ● Efficiency increased by using TEC in hot areas.	Hybrid PV/TC
Najafi H and Woodbury K. [93]	● Model developed to determine temperature in different sections and calculate required power for TEC and excess heat generated. ● Simulation results validate efficiency improvements.	Hybrid PV/TC
Ahadi S, Hoseini H.R. and Faez R. [94]	● Thermoelectric power generation using large pn-junction is discussed. ● Results show efficiency increase from 6.8% to 10.92% at 83 °C.	Hybrid PV/TC
Najafi H and Woodbury K [95]	● Model developed to determine temperatures of system and required power [96]. ● Results show temperature kept within limits and produced maximum output power.	Hybrid PV/TC
van Sark W.G.J.H.M [97]	● Thermoelectric (TE) converters attached to back part of PV panels. ● Developed model shows 24.9% energy yield obtained, where experimental results show 10% increase.	Hybrid PV/TC
Yang D and Yin H [98]	● Water pipelines used for more effective heat transfer and theoretical conversion efficiency limit of system evaluated. ● Results show PV/TE/HW system superior to PV/HW and conventional PV systems as electrical efficiency increased by 30%.	Hybrid PV/TC
Kane A, Verma V and Singh B [99]	● Temperature based maximum power point tracking (MPPT) scheme presented to find optimal temperature of PV system. ● The performance improvement of PV system with thermoelectric cooling is presented through simulated results.	Hybrid PV/TC
Irshad K., Habib K., Basrawi F. and Saha B.B [100]	● Fifteen TEC air duct modules assisted by a 300 Wp PV	Hybrid PV/TC

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Table 1 *(continued)*

Authors	Highlights/Contribution	Technology
	system to cool a 9.45 m^3 test room investigated through experiments and simulations. ● Experimental and simulation results showed good compatibility with one another, where combined system saves 1806.75 kWh/year.	
Enescu D. and Spertino F [101]	● Formulate equations for cooling capacity, heat rejection rate and input power, and model developed PV generator. ● Technical, economic and environmental research must be done in future.	Hybrid PV/TC

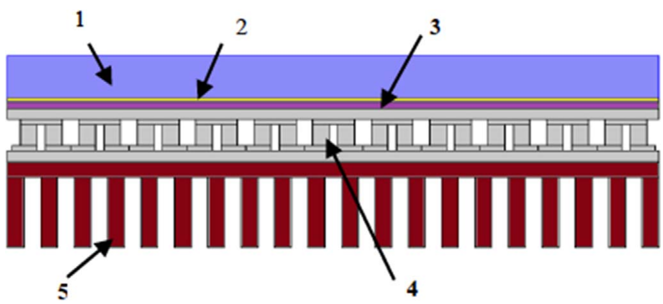

Fig. 11. Thermoelectric cooling system for PV cells [27].

collecting pipes. The heated water flows back to the hot water insulated tank for domestic or other applications.

The numbers on the figure above represent the following components:

(1) PV modules
(2) Circulation pump
(3) Water storage tank

3.5. Improving the performance of solar panels through the use of phase-change materials

One technique that can be used to reduce the surface operating temperature of a PV panel in order to reach a higher electrical efficiency is by incorporating phase-change materials (PCM), such as tungsten photonic crystals. PCM is a latent heat storage material, which is situated on the back part of the PV panel as seen in Fig. 6. When the temperature increases, the chemical bonds within the PCM separate as phase-changing from solid to liquid occurs. The PCM absorbs heat, due to the phase-change being a endothermic process. When the heat stored within the storage material reaches the phase-change temperature, the material starts to melt [21]. The temperature then stabilises until the melting process is completed. It is called latent heat storage material, because the heat is stored during the melting process (phase-change process).

The numbers on the figure above represent the following components:

(1) PV module
(2) PCM module.

3.6. Water immersion cooling technique

Another technique that can be used to reduce the temperature of a PV panel involves implementing the water immersion cooling technique as seen in Fig. 7. With the water immersion cooling technique a PV module is placed in large water bodies like rivers, oceans, lakes, canals, etc. Water is used as the immersing fluid, which absorbs the heat from the PV module and maintains the surface temperature of the PV module. Therefore, when water absorbs the heat from the PV module the electrical efficiency increases [23].

The numbers on the figure above represent the following components:

(1) PV modules
(2) Plastic container
(3) Water

3.7. Transparent coating (photonic crystal cooling)

A technique that can be used to reduce the surface operating temperature of a PV panel in order to reach a higher electrical efficiency involves incorporating transparent coating (photonic crystal cooling). This visible transparent thermal blackbody is based on silica photonic crystals and is placed on the top surface of the PV cells, and it has the capability to reflect heat generated by the PV cells in the form of infrared light (thermal long infrared transparency window, which is in the 8–30 µm range) under solar irradiance back into space [24]. Simultaneously, the PV cells are slightly enhanced by anti-reflection and light trapping effects. Therefore, the PV cells are cooled by enabling more photons to be absorbed by the PV module. A PV module cooled by transparent coating (photonic crystal cooling) is shown in Fig. 8 below.

3.8. Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation

Another technique that can be used to reduce the surface operating temperature of a PV panel in order to reach a higher electrical efficiency makes use of forced air circulation. This system consists of a photovoltaic module, which is placed on top of a steel plate with an air channel underneath, as seen in Fig. 9. Air is used as the working fluid, which is forced through the channels by a fan with a nozzle. The fan is powered by the PV module, where the energy consumption thereof increases when the cavity velocity increases, and also when the channel width and the heat exchanging surface increase. The heat from the PV panel is transferred to the air in the channels via convection, therefore reducing the surface operating temperature in order to reach a higher electrical efficiency [26].

The numbers on the figure above represent the following components:

(1) PV module
(2) Forced circulation fan
(3) Air channel

3.9. Thermoelectric cooling system

Thermoelectric devices comprise an n-type semiconductor and p-type semiconductor, which are connected in series electrically and in parallel thermally. Under a temperature gradient, the majority charge carriers diffuse from the hot side (positively charged electrode) to the cold side (negatively charged electrode) due to the peltier effect, which creates a voltage that results in current flowing. When a voltage is

Table 2
Technical discussion of different PV module cooling technologies.

Technology	Advantages	Disadvantages	Discussion
Floating tracking concentrating cooling (FTCC)	• Avoid energy dispersion problems. • Avoid electric grid stress when using a pumping scheme. • Operates highly efficiently.	• Evaporation causes water wastage. • Sprinklers cannot spray whole surface of PV module. • High capital cost.	The FTCC system operates efficiently. However, when water is sprayed, the whole surface area is partially cooled.
Hybrid solar Photovoltaic/ Thermal PV/T system cooled by water spraying	• Increased energy yield. • More efficient than air cooling.	• Whole surface area of PV panel partially cooled. • Heat wastage.	Experimental results show efficiency increased. However, water is wasted and heat could be utilised to harvest more solar radiation.
Hybrid solar Photovoltaic/ Thermoelectric PV/TE system cooled by heat sink	• Average temperature with heat sink lowered to 8.29%. • Electrical efficiency improved. • Alleviates hot spotting.	• Heat conduction loss between hot and cold parts through semiconductors. • Heat is wasted. • Turbulent airflow with pin fin heat sink.	Experimental results show heat sink can decrease surface temperature. However, turbulent airflow makes heat sink highly unstable. Also, wasted heat rather utilised to increase electrical efficiency.
Hybrid solar Photovoltaic/Thermal (PV/T)	• Electrical efficiency increased. • Supplies hot water for domestic applications. • More efficient combined than separated.	• Cannot achieve optimal efficiency, due to constant flow rate. • High initial cost. • Subsidies needed for these systems.	Hybrid PV/T system increases electrical efficiency effectively. However, cannot reach optimal efficiency, due to flow rate being kept constant. By adjusting the flow rate, optimal efficiency can be achieved.
Phase-change materials (PCM) used to decrease the operating temperature of solar panels	• Able to store large amounts of heat with small temperature changes. • Phase-change occurs at a constant temperature. • Heat absorbed can be used to heat buildings.	• Paraffin has low thermal conductivity in its solid state. • Segregation reducing active volume available for heat storage. • Less efficient in colder areas.	PCM operates effectively. System stores heat from PV panel during melting process, however absorptive capabilities of material degrades over time. Also, superior performance during hot climatic conditions.
PV panel with water immersion cooling	• Highly efficient. • Economic. • Environmentally friendly. • Electrical efficiency increased during clear days. • Land requirements unnecessary.	• Efficiency is low during cloudy days. • Submersion depth influences efficiency. • Ionised water affects the electrical efficiency over time.	Temperature reduced and efficiency increased. However, efficiency low during cloudy days. Also, ionised water exposure affects the electrical efficiency over time.
PV panel cooled by transparent coating (photonic crystal cooling)	• Economic solution. • No space requirement necessary. • PV cell temperature reduced drastically.	• Heat reflected into space is wasted and could rather be utilised for domestic applications.	Temperature problem eliminated, which enhances PV panel efficiency. However, heat is wasted and could rather be utilised for domestic applications.
Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation	• Overall efficiency increased. • Economically viable. • Heated air can be used to heat buildings.	• Efficiency of cooling with air lower than water cooling. • Water cooling more effective in hot climatic conditions than air cooling.	System very effective, but most effective in cold climatic conditions. Also, forced air circulation not as efficient as forced water circulation.
Hybrid PV/TC system	• Clean source of energy. • Waste heat changed into useful energy. • Increasing life span of PV modules.	• Slow technological progression. • Requires relatively constant heat source. • Low conversion efficiency rate.	System efficiently uses waste heat for higher efficiency, but has low conversion efficiency rate and technology progression is slow.

applied across the material it forces a current to flow through it, which causes the heat pump to cool the one side and heat the other, which must be connected to a heat sink for excess heat dissipation. The thermoelectric cooling system described, can be seen in Fig. 10 [8].

The numbers on the figure above represent the following components:

(1) Glass cover
(2) PV cells
(3) Insulator
(4) TEG module
(5) Fin heat sink

4. Relevant literature review

Several authors have tried to improve the efficiency of solar panels by attending to the problem linked to the PV surface's operating temperature. Table 1 summarizes different papers by the different authors in which attempts have been made to increase the efficiency of the PV module by using the different techniques explained above. This table provides the source authors, what the focus area of the study was, a summary of the review contribution and the technology used to address the temperature problem (Fig. 11).

5. Discussion

After investigating the various technologies used to deal with the temperature problem with the aim of increasing efficiency, it is imperative to summarise the findings in an easy and accessible way for any party interested in these technologies, and this is done in Table 2 below. This table indicates the advantages, the disadvantages and the comments for justification of the use of these different technologies.

After analysing this table, it can be concluded that any cooling arrangement selected should be used to keep the photovoltaic cell temperature low and steady with the aim of increasing electrical efficiency. It should also, if possible, allow the use of extracted thermal heat to be used for other meaningful purposes.

6. Conclusion

Extensive reviews of various cooling techniques used to enhance the performance of a PV system are discussed in detail in this paper. Proper cooling of PV systems improves the thermal, electrical and overall efficiency, which in turn also reduces the rate of cell degradation and maximizes the life span of the PV module. Different tools, such as equations, schematic diagrams and pictures have been used to clearly illustrate, analyse and compare these technologies used to address the undesirable influence of temperature on PV efficiency in terms of their advantages, disadvantages as well as their techno-economic and environmental implications.

Several papers from different research fields have been reviewed and classified based on their focus, contribution and the type of technology used to achieve cooling while trying to increase the efficiency of the panel. Future research must be focused on harvesting heat from the surface of a PV module effectively and cooling thereof in a more controlled and stable manner. As learned from the reviewed studies, the following cooling technologies are found to be promising based on materials used, capital cost and performance:

- **Floating tracking concentrating cooling** sprinklers cannot spray the whole surface area of the PV module, which means that only parts of it are cooled. Water is also wasted during evaporation.
- **A Hybrid solar Photovoltaic/Thermal (PV/T) system cooled by water spraying** showed, through experiments that an efficiency increase was obtained and viable. However, water is wasted and heat could be utilised to harvest more solar radiation.
- **A Hybrid solar Photovoltaic/Thermoelectric (PV/TE) system cooled by heat sink** is able to reduce the surface temperature of the PV module effectively. However, the turbulent airflow present makes the heat sink highly unstable. In addition, the wasted heat could rather be utilised to increase the electrical efficiency.
- **A Hybrid solar Photovoltaic/Thermal (PV/T) cooled by forced water circulation** increases the electrical efficiency effectively, However, it cannot reach optimal efficiency, due to the flow rate being kept constant. It is preferable to adjust the flow rate according to the temperature change to achieve optimal efficiency.
- **Improving the performance of solar panels through the use of phase-change materials** reduced the surface temperature, therefore increased the electrical efficiency drastically. The system stores the heat from the PV panel during the melting process, however the absorptive capabilities of the material degrades over time. This system will also not achieve the same performance during cold and hot climatic conditions.
- **The Water immersion cooling technique** reduced PV module temperature and increased efficiency effectively when the exact submersion depth is applied. In addition, ionised water exposure affects the electrical efficiency over time.
- **Transparent coating (photonic crystal cooling)** eliminated the temperature problem completely, which enhances the efficiency of the PV panel. However, heat is wasted and could rather be utilised for domestic applications.
- **A Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation** is very effective, but more effective in cold climatic conditions than in hot climatic conditions. Forced air circulation is also not as efficient as forced water circulation.
- **A Thermoelectric cooling system** effectively uses the waste heat for higher efficiency, but it has a low conversion efficiency rate and the progression of this technology is slow.

The authors of this paper strongly believe that the presented detailed review can be used by engineers working on theory, design and/or application of photovoltaic systems.

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