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Techniques for Enhancing and Maintaining Electrical Efficiency of Photovoltaic Systems

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***Abstract*—Demand for electricity generation from solar energy, which is a clean and renewable resource, is increasing day by day. It is desirable that the panel surface temperature is not excessively hot while generating electricity with PVT panels. High temperature causes thermal degradation and panel electric efficiency decrease. There are many studies in the literature about active thermal cooling of PVT panels used for electricity generation as well as for storing thermal energy. In this study, a review was made on methods developed to increase the thermal and electrical efficiencies of PVT panels.**

***Index Terms*—PVT panels, cooling techniques, active cooling, passive cooling, electrical and thermal efficiency.**

I. INTRODUCTION

Two main systems are utilized from solar energy potential. The first one is solar photovoltaic (PV) system, which produces electricity with photon energy, and the other is solar panel (collector) systems, which use solar energy.The principal factor that influences the electrical performance of a PV panel is the type of PV cells being used[1].The efficiency of PV modules are highly dependent on which called as sustainability parameters surface temperature, dusting, radiation intensity and climatic conditions. The most important of these parameters is undoubtedly the panel surface temperature.

The range of required energy for the electron excitation is between 0,1 and 2 eV, depending on the photovoltaic cell material. When a photon having a photo-energy below or above this energy, the excess part will be stored as heat in the system[2]. Due to the fact that a typical PV can convert 6 to 20% of received insolation into electricity; the remaining incident solar energy, while varying depending on climatic conditions,accumulates in the module body as heat. The heat accumulation notably increases the cell temperature, which as a result increases carrier concentrations and in turn increases internal carrier combinations and decrease cell performance [1].

Module temperature greatly influences the efficiency and yield of the system by decreasing the open circuit voltage. The cell voltage linearly decreases with increasing cell temperature by approximately 2.2 mV per every 1 °C rise. The effect has a linearly adverse effect on efficiency as it is shown in Fig. 1 [3].

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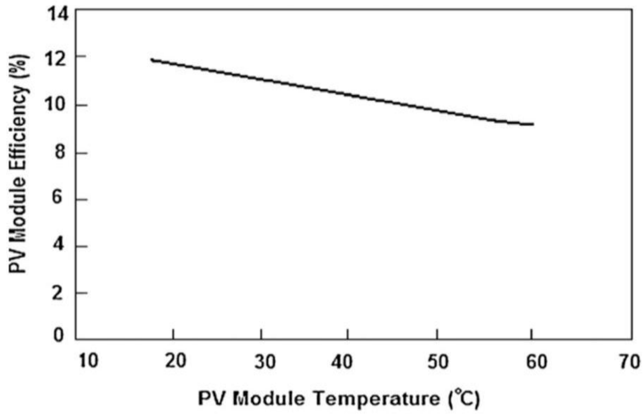

Figure 1: Variation of PV efficiency with module temperature [3]

While the efficiency of an average PV systems is about 15% at current technological level, it falls down to as low as 8% in practical [4].

While also reducing the life of the module by accelerating the thermal degradation of the cells which expose to excessive sunlight during the day and cools at night, overheating of the panel surface reduces the open circuit voltage of the solar cellsin particular. With increasing temperature,the photocurrent increases at a rate of 0.1% per °C due to the reduction of the energy gap of the solar cell and that the opencircuit voltage decreases at 2 mV per °C between 20 and 100 °C due to a decrease of the energy gap and an increase of the saturation current.[4].

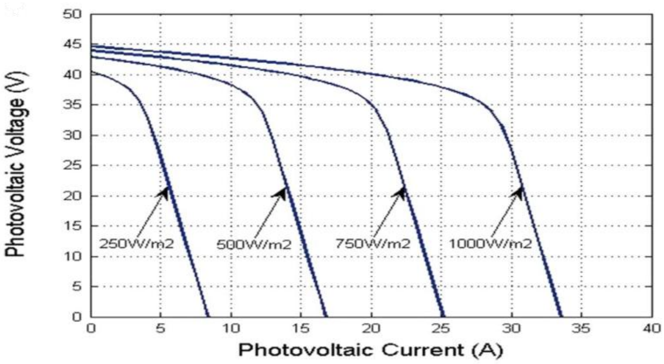

Figure 2: PV module I–V curve characteristics per insolation levels [5]

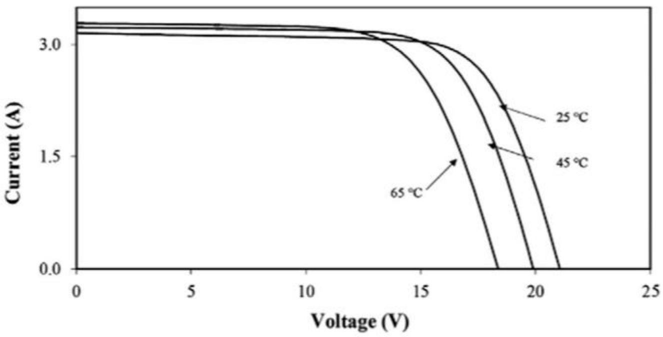

Figure 3: Influence of temperature on PV module I–V curve [6]

As for power, while depending on the cell type, for every 1 °C rise in the temperature causes 0.38% to 0.45% power loss[3]. Figure 4 shows variation of power against temperature for different PV types.

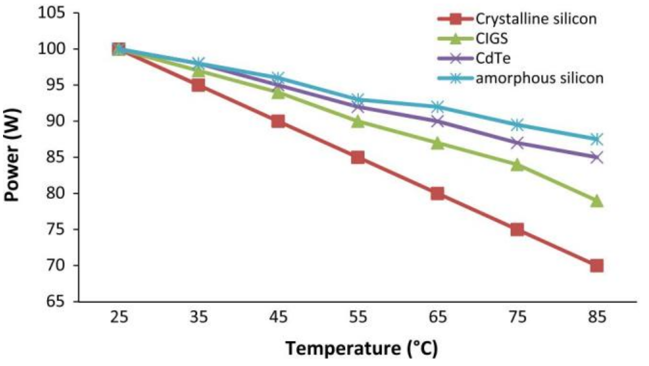

Figure 4: Power loss for different PV types [7]

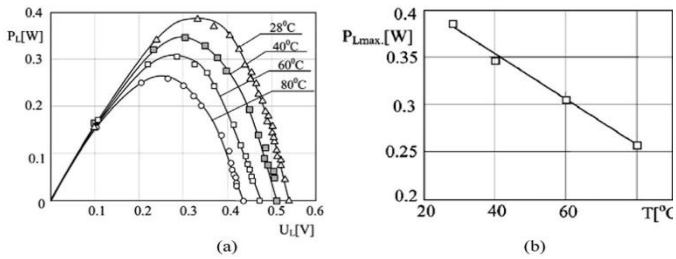

Figure 5: The output power of single-crystalline silicon PV cells at different operating temperatures (a) temperature dependence of the maximum output power (b) [6]

As shown in Fig. 4, up to a critical point the short circuit currentincreases thanks to the drop in the band-gap energy, but in spite, the available output power falls with increasing temperature.

Excessively high temperature, resulting from continuous exposure to the solar radiation, leads to an accelerated degradation of solar cells incurred by thermal fatigue by overheating during exposure and cooling down at non-insolation times [8]. The thermal fatigue, surely, shortens the life cycle of the system. The overall efficiency of solar cells is defined as a function of life cycle and Power Conversion Efficiency (PCE). Therefore, the shorter the life cycle becomes, the lesser the overall efficiency of the system gets[9]. As a result, both the payback time and hence the economically viable initial investment cost are adversely affected.

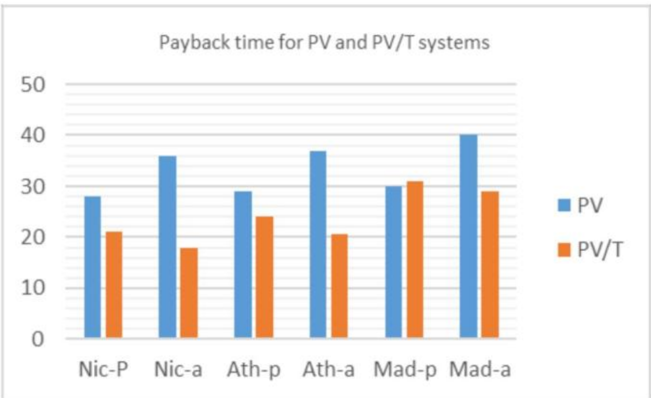

Figure 6: Payback times per solar cell technologies for conventional PV and PV/Thermal systems [8]

As seen in Figure 6, PVT systems significantly shortens the payback time. After all, no need to say, the temperature rise should be avoided or prevented. Since climatic conditions and insolation level cannot be controlled, affordable and cost effective methods and materials are in the focus of related research[10]. An appropriate cooling method may serve to partially solve the issue, whereas many were already proposed to enhance electrical performance of these systems.There are many different means of preventing the solar panel from overheating and to keep it operate under standard operatingconditions. They can be employed at domestic, commercial or industrial scale.

Methods include;

- water spraying or sprinkling,
- Liquid (mostly water) immersion,
- photovoltaic/thermal (PVT) systems cooled by forced water circulation,
- photovoltaic/thermal (PVT) systems with phase-change materials,
- photovoltaic/thermal (PVT) systems cooled by forced air circulation,
- hybrid photovoltaic/thermal (PVT) air-water combi systems,
- transparent coating (photonic crystal cooling),
- photovoltaic/thermoelectric PV/TE systems (with heat sink),
- thermoelectric cooling,
- and many others

All these methods have different advantages, disadvantages and application areas [11]. Most of the abovementioned cooling systems do not necessarily utilize from the thermal energy drawn from the system for low-temperature applications [12].

Air, water and air-water hybrid systems are used for removing heat energy from the solar panel. The reason why water cooling is preferable to air cooling is that the specific heat capacity of water is higher than that of air and the need for hot/warm water is more than air[8].

When we look at literature, there are many studies on the thermal analysis of PV systems,most of which focus on removal of the radiation-induced heat accumulationwhich decreases the electrical efficiency, with appropriate cooling systems[13]. With active cooling systems it is aimed to reduce the panel temperature and thus to increase both the electrical and thermal efficiency of the PVT module. With the active cooling process, which takes heat from the panel surface, the waste heat is used for useful purposes and the reduction of the open circuit voltage is prevented.While the active cooling process is being carried out, some additions are made on the existing system and the cooling process has been carried out with new designs. In addition, researchers evaluated the effects of active cooling on electrical and thermal efficiency as a result of these studies.

II. DIFFERENT TYPES OF PV PANEL COOLING SYSTEMS

Solar power generation has many advantages over other conversion systems. However, a solar energy conversion system with a clean and renewable structure also has problems that adversely affect conversion efficiency, such as hail, dust and surface operating temperatures.There are natural factors such as wind speed, ambient temperature, relative humidity and dust accumulation and solar radiation which affect the surface temperature of the PV panel. For every 1 °C increase of the panel surface temperature, the electrical efficiency decreases by approximately 0.5% [14]. Because of this increase in surface temperature, all of the solar energy absorbed by the solar cells can't be converted to electricity [11]. In this section, the literature describes methods developed to prevent the surface temperature from rising beyond the optimum operating temperature. Figure 1 shows the variation of ideal operating temperatures of the PV panel in the Power-Voltage scatter chart. It is seen that both the electrical power and the open circuit voltage increase with decrease of the surface temperature.

PV module cooling systems are mainly classified as active or passive systems. The notion is that an active cooling system usespowered fans or pumps while a passive cooling systemdoes require no power to operate[7].

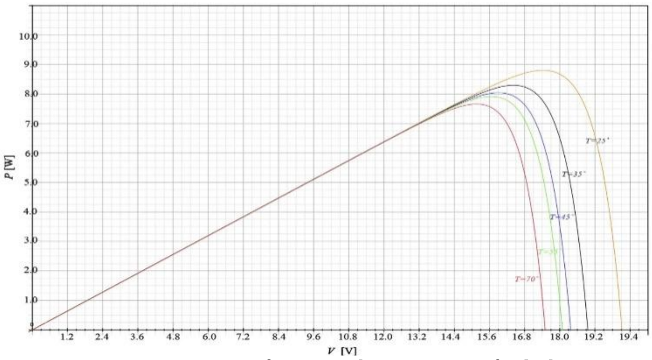

Figure 7: Power Curvesof a PV, the variation of ideal operating temperatures [15].

A. Water Spraying/Sprinkling

In this system, a centrifugal pump is used to pressurize the water from the water tank to the nozzles. A check valve is placed in the suction line and a strainer is placed in the outlet of the tank. After leaving the tank, the water from the strainer and the non-return valve is transferred to an industrial transparent water filter used to cool the PV module. As shown inFigure 8, the water used as a refrigerant is sprayed onto the surface of the PV panel using a fan. Thus, the panel surface temperature decreases and the electrical efficiency increases.

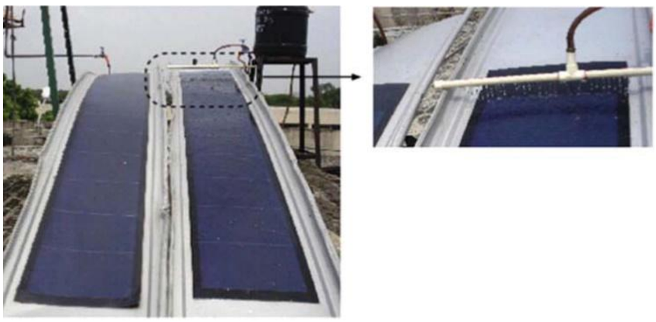

Figure 8. Hybrid solar Photovoltaic/Thermal PV/T system cooled by water spraying[11,16]

PV floating plants which uses reflectors to concentrate solar radiation are built into artificial basins to ensure optimum operating conditions of the PV module and to obtain maximum electrical power. These plants are also equipped with solar tracking and PV cooling systems, hence called Floating Tracking Concentrating Cooling (FTCC) systems. FTCC systemsmostly use water sprinkler systems for cooling. Figure 2 shows the main components of the FTCC system[17].

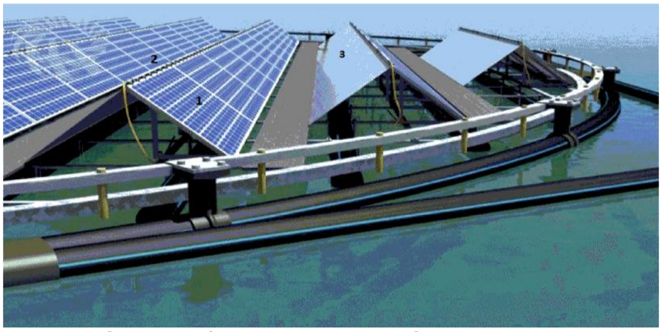

Figure 9. Floating tracking concentrating cooling (FTCC) system in its artificial basin

B. Liquid Immersion

Another technique that can be used to reduce the surface temperature of the PV panel is the water immersion cooling technique, as shown inFigure 10.

The liquid immersion technique is simply immersing the PV module in a dielectric liquid, mostly through a tube or channel, and have the liquid remove heat from the PV module. The refractive index of the liquid should be taken into account, such that it acts as a solar concentrator. With this method the PV module temperature can be maintained around 30–45 °C[10].

In the water immersion cooling technique, the PV panel is placed in large water volumes such as ocean, sea, lake, stream or water channels. The water used as immersion fluid draws heat from the PV panel to maintain the surface temperature and thus the electrical efficiency of the PV panel increases.

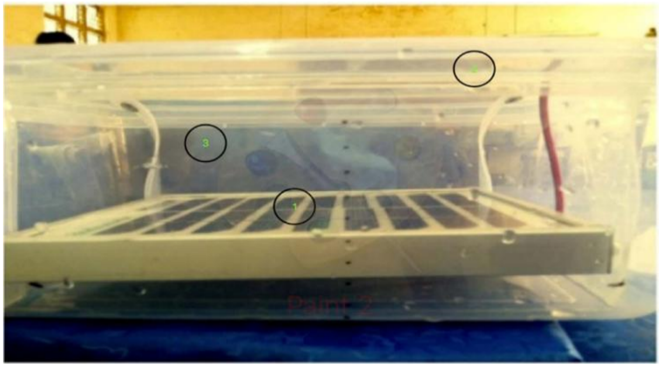

Figure 10. Water immersion cooling technique applied to PV panel (1. PV panel, 2. Plastic container, 3. Water)

Studieson performance of non-water liquids, such as DI water, isopropyl alcohol (IPA), dimethyl silicon oil and ethyl acetatein heat removal from PV panels showed that a thin film (1.5 mm) increases efficiency by 8.5–15.2%. Thicker films absorbmuch of the light and lead to a decrease in performance[18].

C. Photovoltaic/Thermal (PVT) Systems

Photovoltaic thermal PVT systems have been developed to increase the electrical efficiency of the PV system. As Figure 11 suggests, both electric and thermal energy are produced at the same timein these systems.A typical PVT system comprise of a PV module and a tubing or channel which circulate the fluid that draws heat from the module.PVT systems are generally classified according to the type of coolant (air or water) or means of heat drawing (PCM or TE). Additional classification is also made on designs and installations such as glass covered or uncovered, single pass or double-pass, wall-mounted, roofmounted, ground-mounted or building integrated in the literature[19].

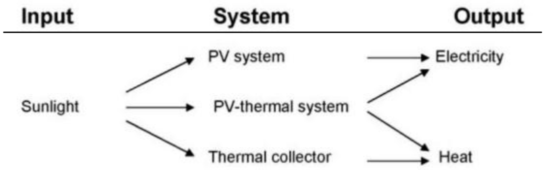

Figure 11: PV, PVT and solar thermal systems[20].

The fluid on the thermal side of a PVT is generally gas, liquid or both of them. The most conventional gas is air, unless specific gas like CFC's are required. And the choice of liquids is water, which is affordable, clean and available, but less than air is [21].

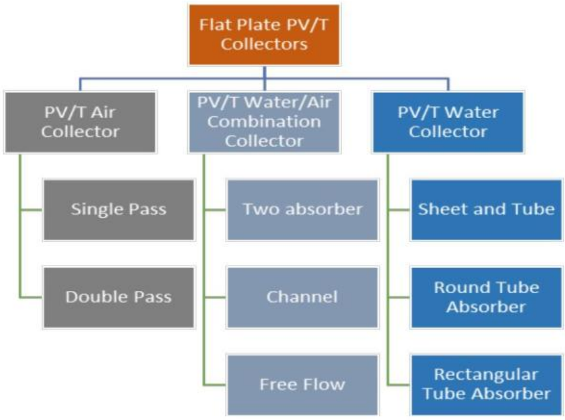

Figure 12: Classification of flat-plate PVT collectors[8]

A number of parameters have been identified to affect PV/T performance. These include mass flow rate, inlet temperature of working fluid, number of covers, absorber to fluid thermal conductance and absorber plate design parameters such as tube spacing, tube diameter and fin thickness. [22].

1) Photovoltaic/Thermal Air (PVT-Air) Systems

In this method, the electrical efficiencies of the PV panels are increased by moving air over the panel surface to remove heat from the PVT system either through natural convection or forced convection.Forced convection systems, where air is blown or sucked by means of an electric fan, can be even classified into continuous or intermittent cooling. Efficiency calculations must account the power to operate the fan, which should surely no greater than the reclaimed power [18]. 2[2]emphasizes that the fan should be a suction pump in order to prevent the fan itself heat up the feed air due to self-body heat after a certain period of operating time.

As shown inFigure 13, an air channel with a steel frame is placed on the bottom of the PV panel. The air used as a working fluid is circulated through the channel to the surface of the PV panel via a fan, or buoyant flow created within a cooling duct attached to the back of the PV module can draw some heat and discharges to the atmosphere naturally. Either way an additional cooling that lowers the operating temperature of the PV module is achieved and hence the efficiency is increased [23].

Air type collectors do not have specific classification, but how the air as the thermal fluid is used, defines the collector's types, such as above the absorber, below the absorber and both sides of the absorber in single or double pass ways[21].

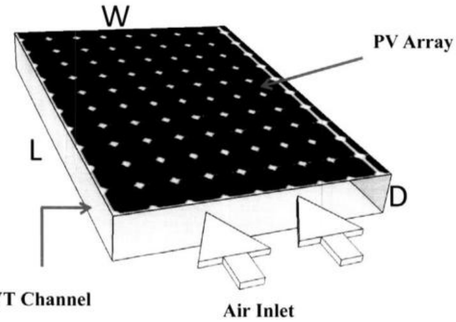

Figure 13: A typical PVT-Air collector[19]

The power of the fan powered by the PV module increases as the cavity velocity increases, as the channel sizes increase, and as the heat exchange from the surface increases. The heat from the PV panel surface is transferred to the air in the channel by convection. Thus, the PV channel surface temperature decreases and the electrical efficiency reaches higher values.

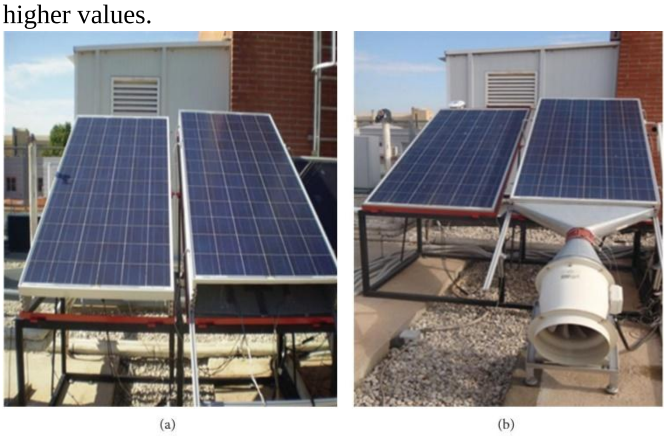

Figure 14. Photovoltaic/Thermal-air system with (a) natural convection and (b) forced air convection configurations [24]

With PVT-air systems, the heat transfer surface area needs to be increased as much as possible unless it becomes costly. Therefore, fins made of different materials and having different shapes are generally attached to the PV modules in order to facilitate removal of heat by increasing heat transfer surface area. 25[25] has conducted CFD analysis and experimental investigations on thermal performance of PVT-air systems actively cooled by using fins and forced air convection. He reported the most effective factor on electrical efficiency to be the Number of Fins, Air Velocity, Arrangement of fins, Irradiation level, Material and Humidity respectively.

While air systems are low-cost and can be upgraded with simple attachments and integrations, due to the lower heat capacity of air and limited application areas of warm air; PVT air systems lose the upper hand in converting waste heat into useful work.

2) Photovoltaic/Thermal Water (PVT-Water) Systems

Water is used as the working fluid to draw heat from the

PV panel. Water systems can also be subdivided into passive and active systems. Provided that a good thermal contact between PV and the collector system is ensured, a passive cooling of PV panel without using a pump may be deemed effective for low temperature applications. For high temperature applications an active cooling with aided with a pump is necessary as cooling performance is improved with increased water flow velocity. Moreover, water flow can not only increase the conversion efficiency but also reduce the reflection losses[10].

In active cooling systems, the circulation of water through the pipes located behind the panel is provided by a DC pump. When the PVT system is exposed to solar radiation, waste heat is transferred to the water that circulates in the pipes. The drawn heat is transferred to an accumulation tank for domestic or industrial use. Typical implementation of PVT-water systems are as given in Figure 15.

Studieson PVT-watersystemscommenced as PVT-airsystems have been concluded to have major problems regarding temperature. Even though PVT-water systemsare costlier than air systems, water systems function more efficiently for their higher density they can be used all seasonsin warm climate countries [26].

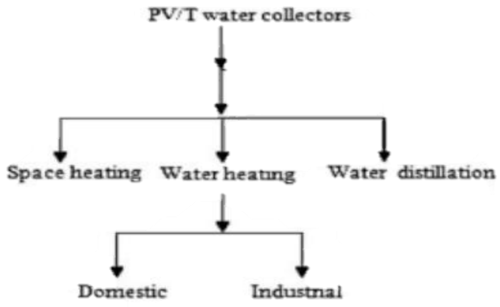

Figure 15: Application areas of thermal energy drawn by PVT-water systems [8].

In natural climates, however,they are not preferred because the large volumetric changeof water upon freezing may break up the collectors in cold night days. The workaround to this is incorporating an integrationof a heat pipe and a solar collector into the PVT system [27].

Figure 16. Photovoltaic/Thermal (PVT) system cooled by forced water circulation (1. PV Panel, 2. Circulation pump, 3. Water storage tank with insulation

As previously given in Figure 12, PVT-water collectors are classified into four categories in terms of heat transfer techniques, which are sheet and tube, channel, free flow, and two absorber systems [21].

Recently, a new approach aimed to solve PV overheating problem with minimum water and energy is developed which makes use of intermittent cooling rather than continuous cooling. In this approach; PV moduleis allowed to reach the Maximum Allowable Temperature (MAT), where maximum energy can be drawn at certain number of cooling cycles, which are calculatedsuch that it allows the panels to be cooled to normal operating temperatures. This way cooling time is minimized and thereby the water and pumping energy needed for cooling decreases [18].

28[28] have reported that cooled panels always offer better exergy efficiency compared to uncooled ones. On the other hand, pumping power reaches only up to 3.3% of the converted power of the cooled module while the increase in the conversion efficiency is 30% higher relative to uncooled module[28].

3) Photovoltaic/Thermal Air-Water Combi Systems

Photovoltaic-thermal combination systems (PVT Combi, also known as PVT bi-fluid or dual system) is a PVT system that merges two different heat carriers in one arrangement. The vast majority of PVT-Combi systems use air and water as the carrier fluids because of their wide availability, large scientific background as well as being practical.

Basic operation of Combi systems is similar to the individual air and water systems [26]. As for the implementation areas, Combi systems may be implemented in water heating, space heating and drying. Most common types of PVT Combi panels are as illustrated in Figure 17.

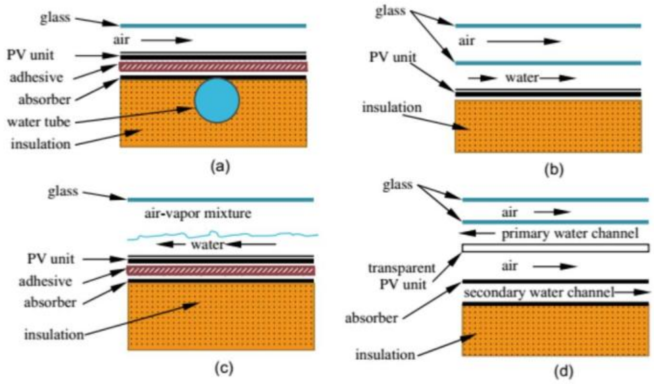

Figure 17: Structure of different types of PV/T collectors (a) sheet-and-tube PV/T, (b) channel PV/T, (c) free-flow PV/T and (d) two-absorber PV/T[8]

4) Photovoltaic/Thermal Heat Pipe (PVT-HP) Systems

Heat pipes are another mechanism to transfer out heat from thermal systems which rely not only on thermal conductivity of the fluid but also on the phase transition. A heat pipe system, which comprises of three main sections as shown in Figure 18, is highly effective and provides an ideal solution for heat removal.

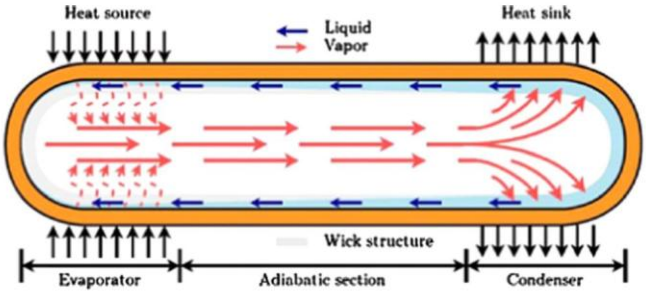

Figure 18: A typical conventional Heat-pipe system [29]

The evaporator section of the heat pipe is placed in contact with the photovoltaic module where it draws heat. The heated fluid evaporates and moves toward the condenser section all way throughthe adiabatic section wherein an annular cross-directional two phase flow occurs.In the condenser section, the fluid releases heat to another passing fluid and condenses owing to the heat discharge[29].

In natural climate regions, as a work around to freezing of water, heat pipesare incorporated into practical PVT systems. Moreover, there are many other studies that conduct PVT systems on heat pipe PVT systems[27].

5) Photovoltaic/Thermal Phase-change material (PVT-PCM) Systems

Another way of achieving a higher electrical efficiency from the PV panel is to use phase change material (PCM) to reduce the panel surface temperature. PCM, placed behind the panel as shown in Figure 6, is a waste heat storage material. When the temperature rises, the PCM material is converted from solid to liquid and the chemical bonds are separated from each other. During endothermic state change, PCM absorbs heat on itself. When the stored energy in the PCM reaches the phase change temperature, the PCM begins to melt. During the melting process, where the phase change is, the temperature remains constant. For this reason, during the melting process, the PCM draws heat from the PV panel at constant temperature.

Figure 19. PV panel with Phase-change materials. (1. PV panel, 2. PCM module)

6) Comparison of Photovoltaic/Thermal Systems

Since the most widely used system for cooling PV systems is the photovoltaic thermal systems, it has a vast variety of methods and parameters involved. Therefor, it needs a comprehensive and detailed comparison in order for the pros and cons of each configuration easily be understood.

Table 1 details photovoltaic thermal systems in terms of how and whether certain parameters affect the thermal, electrical and overall performances of the system. In

Table 2, PVT systems are tackled for their pros and cons per the type of the carrier fluid and design sub-divisions.

Table 1 Fact sheet for the efficiency of Photovoltaic Thermal Systems [21]

Efficiency	Positively affected	Adversely affected	Not affected
Thermal	Mass flow rate increment after optimum mass flow rate	Mass flow rate increment until optimum mass flow rate	
	Ambient temperature increment	Collector length increment	
	Inlet temperature increment	Exit area increment but after a range remains constant	
	Duct length increment	Tilt angle increment	
	Packing factor increment	Inlet velocity increment	
	Heat loss coefficient increment	Fan number increment (because of 2)	
	Mass of water decrement in the storage tank slightly (if PF and MFR is constant)	Packing factor increment (if MFR and MOW are constant)	
		Using fins	
Electrical	Collector length decrement	Solar cell temperature decrement	Inlet velocity variations
	In higher solar radiation intensities ranges increments	Initial solar radiation intensity increment until specific range	Duct length variations
	Absorber plate length increment	Mass flow rate increment	
	Inlet water temperature increment	Packing factor increment	
	Inlet temperature increment	Wind speed increment	
		Mean PV temp. decrement	
		Using fins	
Overall	In higher solar radiation intensities ranges increments	Initially solar radiation intensity increment until specific range	Fan number variations
	Inlet temperature increment	Inlet velocity increment	
	Wind speed increment	Mass flow rate increment	
	Duct length increment	Mean PV temperature decrement	
	Absorber plate length increment	Packing factor increment	

Table 2 Comparison of PVT systems with reference to the working fluid [21]

Fluid Based	Sub-division	Advantages	Disadvantages
Air		More adopted for building project application based on European and north American markets	Low heat capacity and low heat conductivity, which result in a low heat transfer
		No freezing and no boiling of the collector fluid	Low density, which results in a high volume transfer
		No damage if leakages occur	High heat losses through air leakage
		The most popular PV/T collector	Possible noise
		Minimal usage of material and low operating cost	They have less applications compared to the water collectors
			They have relatively slow heat transfer rate due to lower thermal conductivity
			Low specific heat capacity of air necessities greater volume of air per unit collector area for storage of a given unit of thermal energy
Water	Sheet&Tube	Simplest way to construct PV/T	2% less efficient compared to other types of collector
	Channel	Single air pass: more strength for resisting against water pressure because the backside could be strengthened with metal back. Backside of PV laminate is completely watertight Double air pass: can be expected for high efficiency	If a wide channel is used which is covered by one large glass plate, very thick glass may be necessary to withstand the water pressure, resulting in a heavy but fragile construction With double air pass: transparent PV laminates are so expensive.
	Free flow	Comparing to the channel case: one glass layer is going to be eliminated, accordingly reflections and material costs will decrease	Comparing to the channel case: the increased heat loss due to evaporation. Because the evaporation pressure is not low, the evaporation will cause some problems at high temperatures
	Two absorber	High thermal efficiency	Heavy channel cover-even more stronger than channel case

D. Transparent Coating (Photonic Crystal Cooling)

Another way of achieving a higher electrical efficiency by lowering the surface temperature of the PV panel is to make the PV panel surface transparent coating (photonic crystal coating). This visible transparent thermal black body is based on silica photonic crystals that can reflect solar radiation as infrared light and is placed on the top surface of PV cells. Meanwhile, anti-reflection and light capture effects of PV cells are slowly increasing. Thus, PV cells are cooled by finding the possibility of photon absorption by the PV module. Figure 8 shows how a PV module is cooled with a transparent coating.

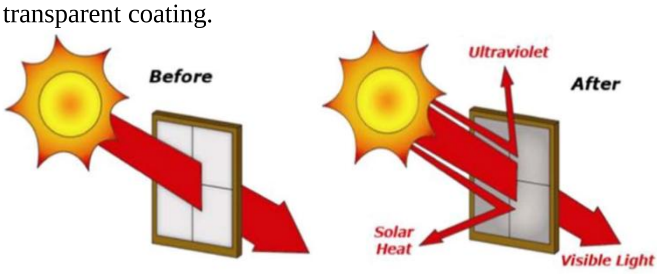

Figure 20. PV panel cooled by transparent coating (photonic crystal cooling)[11]

E. Thermoelectric Cooling

Thermoelectrical elements consist of n and p type semiconductors which are thermally parallel and electrically connected in series. In accordance with the Peltier effect,due to the flow of charge carriers from the hot (positive charged) side to the cold (negative charged) side under a certain temperature gradient, a voltage is created between the two sides and a current flows. The system can be seen inFigure 21.

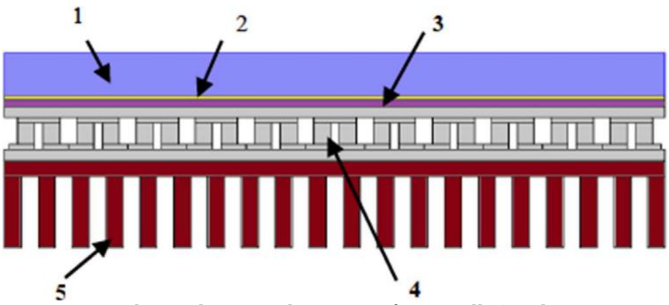

Figure 21. Thermoelectric cooling system for PV cells (1. Glass cover, 2. PV cells, 3. Insulator, 4. TEG module, 5. Fin heat sink

To reduce the surface temperature in PV systems, TE modules are also used, which are produced by transmission loss of photons with low energies and by thermalizationloss of photons with high energies. A TE module is placed in the center of the back of the PV panel, havingone face on top of the PV module and the other thermal resistors on the remaining surfaces. When the PV / TE system is exposed to solar radiation, the surface temperature increases with time[11].While the focus in thermoelectric (TE) cooling is more on increasing the electrical energy output of the panelby converting excess heat into electric rather than helping the PV cell convert better, it still lowers the panel temperature, which is not good for both at all. The lower the surface temperature, the better the efficiency of the PV cell gets, but on the contrary the lower is the TE efficiency[10].

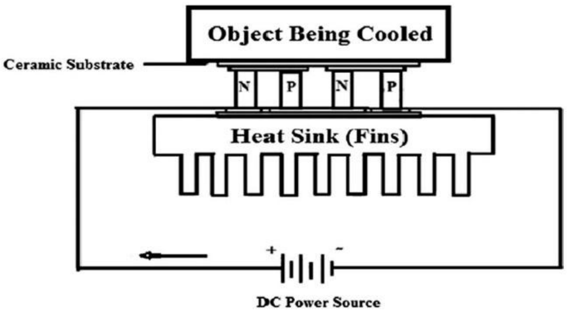

Figure 22: Schematic of a typical thermoelectric cooling system [30]

F. Other Cooling Techniques

There are many other studies focused on PV cooling including using nano-fluids containing suspended metal particles, such as silica/water or MgO-waternano-fluids whichwere found to increase the cooling performance of the carrier fluid by around 30 percent and thermal efficiency of the system up to 15%. Additionally, for further enhancement of the thermal performance alternating magnetic fields are also being implemented[10]. Another additional method for improving cooling performance of nano-fluids is using high frequency ultrasound waves which atomizes the working fluid. These techniques can be employed in combinations, and researches have shown that, atomized nanofluid performs better than atomized pure water which performs better than non-atomized water [31].

Cooling photovoltaic systems is also possible by having them integrated with several devices of appliances that use thermal sources, such as thermal air conditioning systems [32] or thermal absorbers of almost any kind [16].

III. CONCLUSIONS

There are many studies in the literature focused on increasing the electrical efficiency of PV systems by reducing the module temperature of PV systems. In these studies, which use the methods mentioned in the previous section, the electrical efficiency of the PV panel could have been maintained.

33[33]have conducted a comprehensive evaluation of the economic and environmental consequences of PV panels cooled by three different active cooling techniques. The environmental effects and the costs perunit energy are shown in Table 1 and Table 2 respectively.

Table 3. Environmental impact of different cooling techniques.

Environmental impact	unit	Option I	Option II	Option III
Global Warming	tn CO_2eq	33.74028	31.64988	32.28388
Acidification	kg SO_2eq	139.2556	124.539	127.943
Eutrophication	kg PO_4eq	19.59108	18.95546	19.13426
Ozone Depletion	kg CFC eq	0.008813	0.008691	0.008732
Abiotic Depletion	kg Sb eq	23.9409	23.94129	23.94196
Human Toxicity	tn Db eq	18.2467	17.61266	17.77336
Photochemical Ozone Depletion	kg C2H4eq	7.69126	7.0058	7.2748

Opt I:Air cooling on backside PV panel surface.
Opt II: Liquid cooling on front PV panel surface.
Opt III: Water spray cooling on front PV panel surface

From the environmental point of view, it is seen that the most negative effect is by air circulation behind the PV panel surface, while the least negative effect is by the liquid-based cooling of the PV panel front surface.

Table 4. General LCOE (€/kW h) data for the 30 kW PV system

Reference PV system	0.102
Air based cooling	0.101–0.11
Water (PV/T configuration)	0.124–0.159
Water (spray cooling)	0.103–0.108
Water (front water layer)	0.096–0.10

When compared in regards to the energy costs, the most economical method is to cool the front surface of the panel with water, whereas and the PVT-water system is the costliest.

(a) (b)

Figure 23. (a) Helical channel and (b) Straight channel cooling plates.

Salem et al. (2017) investigated the electrical performance of PVT systems coated with two different aluminum plates having flat and helical geometry, as shown in Fig. 11. When compared with the reference non-cooled PVT system, the electrical yield of the flat aluminum plate system varied from 31.6% to 47.2%, while it varied from 34.6% to 57.9% in the helical geometry plate system.

12[12,34]conducted CFD analysis and experiments at different air velocities with different fin configurations to investigate effects of fin arrangement on efficiency of PV modules in comparison with other governing parameters, such as number of fins and fin material. Fin arrangement has been found to be another governing parameter among other common parameters.

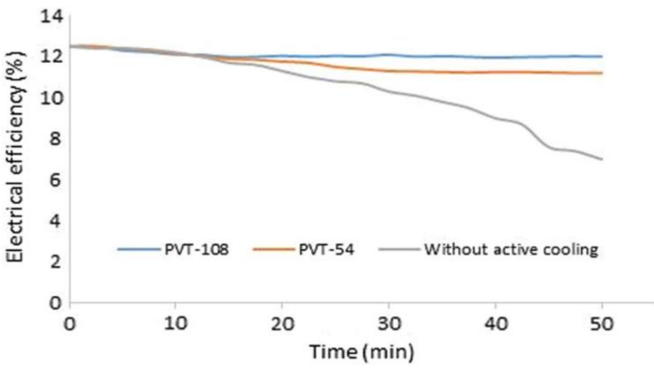

Figure 24. Change in the electrical efficiency of a cooled and un-cooled PV with time.

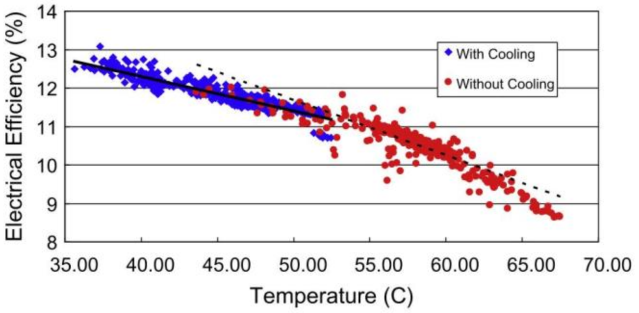

Figure 25: Electrical efficiency of a PV panel as a function of cell temperature, with and without cooling [35]

As seen in Fig. 24 and Fig. 25, cooling PV panels considerably affects electrical efficiency. In Fig 24, while electrical efficiency of a conventional PV falls from aroun 12.5% down to as low as 6%, active cooling of the PV module helped electrical efficiency to maintained at around 11.5%, as well as benefiting from the heat drawn from the system.

While cooling is beneficial in terms of both electrical and thermal yield obtainable from a PV module, no cooling method can be entitled to be the best. There are numerous different cooling techniques as we have reviewed so far here, with reference to the sub divisions and other involved parameters, there is an abundance of cooling configurations. Every single technique has its pros and cons, advantages and disadvantages, benefits and drawbacks. Any system optimal for a purpose, in any location at any stage or scale could lose upper hand for another case.

Table 5 is a brief comparison of cooling technologies in terms of their beneficial sides and disadvantageous sides.

For example, When thermal energy gain is not important or there is no room for thermal utilization, and/or the main focus is the electrical efficiency and cost-effectiveness the PVT-air systems may be chosen as the best option. If, thermal exergy becomes a preference along with the greatest possible electrical yield, one can surely go for PVT-water or combi systems. Pros and cons of other techniques are as follows.

Table 5 Comparison of different cooling technologies, advantages and disadvantages.

Cooling Technology	Advantages	Disadvantages
Water Spraying/Sprinkling [36]	High electrical efficiency. Consumable material (water) is cheap.	High cost and difficulty of applicability. The recovered heat becomes waste.
Immersion Cooling [37]	High electrical efficiency. Easy setup.	Evaporation of dielectric fluid. High cost.
PV/T-Air Systems [38,39]	High electrical efficiency. Lower cost.	Low thermal exergy. Uneasy to store thermal energy.
PV/T-Water Systems [39,40]	High electrical and thermal efficiency. High thermal exergy.	High cost. High installation and operating cost.
PV/T Air-Water Combi Systems [41]	High thermal and electrical efficiency. High thermal exergy.	High cost. High installation and operating cost. Complex structure.
Photovoltaic/Thermoelectric System Cooled By Heat Sink [42]	Highest electrical efficiency. Double electrical energy source	Low thermal efficiency. Low thermal exergy. High installation and operating cost. Life problem of TEC modules.
Photovoltaic Thermal Phase-Change Material Systems [43]	Lowest cost. High thermal and electrical efficiency.	Difficulty of applicability. Phase Change Material lose its characteristic over time.
Transparent coating (Photonic Crystal Cooling) [44]	High electrical efficiency. Easy applicability.	Low thermal efficiency. High initial investment cost.

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