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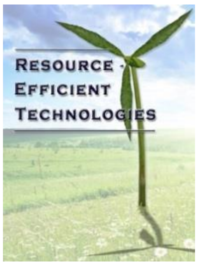

Review Article

THERMAL MANAGEMENT OF SILICON PHOTOVOLTAIC PANELS: A REVIEW

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Abstract

Photovoltaic (PV) technologies represent a key role in the ongoing energy transition towards the decarbonisation of convectional power systems and to reduce the harmful population impact to environment. Nowadays, the majority of market available photovoltaic PV technologies are silicon based with a usual energy conversion efficiency of less than 20 %. The major drawbacks of the widely used silicon PV technologies are related to performance degradation due to aging as well as performance drops that occur during periods of elevated operating temperatures. In order to improve performance, as well as the lifetime of the PV systems, various cooling techniques have been investigated in the last two decades. The main goal of the specific cooling approaches for PV panels is to ensure efficient thermal management, as well as economic suitability. In this review paper, different cooling strategies are categorized, discussed and thoroughly elaborated in order to provide deep insight related to an expected performance improvement and economic viability. The main results of this review indicate that the cooling approaches for PVs can ensure a performance improvement ranging from about 3 up to 30 %, depending if passive or active cooling approaches are applied. The main results also indicate that the economic viability as well as environmental suitability of the specific cooling approaches is not sufficiently discussed in the existing research literature.

Keywords: photovoltaics, cooling techniques, performance, solar energy, renewable energy.

Manuscript highlights:

- strategies for thermal management of photovoltaic panels discussed;
- passive and active cooling approaches analyzed;
- the average performance indicators reported;
- future directions in the field elaborated.

1. Introduction

According to the latest Franuhofer ISE, [1] the data of overall installed PV capacities in 2019 nearly approached 600 GW and will probably exceed 600 GW in 2020 (Figure 1). Moreover, by 2050 there are projections that the globally installed PV capacities will reach over 8,000 GW with a power generation capacity of about 20 GW, [2]. There is no doubt that PV technologies are crucial in energy transition, moreover, PV technologies are dominant with respect to the overall installed capacities, when compared to other generation technologies.

More specifically, PV technologies were dominant regarding installed capacities in 2019, together with wind generation technologies, [3] (Figure 2). Even though there is a constant rise in installed PV capacities; there are still certain barriers that are hindering the desired targets with respect to overall PV

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capacities. Namely, in specific economies, the overall initial investments in PV systems are still relatively high ones and are usually followed by legislation issues, i.e. complicated administration with lengthy procedures.

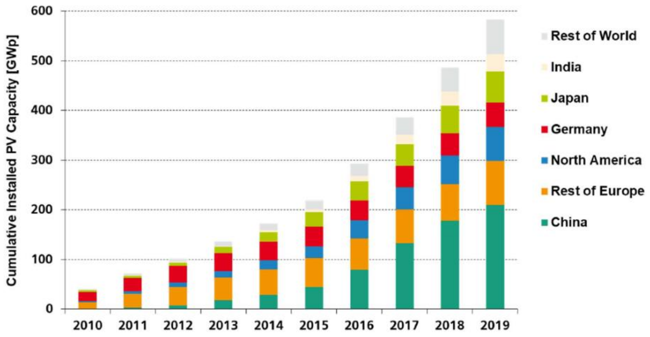


Fig. 1. Overall installed PV capacities worldwide, [1]

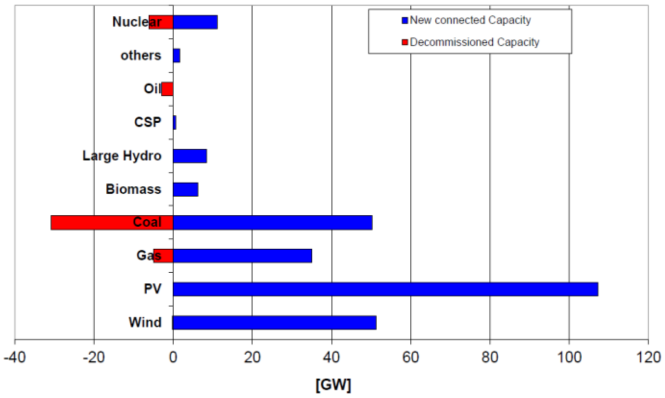


Fig. 2. Overall installed PV capacities worldwide, [3]

The main PV technologies on the market are silicon based ones (c-Si) with a share of 95 %, while the rest being Thin film PV technologies. The majority of the installed PV panels are in a Multi-Si variant (Si-poly), while the share of Mono-Si PV technology was around 66 % in 2019, [1]. Therefore, the market strongly relays on the oldest, but most reliable silicon PV technologies. When analyzing the economic structure of PV systems, it could be noticed that the highest unit cost of a PV system is due to PV panels, which usually ranges from 0.6 USD/W to 0.8 USD/W, [4]. Thus, PV panels should be in the focus of novel approaches and improvements in order to obtain a performance increase and unit cost reduction.

One of the key issues related to the widely used silicon PV systems is performance drops that can noticeably reduce the performance of PV systems due to reduced electricity production. The main reasons for the performance drops are associated with the pure aging of the PV panels, [5] and due to the degradation of the energy conversion efficiency [6] that occurs in periods of elevated operating temperatures (usually over 50 °C). The aging caused degradation of the PV panels depends from the specific climate conditions and specific setup of the PV system (roof-top, building integrated, concentration PVs, etc.), and is usually below 1.0 % per year, [7]. Ultraviolet (UV) solar irradiation could be one of the main reasons for the PV panel aging, since it causes the aging of some other PV panel layers according to latest research findings, [8]. The performance degradation caused by elevated operating temperatures is also complex and linked with thermal processes inside the silicon layer (thermal dilatations), together with the impact of UV radiation. Performance degradation due to elevated operating temperatures depends from the specific PV technology but is usually below 0.5 %/°C, [9]. Other factors can also affect performance as well as the overheating of the PV panel such as accumulated dust or impurities over the PV panel surfaces, [10].

Normally, a PV panel is exposed to solar irradiation and heat is accumulated in the constructional layers of the PV panel (frame, glass, encapsulate, silicon, back-sheet), which increases the internal energy of the overall PV pane layers, i.e. rise in the PV panel operating temperature occurs. Heat rejection from the PV panel is ensured via heat convection and thermal convection in usual operating conditions. The PV panel is generally exposed to stochastic operating conditions that cause PV panel temperature stratification, Figure 3.

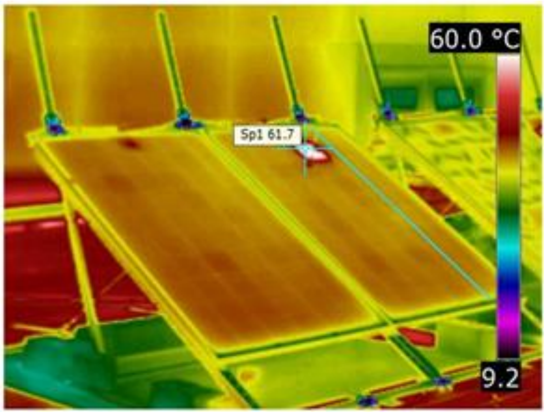


Fig. 3. Temperature contours of PV panel in typical operating conditions

In order to reduce the aging of the PV panels (as well as reduce thermal stress) and improve the performance of the PV systems, different cooling strategies have been examined in recent decades, [11]. Cooling approaches for PV panels are different but in general could be divided into passive, [12] and active, [13] ones. The passive cooling approaches are generally simple in design, associated with lower costs, but on the other side the performance improvement is less when compared to active cooling. Active cooling allows for more flexibility, ensures higher performance improvement, but requires operational energy and the design is more complex. The main issue with active cooling approaches is the techno-economic viability since most researchers mainly focus on performance improvement, while the economy is less investigated. However, a crucial element of all engineering concepts should be the techno-economic viability, thus more efforts are needed from the research community.

The important aspect of cooling is linked with the coolant selection, since it can have an important impact on the effectiveness of the cooling method as well as on the economic aspect. The usual used coolants for the considered application are water, [14], air [15], phase change materials (PCM), [16] or even nanofluids, [17]. Finally, the configuration of the PV system is also crucial as already emphasized above since it could strongly affect the main design, as well as the solutions related to the specific cooling approach. The environmental aspect for cooling techniques is also important since in the case of large scale cooling systems for PV plants, various materials, as well as resources are assumed to be used, thus environmental suitability should be also verified. Unfortunately, very few research works have considered the environmental aspect of the proposed cooling approaches for PV panels. Heat removed from the PV panel (waste heat) could also be considered for utilization in different configurations, which would certainly improve the economic viability of the cooling approaches. A recent successful real-field experience from Portugal [18] merely demonstrates the potential suitability and viability of cooling approaches for PV systems. In that sense, it is important to understand and categorize the cooling strategies in order to select the most appropriate one for the given purpose and general climate circumstances.

The main objective of this work is to provide a review and in depth analysis of various cooling strategies for the thermal management of photovoltaic panels. The herein provided discussion and presented results are useful as a guideline for the design of novel and advanced cooling approaches for photovoltaic panels, or for the improvement of existing solutions.

2. Elaboration of review methodology

In this work, the most relevant studies were selected using the Scopus® research database in the period of 2010 to 2020. Conceptually, in this paper the analysis of cooling techniques was divided into the examination of passive and active ones, Figure 4. The detail division on examined cooling approaches was also presented on the Figure 4. The focus was directed towards specific coolants being used for cooling approaches and operating configurations, since they also strongly affect the selection of specific cooling strategies.

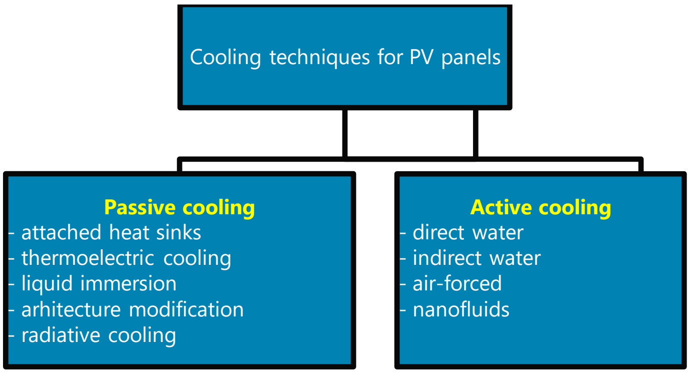


Fig. 4. The main division of cooling techniques for PV panels

The conducted review was mainly focused on performance improvement as well as the discussion of specific design approaches, advantages and disadvantages, i.e. discussion of possible improvements. The economic as well as environmental aspects were also briefly discussed taking into account the limited available data in the existing research literature. The main focus of the review was to discuss and to elaborate various conceptual approaches related to the thermal management of the PV panels. Selected works from the last two decades were analyzed with respect to the specific cooling strategy.

3. Passive cooling approaches

3.1. Cooling strategies with attached heat sinks

In order to reduce the operating temperature of PV panels, as well as to enable thermal management, heat sinks can be attached on the backside surface of PV panels. Various heat sinks methods have been explored in recent years, which will be discussed and elaborated in the continuation.

Fin based cooling is one possible approach, Figure 5, where the authors have provided a techno-economic analysis of a free standing PV panel (260 Wp) in typical Mediterranean climate operating conditions, [19]. An economic and environmental analysis was also conducted in the same study. The geometry of the fins was specially designed in order to provide more efficient heat rejection from the PV panel to the surrounding air. More detail about the fin geometry development, as well as insights into the fin based cooling method can be found in study [20]. The results directed that the efficiency improvement was up to 5 %, which was in accordance with other passive cooling approaches. Moreover, based on the gained results, an economic (LCOE) evaluation was provided on a 30 kW PV system, which showed that the LCOE can go below 0.10 €/kWh for the examined cooling approaches. An environmental analysis directed that a positive contribution to CO2 emission reductions will occur after 7 years of operation.

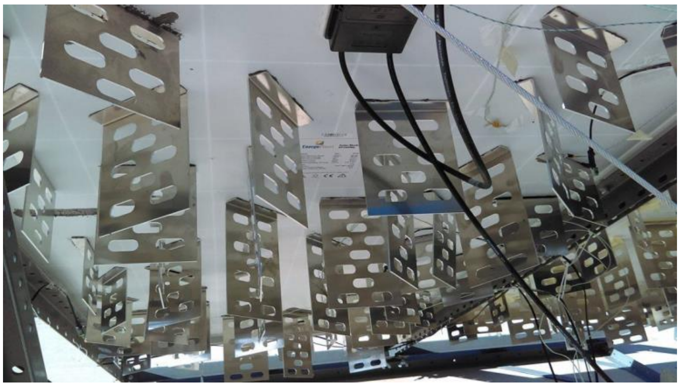


Fig. 5. Example of fin cooling for PV panels (free-standing), [19]

One of the main issues related to the fin based cooling is related to the durability of the materials (glue) used to attach the fin on the backside surface of the PV panel. Moreover, glue is also affects the heat transfer from the PV panel to the fin material (aluminum). In that sense more investigations should be directed in order to discover more reliable and economically viable fin attaching options. A further development of the fin geometry could also be useful, i.e. to ensure in depth analysis for various geographical regions. A similar approach, but with different fin geometry and PV cell size, was applied in work [21]. A compact aluminum fin cooler was attached on the backside surface of the PV cell, Figure 6.

Experiments were conducted in laboratory conditions with a maximal solar insolation level of 800 W/m^2, while the solar irradiation range was from 200 to 800 W/m^2. Surrounding air temperatures ranged from 15°C to 35 °C. Efficiency improvement (electrical) was over 4 % for peak solar irradiation, while for other regimes it was below 1 % on average. The main issue with this experiment is the fact that it was obtained on a small sized PV cell where the thermal effects are quite different with respect to the large sized PV panels. The data related to the fin attachment system were not reported as well as economic and environmental evaluations.

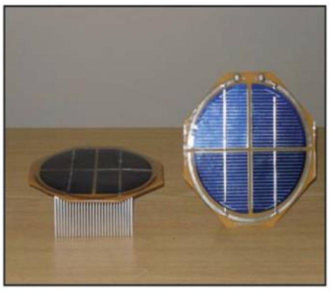
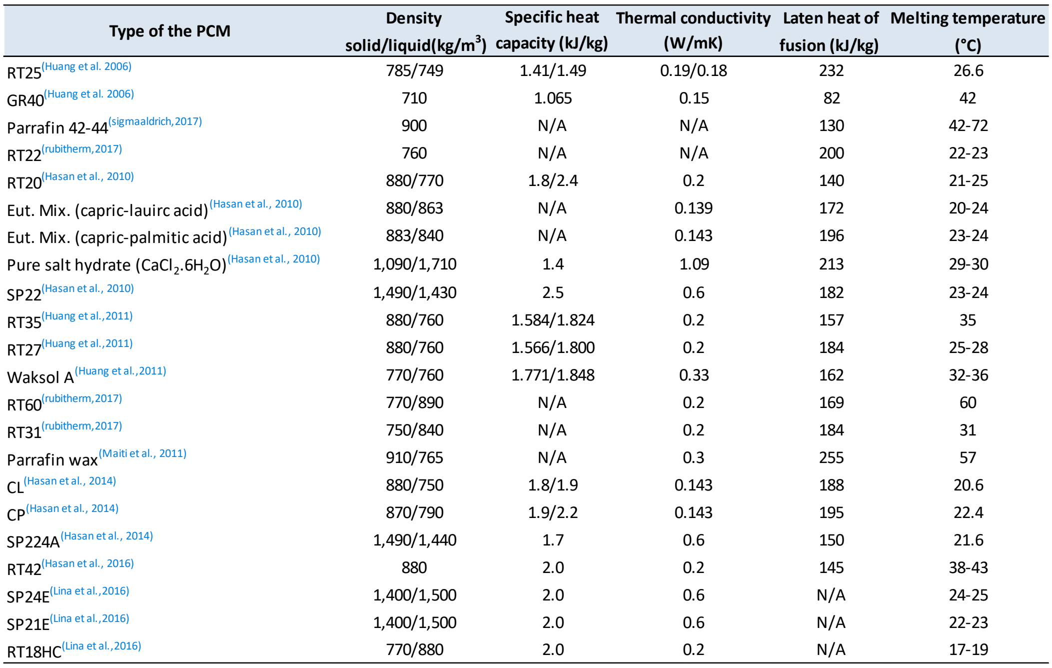


Fig. 6. Compact aluminum fin based cooler (heat sink), [21]

In order to boost up the efficiency of heat rejection from the PV panel, an addition of a phase change material is also considered as a cooling strategy (PV-PCM systems). Phase change materials can efficiently absorb rejected heat but on the other side, the critical issue is with the efficient (suitable) thermal management of the PCM layer. In practical terms, PCMs are suitable in one period of the day since they have a favorable effect on cooling, while in other periods of the day, there is an issue with accumulated heat (slowed heat rejection). There are different PCM materials that were used for PV-PCM cooling configurations, Figure 7 which are mainly selected regarding the melting temperature and latent heat. Besides thermal management, one of the main issues related to the PCM is its high unit cost that is usually between 5 to 10 €/kg. In some circumstances, the weight of the PCM layer is also a critical feature. Due to the previous issue, the economic viability of PV-PCM systems is usually questionable, which requires a necessary optimization as well as for the special design of PV-PCM cooling systems that would be suitable for specific climate circumstances. A typical PV-PCM cooling configuration is a container filled with a suitable PCM material and attached to the backside surface of the PV panel to secure thermal management. One specific concept is presented in Figure 8, which was used for building integrated photovoltaic (BIPV), i.e. for the regulation of PV panel operating temperatures, [23].

In order to improve heat transfer in the PCM layer, the fins are usually added, as it was also the case in configuration, Figure 8. Study [23] considered a paraffin based PCM material where a BIPV system was tested in laboratory conditions. The results showed that a reduction in the peak PV panel operating temperature was about 20 °C. The addition of fins helped in more efficient heat transfer but increased the overall weight of the system. An economic analysis was not reported for considered configuration and more realistic data should be ensured for real-field experimentation.



Type of the PCM	Density solid/liquid(kg/m^3)	Specific heat capacity (kJ/kg)	Thermal conductivity (W/mK)	Laten heat of fusion (kJ/kg)	Melting temperature (°C)
RT25(Huang et al. 2006)	785/749	1.41/1.49	0.19/0.18	232	26.6
GR40(Huang et al. 2006)	710	1.065	0.15	82	42
Parrafin 42-44(sigmaaldrich,2017)	900	N/A	N/A	130	42-72
RT22(rubitherm,2017)	760	N/A	N/A	200	22-23
RT20(Hasan et al., 2010)	880/770	1.8/2.4	0.2	140	21-25
Eut. Mix. (capric-lauirc acid)(Hasan et al., 2010)	880/863	N/A	0.139	172	20-24
Eut. Mix. (capric-palmitic acid)(Hasan et al., 2010)	883/840	N/A	0.143	196	23-24
Pure salt hydrate ($CaCl_2.6H_2O$)(Hasan et al., 2010)	1,090/1,710	1.4	1.09	213	29-30
SP22(Hasan et al., 2010)	1,490/1,430	2.5	0.6	182	23-24
RT35(Huang et al.,2011)	880/760	1.584/1.824	0.2	157	35
RT27(Huang et al.,2011)	880/760	1.566/1.800	0.2	184	25-28
Waksol A(Huang et al.,2011)	770/760	1.771/1.848	0.33	162	32-36
RT60(rubitherm,2017)	770/890	N/A	0.2	169	60
RT31(rubitherm,2017)	750/840	N/A	0.2	184	31
Parrafin wax(Maiti et al., 2011)	910/765	N/A	0.3	255	57
CL(Hasan et al., 2014)	880/750	1.8/1.9	0.143	188	20.6
CP(Hasan et al., 2014)	870/790	1.9/2.2	0.143	195	22.4
SP224A(Hasan et al., 2014)	1,490/1,440	1.7	0.6	150	21.6
RT42(Hasan et al., 2016)	880	2.0	0.2	145	38-43
SP24E(Lina et al.,2016)	1,400/1,500	2.0	0.6	N/A	24-25
SP21E(Lina et al.,2016)	1,400/1,500	2.0	0.6	N/A	22-23
RT18HC(Lina et al.,2016)	770/880	2.0	0.2	N/A	17-19

Fig. 7. Various PCM materials for PV-PCM cooling purpose, [22]

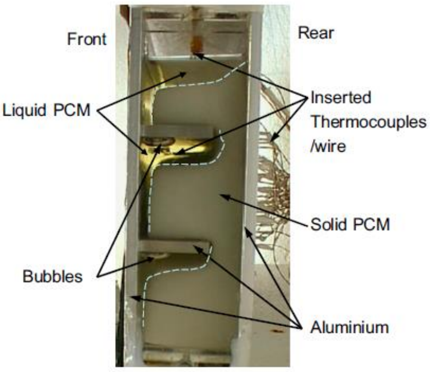


Fig. 8. Typical PCM based heat sink, [23]

A cooling PV-PCM approach for free-standing PV panels was examined as a field experiment in work [24] (Figure 9). The mix of fatty acids and capric acid-palmitic was used as the PCM and the system was tested in Irish climate conditions (Dublin). The application of the above mentioned PCM enabled the drop of the operation temperature ranging from about 6 to 10 °C. The numbers related to the efficiency improvement were not reported, however, the rise in PV panel power output was reported in a range of 4 % to a maximal 6.5 %. An economic elaboration was not discussed for the examined configuration. An optimization of the PCM layer could be provided to determine a suitable thickness for specific climate conditions.

Fig. 9. PV-PCM cooling system for free-standing PV panel, [24]

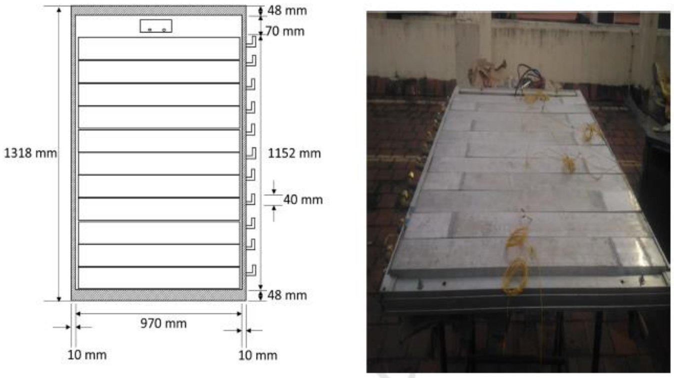


Fig. 10. PV-PCM cooling system with containers, [25]

Study [25] was the first to consider a PV-PCM system assembled from small containers, i.e. which was different in approach since one solid PCM containers were usually used in experimental investigations (Figure 10). The system was checked in an experimental manner in Indian climate conditions (Chennai), together with provided simulations. The main results showed that the proposed approach reduced the peak PV panel temperature for about 20 °C, while the improvement in electrical efficiency ranged from about 6.2 to 10.5 %. The results are in accordance and comparable with already examined PV-PCM configurations. It is not clear why authors proposed such an approach while the quantity of used PCMs remained almost the same (when compared to one compact PCM containers). Moreover, an economic aspect was not analyzed, and to obtain a more precise comparison of results, a configuration with a full solid container filled with PCMs should have been provided. The most efficient PV-PCM techniques were discussed in work [26] where several different PCMs were examined in an experimental manner in realistic circumstances and monitored with an infrared thermal camera (Figure 11). A heat sink with aluminum ribs was provided and two polycrystalline PV panels were examined (5 Wp).

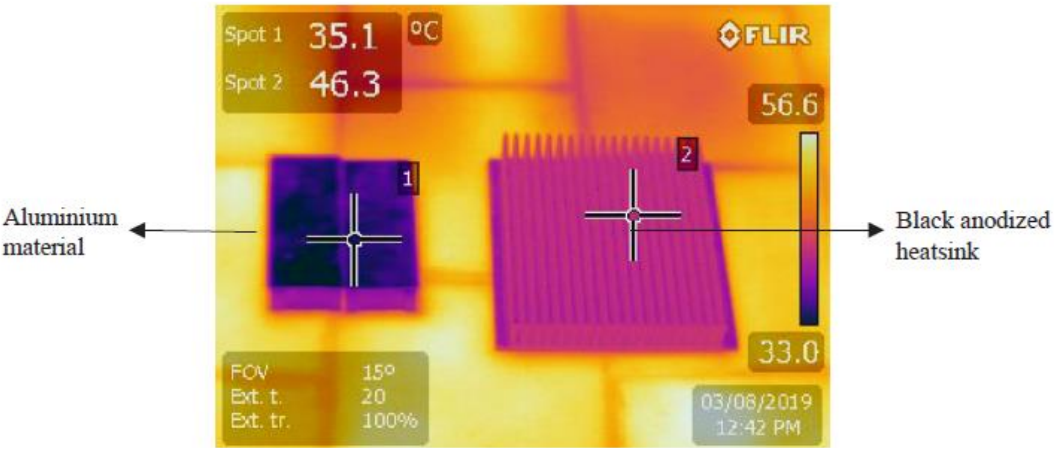


Fig. 11. PV-PCM cooling system with containers, [26]

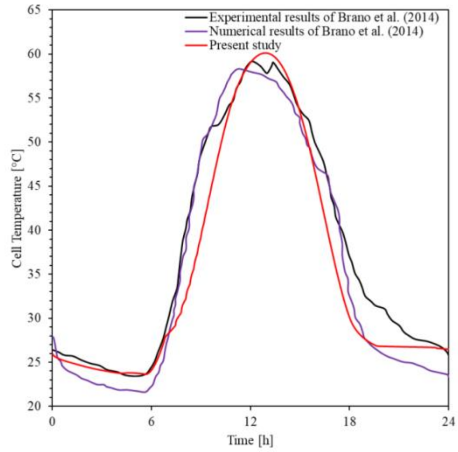


Fig. 12. Comparison of developed PV-PCM model with experimental readings, [27]

The results revealed the best PCM material for the given purpose (HS29), since it was the most effective one. The same experimental approach should be provided on PV panels of the highest rated power output since the thermal effects could be rather different. The economy of the proposed cooling approaches was not considered. Besides the experimental approaches related to the PV-PCM systems, intense numerical investigations are also in the focus of the research community in order to develop a precise and reliable numerical (simulation models) that would allow for a better design of the PV-PCM systems. A numerical model related to a PV-PCM free-standing PV panel was developed in [27], together with an economic evaluation. The developed numerical model was successfully validated, Figure 12.

The efficiency improvement was over 3 % with a decrease in the PV panel operating temperature (about 10 °C for Turkish climate conditions). The optimization of the PCM layer thickness was also provided in the same study taking into account melting temperature. In general, there is rather few numerical studies related to PV-PCM cooling which focus on passive cooling approaches.

The introduction of novel PCM materials or enhanced ones with nanomaterials for instance could also be a step further in the improvement of PV-PCM passive cooling systems. Pork fat was proposed in [22] as a novel PCM material for PV-PCM configurations. A numerical model was also developed in the same study and compared with existing experimental data in the literature. The results indicated that pork fat has a similar impact on the performance improvement as other convectional PCMs, while the key problem is the long term stability of the pork fat as a novel PCM. The main advantage of pork fat as a PCM is its economic suitability when compared with regularly used market available PCMs that have higher unit costs. The addition of nanoparticles in the PCM was considered in study [28] for the case of building integrated concentrated photovoltaics (BICPV). Several configurations were examined, i.e. unfinned, unfinned+PCM, unfinned+nPCM, etc., Figure 13. The configuration with the micro finned+n-PCM showed highest potential for temperature decrease from 9.2°C to 11.2°C on average, this innovative approach resulted in being effective. The issue with the proposed approach could be the long term stability of the PCM in concentration systems and its economy which was not examined in the same study.

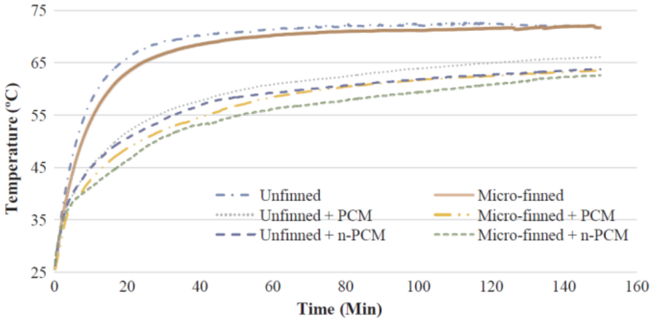


Fig. 13. Effect of nanoparticle addition in PCM on temperature profiles, [28]

A global analysis related to the potential of PV-PCM cooling in various climate zones was discussed and elaborated in [29]. The study indicated that depending from the specific climate zones, the improvement of the PV panel performance ranges from 2 to 6 %. Currently, PV-PCM cooling is not economically viable for the examined configuration. The best results were achieved for warmer climates and a study was conducted via a numerical investigation.

3.2. Thermoelectric cooling

One of the also examined heat sink methods for PV panel thermal regulation is related to thermoelectric cooling systems PV-TEG. Thermoelectric systems are attractive since they are easy for regulation, but economic viability represents an issue. A thermoelectric cooling system was proposed in work [30] for the thermal management of the PV panel, Figure 14. The study included a numerical investigation with optimization via genetic algorithms. The performance improvement was not significant, while the PV panel working temperature decrease was about 16°C for a solar irradiation of 1,000 W/m2. An experimental approach was not conducted as well as an economic evaluation to explore suitability of the proposed cooling method. The study also indicated the necessity for further thermoelectric material development in order to rise the effectiveness and economic viability of PV-TEG cooling systems.

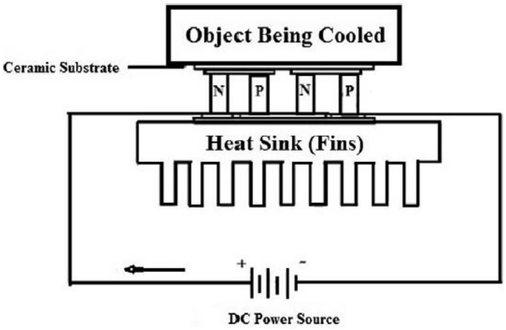


Fig. 14. Schematic of thermoelectric cooling of PV panel, [30]

The feasibility of the passively cooled small sized PV cell via a thermoelectric generator was discussed in [31] for the case of CPV-TEG systems, Figure 15. The annual global performance improvement was about 4.3 % for the examined configurations. The impact of various atmospheric conditions on the CPV-TEG system was also examined where useful data were provided. The economy of the proposed hybrid cooling system was not considered, but the design has potential for further improvements.

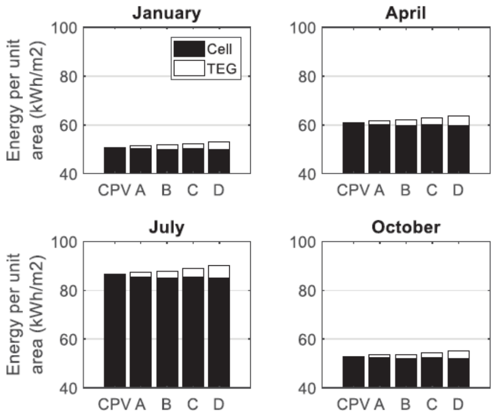


Fig. 15. Improvement of energy performance for different configurations, [31]

The advancements in the effective management of PV panel cooling systems by thermoelectric generators were discussed in work [32]. The integration issues between PV and TEG systems were discussed in detail and performance improvements for different photovoltaic technologies as well as application areas. The implementation of the PV-TEG cooling systems secured an average performance improvement of about 3 to 5 % for silicon PV panels. A performance comparison between solar photovoltaic thermoelectric generations and solar PV-TEG cooling systems was elaborated in study [33]. The study compared two hybrid systems and both the examined TEG based systems showed performance improvement, where the cooling rate of the considered systems ranged from 0.06 W/K to 0.3 W/K. An analysis was conducted by the modelling approach while a real experiment is missing and an economic evaluation as well. Study [34] explored a novel interface material for a performance improvement of photovoltaic-thermoelectric devices, Figure 16. The addition of the novel interface materials showed favorable benefits related to the improvement of the PV panel power output (14 % for considered case). The economic aspect was not examined as well as the possible further developments of the examined approach.

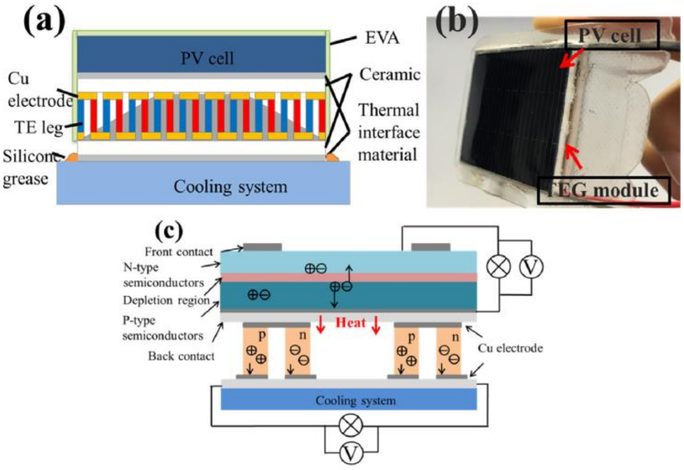


Fig. 16. Improvement of energy performance for different configurations, [34]

3.3. Liquid immersion method

The submerged (immersions) technique is one of the most interesting approaches related to the thermal management of PV panels. The main idea is to flood the PV panel into liquid to ensure a reduction of PV panel operating temperature. The optical as well as thermal behavior of the submerged PV panel was examined in work [35]. The PV panel (20Wp) was flooded into a water basin, Figure 17 and tested under Mediterranean climate conditions. Besides the experimental approach, a simulation model was also developed, which had reasonable matching with the readings. Different water depth layers were investigated in order to check the performance response.

The results revealed increase in performance for about 15 % at specific water depth of 4 cm. The water depth is critical for this cooling technique since it affects optical losses and performance of the cooled PV panel as well, Figure 18. The issue related to the long term impact of the submersion environment on PV panel lifetime was not discussed as well as the impact of demanding working conditions in general. Moreover, the economy and environmental impact was not discussed.

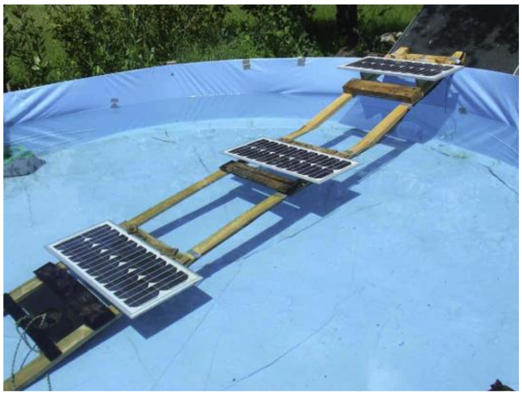


Fig. 17. Thermal management of PV panel by water submersion, [35]

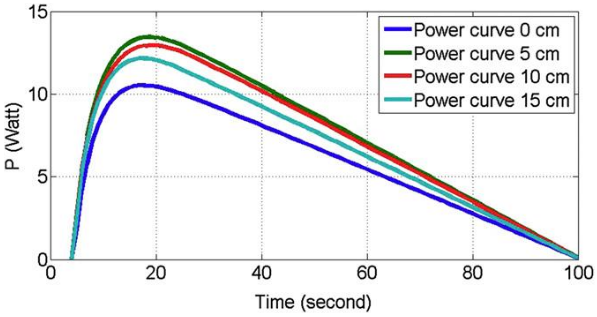


Fig. 18. Impact of water depth on PV panel power output, [35]

An investigation related to a flooded small scale polycrystalline PV cell (0.119 W and flooded in distilled water) was discussed in [36]. The PV panel was examined in Iraqi climate circumstances with a solar insolation of about 700 W/m^2. The maximal energy conversion efficiency (22 %) was detected for a 6 cm thick water layer depth, while the average was about 11 % (6 cm water layer depth). The water temperatures varied from 28 to 30 °C. More discussion should be provided on the impact of water quality regarding performance improvement and water depth layer. Economic and environmental evaluations were not conducted. The liquid immersion technique is especially interesting for CPV systems in order to secure efficient thermal management. Concentration PV systems are usually exposed to higher operating temperatures where water is not suitable, thus other liquids are used such as various oils that can withstand higher operating temperatures. An analysis of optical properties as well as coolant thermal properties for CPV systems was discussed in work [37]. Different immersion cooling liquids were examined with respect to the optical transmittance and durability. The impact on the average optical transmittance was presented in Figure 19, where it is clear that the best property has dimethyl silicon oil. The tests were performed at different temperatures, together with accelerated aging tests. Even though silicon oil showed to have the best results, all other coolants also showed suitability due to relatively low optical transmittance degradation.

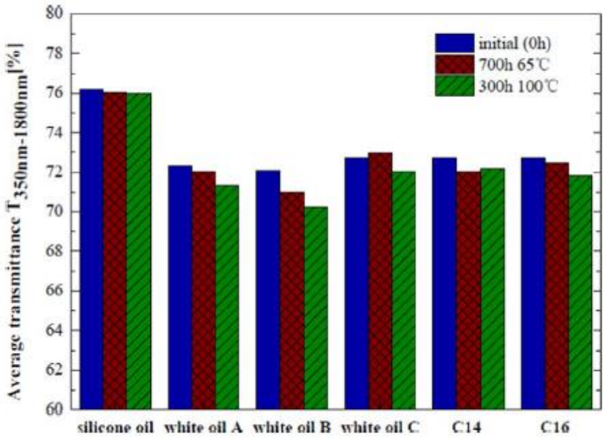


Fig. 19. Impact of immersion fluid on optical transmittance, [37]

3.4. Changing of PV panel architecture

The change of the standard PV panel architecture is an interesting passive cooling approach, since convectional market PV technologies are considered with the proposal of specific modifications that would improve PV panel performance. The modification of existing PV panel architecture was proposed in [38] with the introduction of holes (perforations) on the front side of the PV panel, Figure 20. The holes affected the fluid flow over the PV panel and enhanced passive cooling. The introduction of the holes enabled the drop of the PV panel working temperature from about 70 to 51°C.

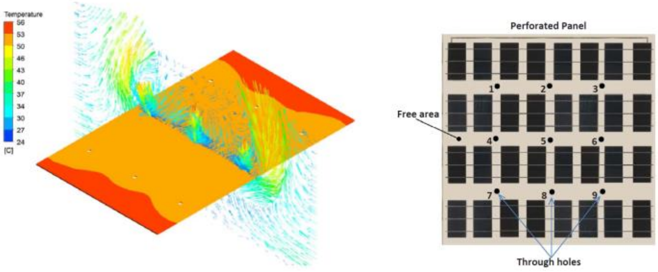
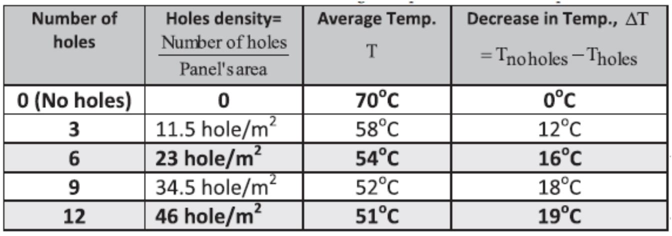


Fig. 20. Passive cooling strategy with of holes on front side of PV panel, [38]

The impact of the number of holes was also examined (simulations and experimental results) and the results directed that the number of holes should be optimized (as well as diameter of holes), Figure 21. Economic and production process evaluations were not discussed if serial production were to be considered with the proposed modification.



Number of holes	**Holes density=** $\frac{\text{Number of holes}}{\text{Panel's area}}$	**Average Temp.** T	**Decrease in Temp.,** $\Delta T = T_{no holes} - T_{holes}$
0 (No holes)	**0**	**70°C**	**0°C**
3	11.5 hole/m^2	58°C	12°C
6	**23 hole/m^2**	**54°C**	**16°C**
9	34.5 hole/m^2	52°C	18°C
12	**46 hole/m^2**	**51°C**	**19°C**

Fig. 21. Effect of number of holes on PV panel temperature decrease, [38]

A novel approach related to PV panel architecture modification was elaborated in work [39] (Figure 22). Several passive cooling approaches were discussed and numerically tested. The first modification was related to the change of the PV panel frame material where the effect of thermal conductivity on the PV panel temperature contours was investigated. The second passive cooling approach was related to the modification of the PV panel geometry with the introduction of perforations on the aluminum frame. The third approach was directed to the introduction of slits on the front surface of the PV panel.

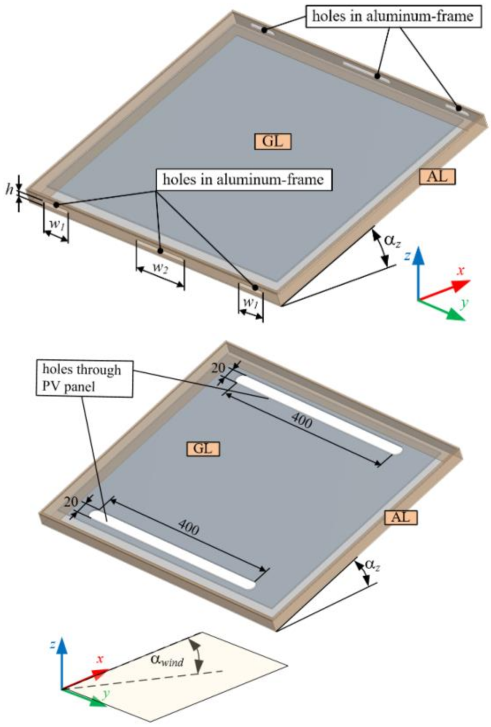


Fig. 22. Passive cooling approaches with modification of PV panel architecture, [39]

The results revealed that the frame material doesn't have effect on the PV panel working temperature and which indicates the possible utilization of some alternative and suitable frame materials. The introduction of perforations in the panel frame does not significantly affect the cooling effect (PV panel temperature reduction of about 0.5 °C). The introduction of slits showed potential, since the achieved temperature drop was about 4.0 °C. However, further optimization is necessary and a careful investigation on how the proposed modifications would affect the standardized production process of PV panels.

3.5. Radiative cooling

The radiative cooling of PV panels or photovoltaic thermal (PVT) systems was recently investigated in several research works. In study [40], the authors investigated the effect of radiative cooling for a typical PVT system, Figure 23. A numerical model was developed in order to analyze the performance improvement and investigate the impact of various working circumstances. The main objective was to examine its nocturnal cooling capacity. The data directed that the absorber plate was cooled to about 9.5 °C below the surrounding temperature in a period of a few hours. It was found that the absorber plate can achieve a stagnation temperature of about 11 °C with a maximum cooling capacity of about 50 W/m^2. The economy of the proposed approach was not discussed and it would be interesting to consider the application of some alternative materials that could boost the radiative cooling effect.

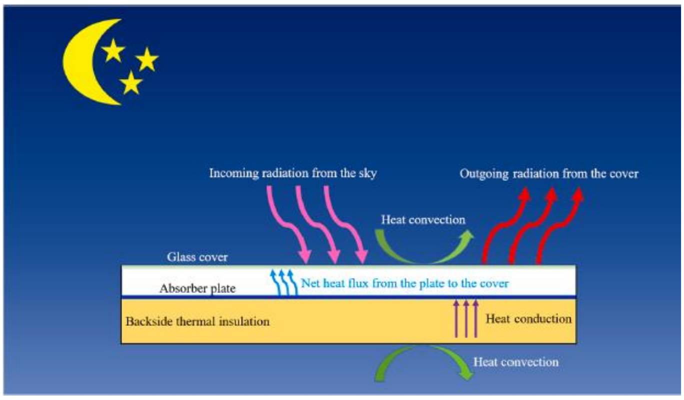


Fig. 23. Concept of radiative (nocturnal) passive cooling strategy, [40]

The introduction of low-cost radiative coatings for the thermal regulation of PV panels was discussed in [41]. Spectrum selective coatings were selected to investigate the radiative cooling performance. The coatings were made from liquid acrylic resin that has a high value of spectral selectivity. For way testing was applied on a silver-plated aluminum sheet where a maximal cooling rate was achieved in the amount of about 108 W/m^2. A numerical model was developed in order to estimate the emissivity of the produced coatings and the results were successfully compared with the experimental readings (Weihai, China.), Figure 24. The economic analysis showed that the expected coating cost is about \$0.39/m^2, which is acceptable from an economic point of view. The further development of the examined cooling approach should be provided, especially in the sense of new selective coating materials.

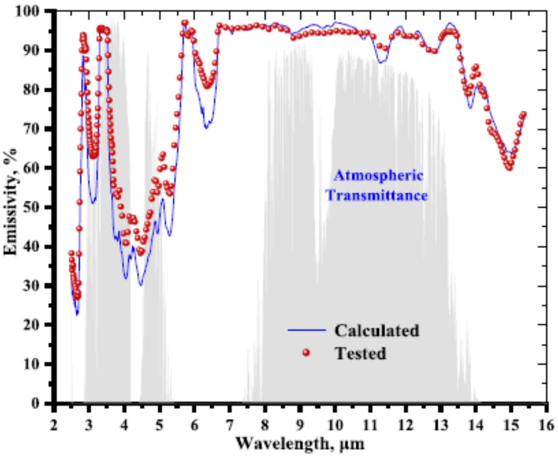


Fig. 24. Comparison of calculated and tested emissivity, [41]

Radiative cooling approaches for the thermal regulation of silicon PV panels were presented and discussed in study [42]. A modelling approach was applied in order to analyze mechanisms and requirements for an efficient radiative cooling. According to the gained results, it was found that a combination of radiative cooling with a sub-bandgap reflection leads to the best results regarding performance improvement. The PV panel operating temperature could be reduced in that case by about 10 °C, followed by efficiency improvement of 5.8 %. Electric thermal modelling was also discussed and complex mechanisms were selected. The economy of the proposed radiative cooling strategies was not discussed, which would be an important added value to the work. A radiative cooling approach (photonic radiative cooler) was proposed in [43] for the cooling of PV cells, Figure 25. The examined cooling approach enabled a temperature reduction of the PV cell by about 10 °C, with an efficiency improvement in the amount of 0.45 %. An economic approach was not evaluated as well as the long term stability of the introduced reflective materials.

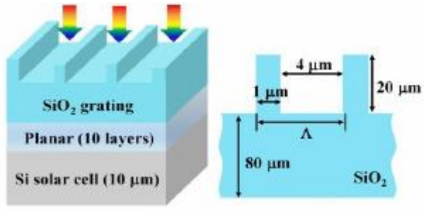


Fig. 25. Specific design of radiative cooler, [43]

The evaluation of different antireflection coatings for the thermal management of silicon solar cells was reported in work [44]. Thin film materials were used as coatings such as Al_2O_3, Si_3N_4, SiO_2, HfO_2, et., in the modelling approach. The results of the study showed different emissive power for various antireflective coatings with respect to their thickness. The economic evaluation was not included in the experimental investigation, Figure 26.

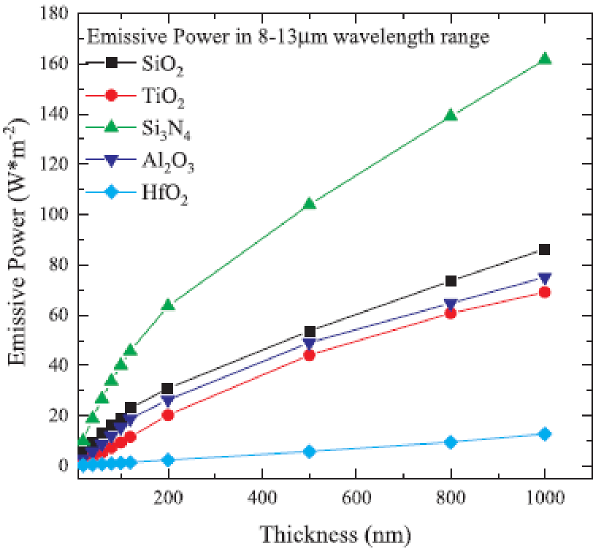


Fig. 26. Emissive power of different antireflection coating materials, [44]

Ultra-broadband versatile textures were proposed in [45] for the radiative cooling of photovoltaic panels. The application of specially designed imprinting coatings, Figure 27, ensured an efficiency improvement of about 3 to 5 %. The durability and cost-effectiveness of the proposed coatings were not analyzed.

A detailed elaboration of a photonic radiative cooling approach for solar cells in regular and concentration applications was discussed in work [46]. A specific photonic cooler was designed and experimentally tested. The solar cell temperature was decreased from 5 °C to 7 °C and the concept also showed potential for concentration PV applications. The efficiency and lifetime of the solar cells could be achieved with the proposed cooling approach. A cost-benefit analysis is missing in the reported work.

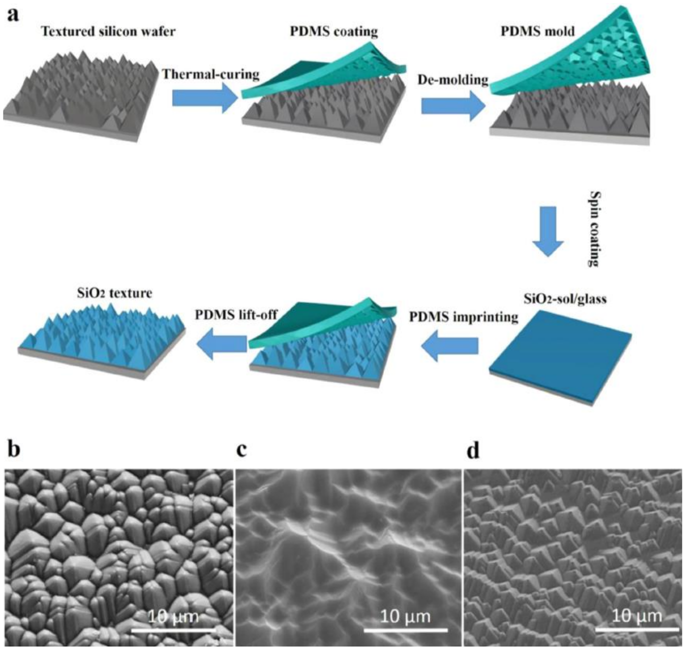


Fig. 27. Specially designed imprinting coatings with texture images, [45]

3.6. Summary and discussion

Based on the above elaborated recent research findings related to the passive cooling approach, some important findings will be discussed and summarized in the continuation. The main effect of certain cooling approaches on the performance response is given in Table 1. Heat sink methods are reasonably effective for the thermal regulation of the PV panel operating temperature. The expected performance improvement related to the heat sink cooling approach is from about 3 to 10 % on average followed by a decrease in the PV panel operating temperature by less than 10 °C, Table 1. The most convenient heat sink method is one with the application of specially designed fins on the backside surface of the PV panel, but with a limited performance improvement of up to 5 %. On the other side, a fin based method can have economic viability since it is rather simple and followed with a reasonable investment cost. Heat sink methods with the application of a PCM can ensure a higher performance improvement, i.e. over 5 % but the main issue with the application of PCMs is the complex thermal management of the PCM layer in specific working circumstances, which causes overall performance benefit. Moreover, the economic aspect of the PCM is also critical due to high unit costs, which affects the economic feasibility of PV-PCM cooling systems. There is also an issue with the long term stability of the PCM materials for the given application. The thermoelectric cooling approach is also effective regarding the reduction of the PV panel operating temperature that can go over 15 °C, however, the performance improvement is usually quite limited and up to 5 %. The economy of TEG cooling approaches is also questionable and requires special attention for the considered TEG cooling approach.

Table 1. Expected average performance improvement of PV panel for passive cooling approaches

Heat sink	3 up to 10 %
Liquid immersion	up to 15 %
PV panel architecture	up to 5 %
Radiative	up to 6 %

The liquid immersion method is the most effective method for the thermal regulation of PV panels since the performance improvement can go up to 15 %, with a decrease of the PV panel working temperature by about 15 °C. The main problem with these techniques is the fact that the method is effective for specific depths of the liquid layer (it is about 4 cm for water). The previous creates an issue if this technique is for instance implemented for swimming pools, which can have higher depths, thus optical losses could be more intense. The second issue is also the long term impact of the submerged environment on the durability of the PV panels. In any case, the most effective cooling approach but with several limitations mainly oriented on practical issues.

The modification of the PV panel architecture is interesting in a sense since it is related to the direct modification of market available PV panels. The performance improvement is limited and up to 5 %, while the reduction of the PV panel operating temperature varies from 2 up to 20 °C. The most promising one is with the introduction of holes or slits on the front side surface of the PV panel. However, further optimization is needed for the specific application, to maximize the effectiveness of the cooling method. The consideration of a novel PV panel frame material could also be an opportunity for more advanced solutions. The main potential problem with this technique is that it affects the standard production process of PV panels with respect to the proposed modifications.

Radiative cooling methods are quite simple and can ensure performance improvements up to 6 % on average with a reduction of the PV panel operating temperature by up to 10 °C. The coating materials have a considerable effect on the performance of the radiative coolers, which affects the overall economy. Some solutions were found to be economically viable, but more research work should be focused on development of the proposed cooling approach in order to improve performance and economic viability.

The main issue with the conducted research works is the lack of economic as well as environmental evaluations regarding passive cooling approaches. The main focus of the research was related to performance improvements; however, integral techno, economic and environmental evaluations are key and should be ensured. The passive cooling approach has limited performance improvement, but the main advantage is in its simplicity and there are no operational costs present.

4. Active cooling approaches

4.1. Direct water cooling

Direct water cooling approaches are usually implemented in a manner that the PV panel is exposed to a water layer (front surface of the PV panel) or as a combination of PV panel front and backside direct water cooling. The first investigation related to active direct water cooling was reported in work [47]. The water layer was provided on the front side of the PV panel, Figure 28 in a quantity of about 4.4 liters per min and per m^2.

Fig. 28. Direct cooling with water layer, [47]

The energy conversion efficiency of the non-cooled PV panel was around 10.5 %, where cooled PV panel had an efficiency increase of about 12 %. The PV panel operating temperature decreased from 60 to about 38 °C. The economy of the proposed active cooling approach was not discussed as well as the evaporated water rate. It was indicated that the utilization of highly efficient circulation pumps could ensure the economic suitability of the cooling approach. A prototype of a 5 kWp actively cooled PV plant was reported in [48] and was successfully tested in Portuguese climate conditions, Figure 29.

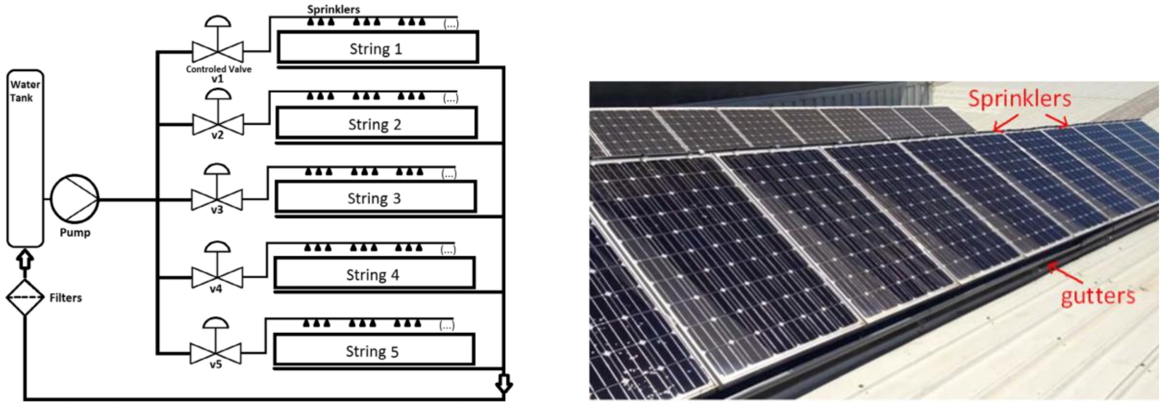


Fig. 29. Schematic of actively cooled 5 kWp PV plant in Portugal, [48]

The cooling of PV panels was ensured via sprinklers mounted on the front side of the PV panels. The economic feasibility of the cooling system was also elaborated and discussed. The results showed that it was possible to ensure performance improvement in a range from 12 to 17 %, followed by a reduction of the peak operating temperature from 60 to about 30 °C. The detected water losses ranged from 10 to 20 l/h. Based on the experimental data from the 5 kWp PV system, a calculation was obtained for a 25 kWp PV system and the results showed that the payback time was about 2 years with a revenue ranging from 10,000 to 22,000 USD, depending from the specific considered location in Portugal. A useful further approach would be to test and compare different PV technologies in order to get more detailed results for further consideration. An active direct water based cooling system was proposed in [49] as the TESPI concept (Figure 30).

A standard PV panel was covered with a polycarbonate box at the front side where water circulation was ensured with a 2.5 cm thick water layer. The proposed system enabled an annual improvement of the electrical energy conversion efficiency from 15 to 20 %. Possible PV cell connection setups were also thoroughly discussed with respect to the temperature distribution of the PV cells. The economy of the proposed solution was not calculated and discussion related to the durability of the polycarbonate material should also be discussed as an important feature. An active direct water based cooling system with water droplets was discussed in study [50], where six PV panels (185Wp) were experimentally tested in Cairo climate conditions. The water droplets were used for the cooling of the front PV panel surface, Figure 31, where the water flow was fixed at about 29 lit/min. The temperature of the water was also constant and about 25 °C. The cooling performance was about 2 °C/min and where the activation of the cooling system was found to be suitable when the PV panel working temperature reached 45 °C (cooling system activated each 5 minutes). The economy of the cooling was not considered and the rate of the evaporated water was not examined. The variation of the water flow was not discussed, which is critical for the performance improvement, since the efficiency improvement for the considered case was less than 10 %.

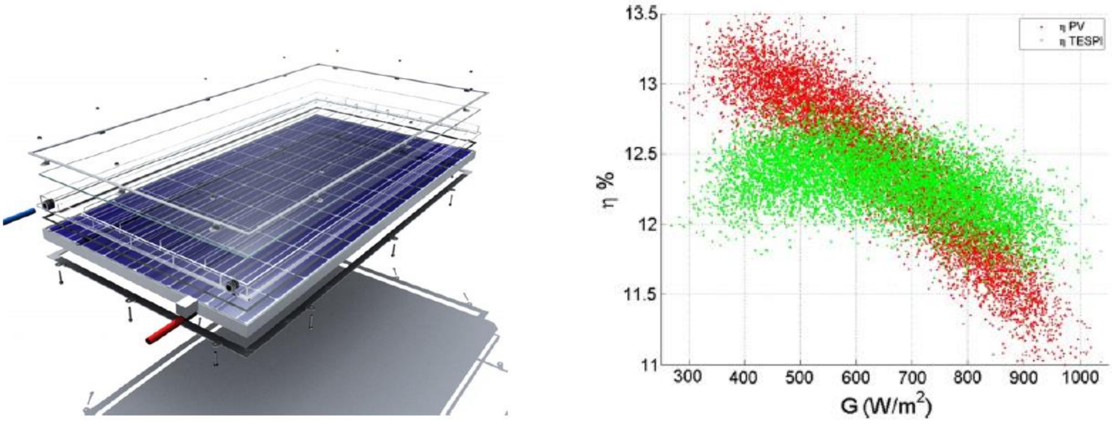


Fig. 30. TESPI concept and performance response, [49]

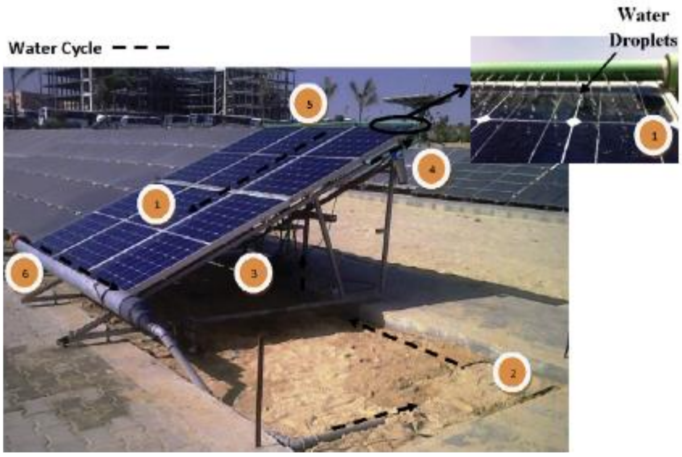


Fig. 31. Direct water-based cooling of the PV panel, [50]

The water spray cooling strategy was discussed in study [51] for Mediterranean climate conditions, Figure 32. A 50 Wp monocrystalline PV panel was examined in different cooling configurations (front cooling, backside cooling or simultaneously front and backside cooling).

The temperature of the water spray remained at about 17 °C with a variation of water spray flow. The performance improvement ranged from 12 to over 14 % (net performance improvement taking into account the pump work for the circulation system). The best cooling effect was found when both sides of the PV panel were cooled (front and backside). However, the difference between front cooling and simultaneous front and backside was negligible, hence the results indicate that front water spray cooling could be a reasonable solution. The economy of the proposed cooling approach was also discussed.

A step further could be directed towards the optimization of the water spray cooling approach and to investigate the impact of the water temperature with respect to the performance response.

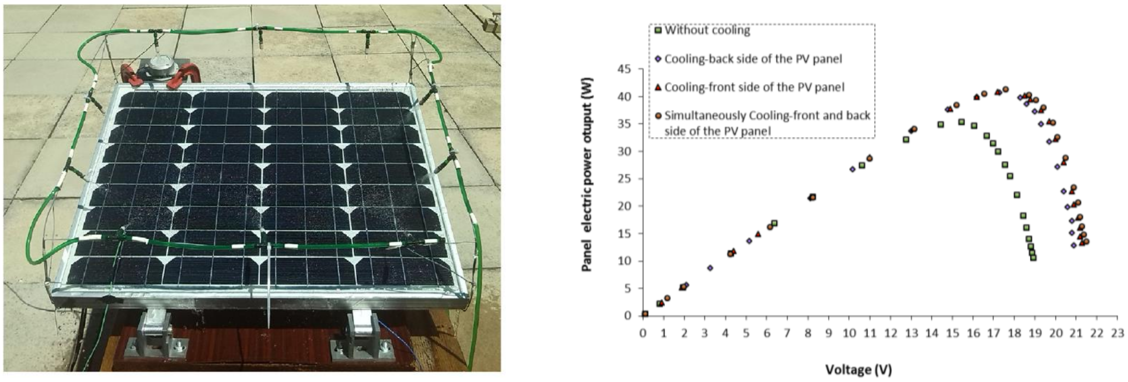


Fig. 32. Water spray cooling approach, [51]

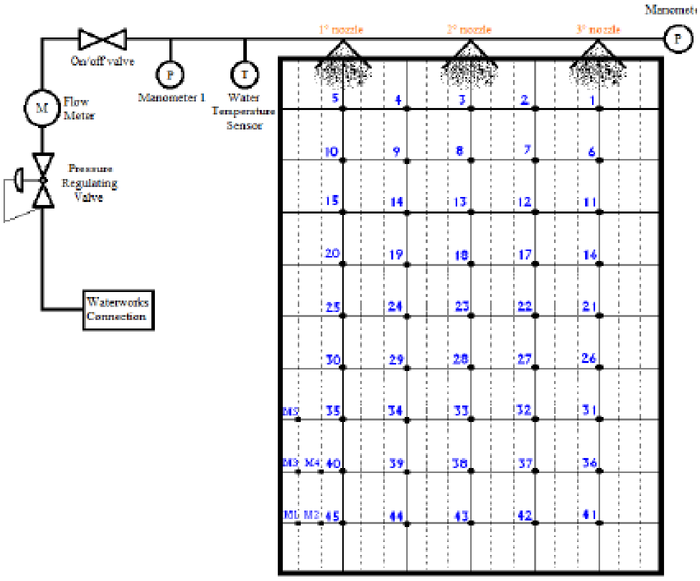


Fig. 33. Tested cooling approach with three nozzles, [52]

An experimental setup with three nozzles at a spray angle of 90 ° was tested and discussed in work [52], Figure 33. The main goal of the work was to simplify the water spray cooling technique and reduce costs. The experimental results indicated an average PV panel performance improvement of about 14 % with an overall expected investment cost per PV panel of about 15 € (230 Wp). The investigation was done in laboratory conditions and the data related to the evaporated quantity of water were not reported. For more precise performance indicators, as well as determination of operation costs, real field experimental investigation is needed.

The double active water based cooling approach was proposed in work [53] where water spray was implemented over the front surface of a PV panel (20 Wp), while on the backside surface of the PV panel, direct water cooling was ensured. The configuration was tested in UAE (Sharjah) climate circumstances. The performance improved from 2.0 to 4.0 %, with a reduction of the PV panel working temperature to maximal 7.7 °C. The economy of the cooling approach was not provided and analysis of evaporation as well.

4.2. Indirect water cooling

Indirect water based cooling methods are mainly directed to photovoltaic thermal (PVT) systems. Usually it is a kind of heat exchanger attached on the backside surface of the PV panel where the water removal of waste heat is enabled via a cooling system of pipelines. Moreover, the addition of PCMs layer with a combination of water tubes is also an option in order to improve cooling capacity and thermal management. The main advantage of PVT systems is the fact that both electricity and hot water can be produced simultaneously. From the previous aspect, the cooling of PV panels with the utilization of removed waste heat is an efficient approach, showing how cooling techniques can have added value. Study [54] examined the previously mentioned possibility and compared it with a referent PV panel. The two other panels were cooled indirectly with a PCM layer (passive) and the third with a PCM layer with water tubes, Figure 34. 40 Wp poly-crystalline PV panels were used for an experimental investigation in UAE climate conditions. The achieved decrease in the PV panel working temperature was around 10 °C and followed by a 6 % increase in produced power output. The calculation of the operational energy was also provided with an achieved detected overall increase in electricity of 18 Wh/day, while the required average energy was 12 Wh/day, thus the system showed feasibility. An overall economic evaluation was not provided, which needs to be done for these kinds of systems.

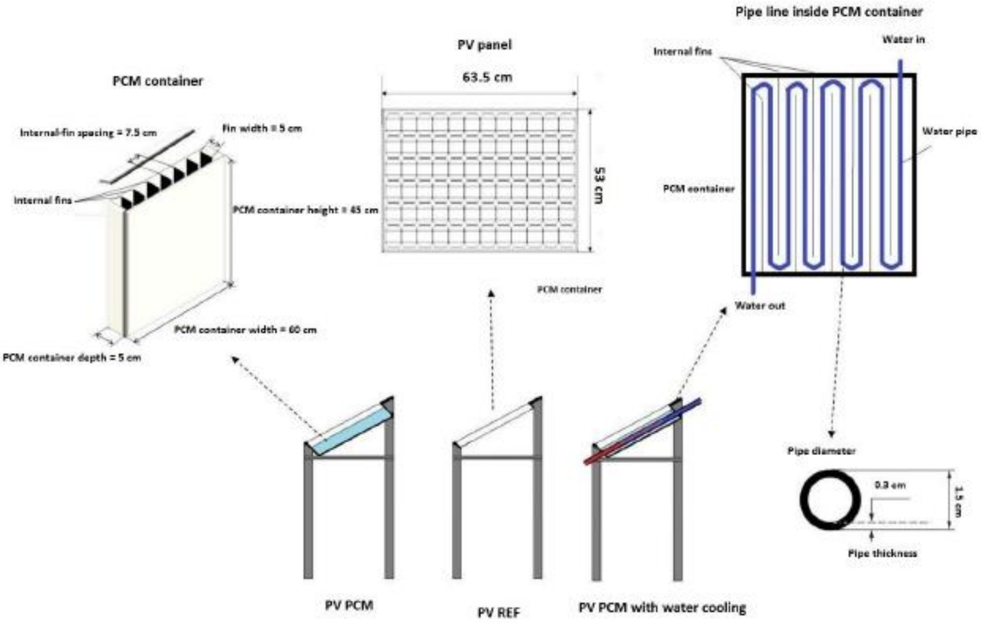


Fig. 34. Different tested cooling approaches for PVT panels, [54]

A theoretical analysis as well as experimental approach were reported in [55] for a novel PVT collector, where the PV panel was cooled indirectly by water, Figure 35. The novel dual oscillating absorber was introduced in order to improve the performance of the PVT system. A numerical investigation was conducted together with an experimental analysis (Malaysia).

The PV panel working temperature was decreased from about 64 to 57 °C, while the efficiency of the PV panel was improved from 10.7 to 11.9 %. The study showed that the proposed concept ensured both an improvement both in thermal and electrical efficiency. An optimization of the proposed structure should be provided as well as an economic analysis.

Fig. 35. PVT panel cooled by water, [55]

Fig. 36. Special spiral absorber design of PVT panel, [56]

A concept of a PVT system with a special absorber was analyzed in [56], where the absorber was made from a roust-proof material with thermal conductivity, which ranged from 16 to 20 W/mK, Figure 36. The specific material was selected since it is more economically suitable than copper and has high calorific resistance. The system was tested in laboratory circumstances using a solar simulator. The referent PV panel without the spiral absorber had an energy conversion efficiency ranging from 3.0 to 3.7 %, while with the introduction of the spiral absorber and water cooling, the electrical efficiency reached about 8.7 %. The proposed setup showed to be effective and useful for PVT systems. More details should be provided on the selected final design of the spiral absorber. The optimization of the spiral absorber and economic evaluation are missing. A novel polymer hybrid PVT panel was proposed and experimentally tested in work [57]. A polymeric material was used as an absorber, which was a novelty when compared to existing PVT conceptual approaches, Figure 37. An optimal PVT efficiency was found for a water temperature ranging from 40 to 45 °C, with a reach of 80 % in thermal efficiency. The electrical efficiency varying from about 6.8 to almost 8 %. The durability of the polymer material could be an issue and should be discussed in detail. Moreover, the economy of the proposed approach was not reported.

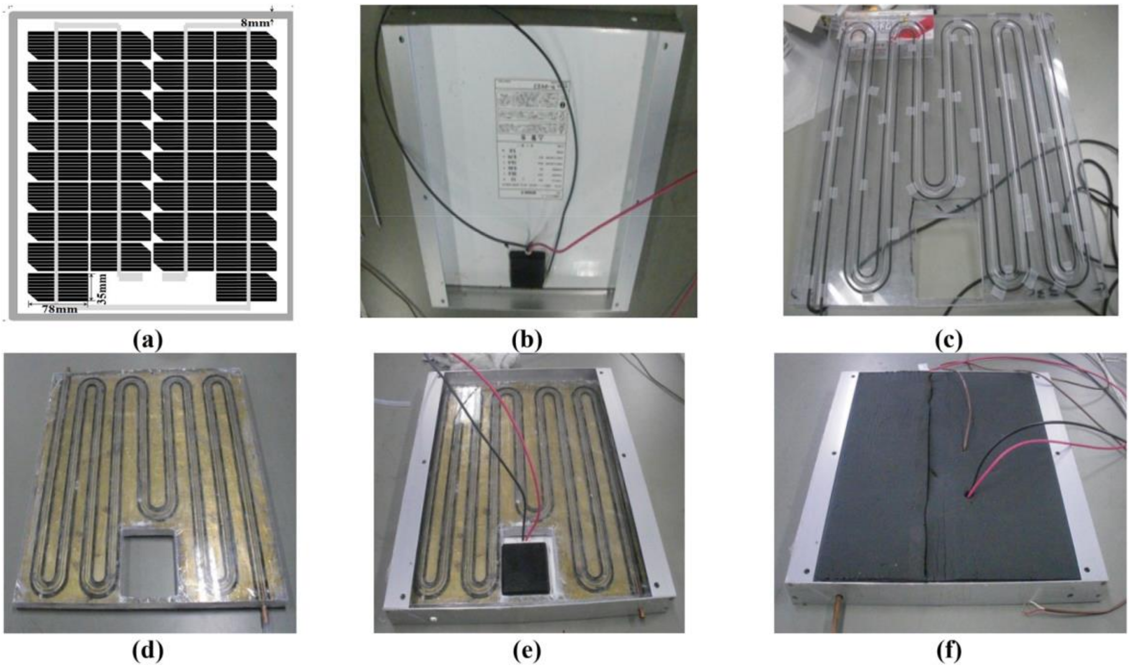


Fig. 37. Hybrid PVT panel made from polymeric material, [57]

A thermosiphon PVT system was proposed and examined in [58] for Chinese climate conditions (Hebei). Copper tubes were mounted on the backside surface of the PV panel and fixed on an aluminum absorber plate. The complete system was covered with thermal insulation, Figure 38.

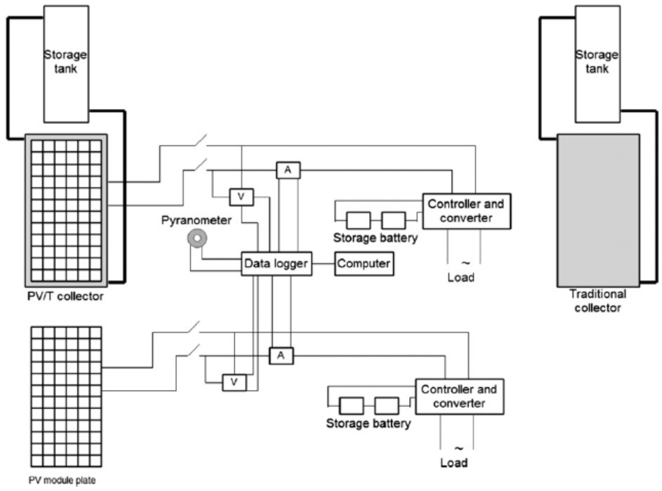


Fig. 38. Schematic of experimental approach, [58]

The experimental tests showed an increase in thermal efficiency in an amount of about 40 %. However, the electrical efficiency was reduced from 10 to over 25 % on average. The design was not proper with respect to the electrical efficiency improvement. The design improvements were not reported in that sense, i.e. to ensure increase in electrical efficiency. A cost-benefit analysis is also missing.

4.3. Air forced cooling

Air as a coolant has lower heat capacity when compared to water which affects overall performance indicators. Cooling systems with air are simpler and easier for maintenance and are generally easier for assembly. An air-flow induced cooling system for PV panels was elaborated in [59], where the system consisted of two blower fans, MPPT controller and PV cell cooled via an air duct, Figure 39. Four 55 Wp PV panels (Si-poly) were examined in Singaporean climate conditions.

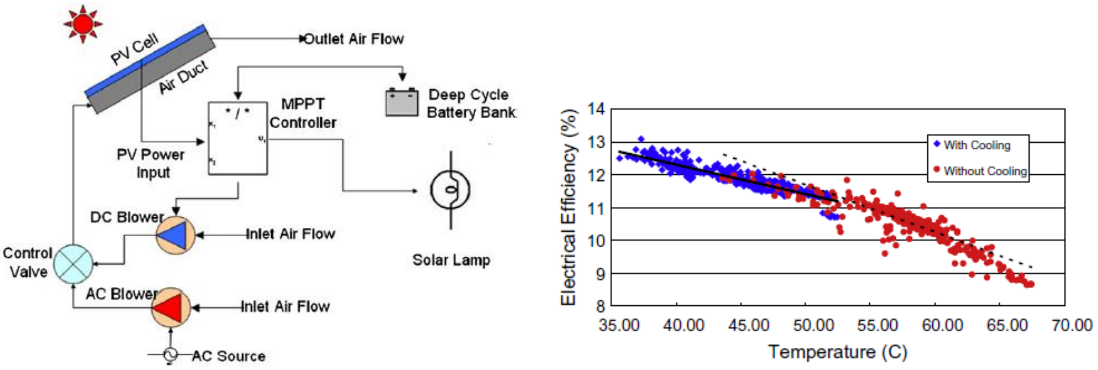


Fig. 39. Concept of forced air cooling with performance improvement, [59]

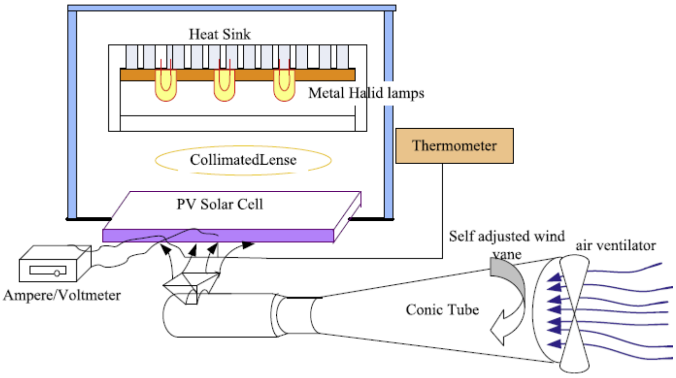


Fig. 40. Impingement jet air based cooling system for PV panels, [60]

The non-cooled PV panel had an efficiency of about 6.8 % with a PV panel operating temperature of 68 °C. The proposed cooling approach reduced the PV panel temperature to 38 °C with an efficiency improvement of about 12.5 %. The optimal specific airflow rate was found considering improvement in electrical efficiency. The overall economy of the proposed cooling system should be discussed in order to determine its feasibility. An impingement system for the air based cooling of PV panels was reported in [60] (Figure 40). The special design of this conic tube system, with adjustable wind vanes ensured an active cooling system. Airflow was applied over a small sized PV cell (5Wp) with a nominal efficiency of 16 %. The experiment was done in laboratory enclosure with a solar simulator.

The average decrease of the PV panel working temperature was from 57 to about 40 °C, which ensured a PV panel performance of about 12.5 % (the air flow ranged from 100 to 300 m^3/h). A higher performance improvement (about 21 %) was ensured with the inclusion of a turbine assembly, where heat recovery was also considered. The major issue with the considered experiment is the fact that it was obtained on a small PV cell and it would be interesting to apply the same approach on a large sized PV cell. Moreover, the configuration should be tested in real conditions and an economic evaluation should be obtained. The concept of PV panel forced air cooling was elaborated in work [61]. The system consisted of two PV panels, the first referent, i.e. non-cooled, and the second cooled with a fan and duct system, Figure 41.

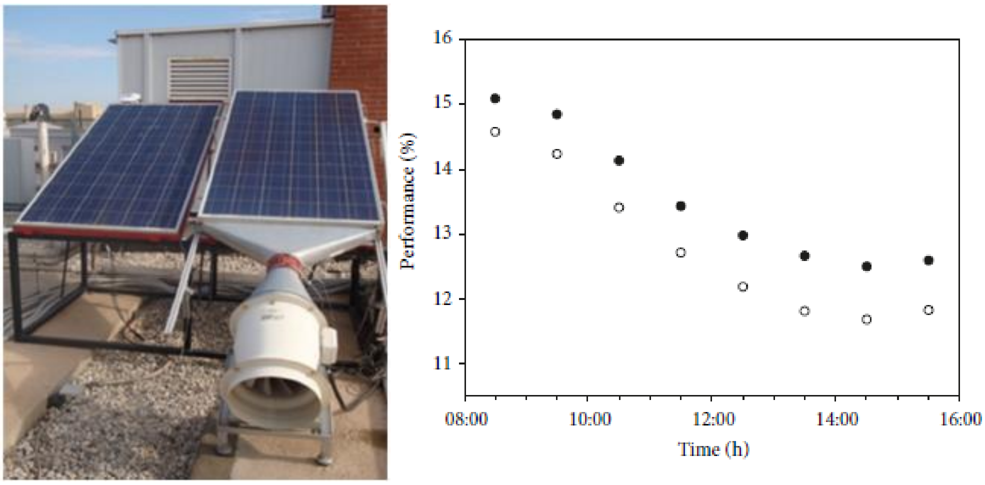


Fig. 41. Air forced cooled PV panel and performance improvement, [61]

The PV panels (240 to 280 Wp) were exposed to a forced airflow on the backside surface. The maximal airflow velocity was about 4.0 m/s, which provided a reduction in the PV panel working temperature from 10 to about 16 °C. The performance response is shown in Figure 41 (black dot referees to the cooled PV panel and ones for non-cooled). The highest performance improvement was by about 6 %. The discussion related to the fan selection as well as optimization of the proposed approach was not provided. A cost benefit analysis was also not provided. The concept of a hybrid PVT collector, cooled with water and air-forced was proposed in work [62]. The examined concept ensured the cooling of the PV panel with both air (forced) and water via a system of tubes, Figure 42. The fan was equipped with a controller in order to regulate fan operation. The improvement in electrical efficiency ranged from around 0.27 to 0.88 %, while the economic analysis showed a payback time of 7.1 years (economic evaluation considered both hot water and air). Overall, the feasibility of the system was proven, however, a discussion related to the durability of the system was not provided as well as for an environmental evaluation.

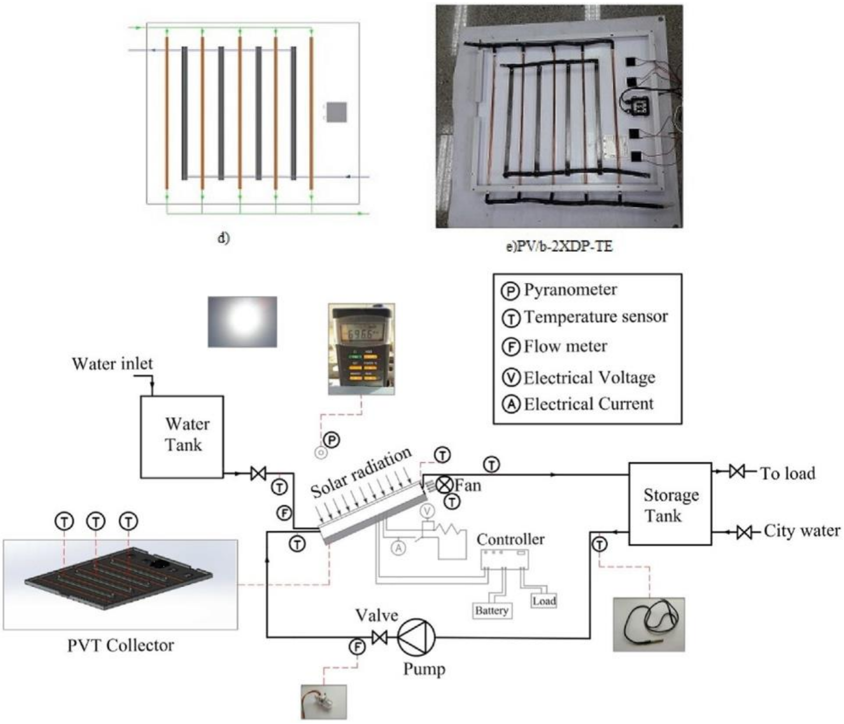


Fig. 42. Air forced and water cooled hybrid PVT panel, [62]

The effect of the forced air cooling in building integrated photovoltaics (BIPV) was examined in study [63]. The effect of the air cooling on the PVT integrated systems in buildings was examined by a developed numerical modelling approach. The system was examined for various climate conditions and discovered that due to present cooling effect, the reduction of the final energy consumption in the considered buildings ranged from 56 to over 100 %. The importance of the design was highlighted. An evaluation in realistic circumstances is needed in order to confirm the performance potential from numerical investigations, and different PV technologies should be considered. The impact of the air gap below the PV panel was discussed in [64] for BIPV systems, where different geometries were considered as well as air flow circumstances. The experimental approach was applied on several air-forced configurations that were examined and discussed. Critical channel geometry was determined in order to reduce an overheating effect. The forced air cooling ensured an improvement in the PV panel performance by about 19 % (airflow velocity around 6 m/s), when compared to passive air cooling. A step further would be to examine different PV technologies and discuss the economic viability of the proposed cooling system.

4.4. Cooling with Nanofluids

The implementation of nanomaterials in energy applications has become attractive in recent years, [65] due favorable effects on system performance. The addition of nanomaterials can ensure an improvement in thermal constants such as thermal conductivity, specific heat capacity, latent heat etc. In the case of PV panel cooling, Nano-enhanced PCMs are usually considered, or in other cases various nanofluids. The important issue with nanofluids is the preparation procedure since it can strongly affect the properties and long term stability of nano-enhanched systems, [66]. The cooling of a concentrator PV (CPV) with nanofluids was discussed in study [67]. The nanofluid (SiO2 and water, with weight concentration of 1.0 to 3.0 %) was used for the thermal management of a conventional PVT system, Figure 43.

The system was examined in Iranian operating conditions (Mashhad) with solar insolation levels from 600 to about 1,100 W/m^2. The temperature of the non-cooled PVT panel ranged from 48 to 69 °C. In the circumstances of the nano-cooled panel, it ranged from 38 to 59 °C. The magnitude of the temperature reduction depends from the nanofluid weight factor. The improvement in the electrical efficiency ranged from about 7 to 11 %, where the highest improvement was by 3.0 wt % nanofluid. The preparation procedure for the nanofluid should be discussed in a more detailed manner, as it is very important as already highlighted and an economic evaluation was not reported. The application of a nano-enhanced PCM material (paraffin wax) was discussed in work [68] for a typical PVT configuration, Figure 44. The configuration was tested in Malaysian climate conditions (Bangi) and consisted of a PVT panel, reference panel, heat exchanger and water storage tank. The PCM material was enhanced with a silicon-carbide nanomaterial with weight concentrations ranging from 0.1 to 3.0 %. The PCM layer was cooled with a system of water tubes in order to provide better thermal management of the PCM layer.

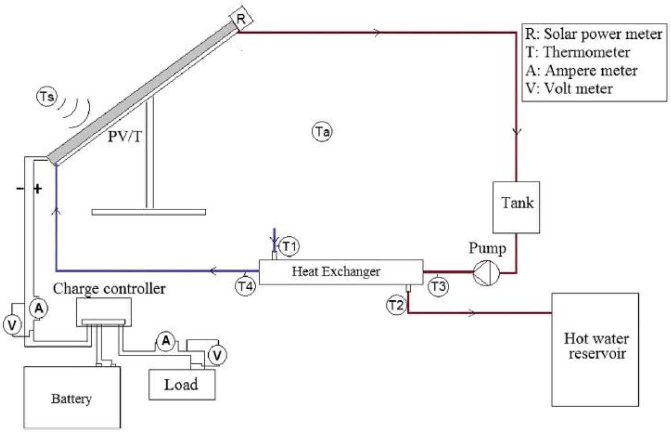


Fig. 43. Cooling of PVT panel with nanofluids, [67]

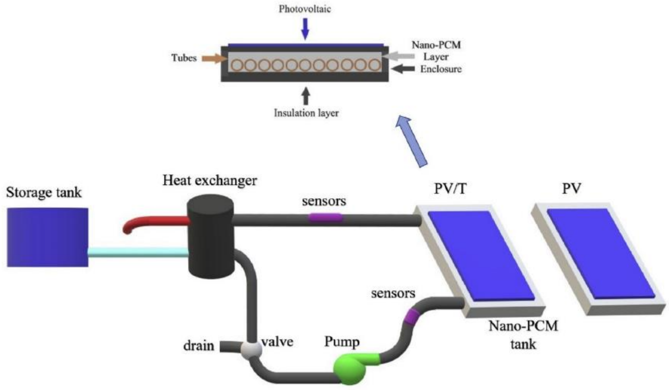


Fig. 44. Thermal management of PVT collector with nano-enhanced PCM, [68]

The experimental investigation showed improvement in PV panel efficiency from 7.1 to 13.7 %. It is not clear for which weight factor this improvement was achieved and an economical evaluation is also missing. Moreover, the preparation process related to the nanomaterial addition was not properly described. Blended Ag based nanofluids were proposed for the efficient thermal regulation of the PVT system and an optimization of the optical properties was performed, [69]. The impact of the nanoparticle size was investigated with respect to the optical properties (spectral transmittance). The results revealed that an increased volume concentration reduces spectral transmittance and lowers the PV cell temperature. The efficiency of the PV panel was reduced from 11.8 to 11.0 % for the 20 nm Ag blended nano-fluid. The results indicate that the addition of nanoparticles for this case is not viable from an efficiency point of view. The economy of the proposed approach was not discussed. A comprehensive review related to the use of nanofluids in solar concentration technologies (CPV) was discussed in work [70]. The application of nano-fluids was elaborated for heating, cooling applications and regeneration systems. A performance improvement was reported for each specific case and development trends and future challenges were also discussed. The results of the review work revealed that the electrical efficiency of concentrating CPV systems can increase electricity production by up to 8 % with the utilization of nano-fluids. Moreover, an improvement in thermal efficiency was not recorded. A stability as well as agglomeration issue related to the nano-fluids was also highlighted as one of the critical issues related to nano- enhanced CPV systems.

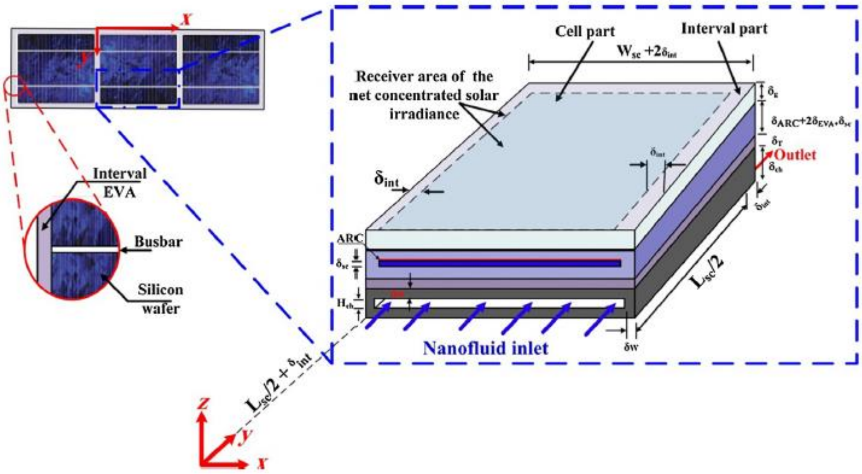


Fig. 45. Thermal management of PV panel with nano-fluid, [71]

The thermal management of a CPV cooled panel was elaborated in work [71], where Al_2O_3 water and SiC water nano-fluids were considered for cooling and a novel approach was proposed. The proposed setup considered a provided micro-channel below the PV panel, Figure 45, where nanofluid flow passes and cools the PV panel. The experimental results showed that the reduction in the PV panel working temperature varied from 3 to 8 °C, with a 4 % nanofluid weight concentration and a solar concentration ratio of 20.

A three-dimensional model was developed to examine the impact of nanoparticle types, volume fractions and coolant flows. The electrical efficiency improved from 13.5 to about 15.0 %, depending from the nanofluid concentration and type of nanofluid (1 and 4 %). The highest improvement in electrical efficiency was achieved for the highest nanofluid concentration and for the case of SiC nanofluid. The study was only conducted through numerical investigation; however, an experimental approach should be obtained to confirm the performance indicators gained by in the numerical manner. An economical evaluation was not discussed. A serpentine heat exchanger with aluminum oxide nanofluid was examined in the case of a PVT system, [72]. The nanofluid concentration ranged from 0.1 to 0.2 %, where various water flow rates were examined. An improvement in both electrical and thermal efficiency was reported. The efficiency improvement for a water based cooled PVT panel ranged from 10.8 to about 11.0 % (depending from the flow rates), while the nanofluid electrical efficiency ranged from about 12 to 13.4 %, depending from the specific nanofluid concentration (highest nanofluid concentration ensured highest efficiency improvement). Therefore, the overall performance improvement with nanofluid addition ranged from 11 to about 20 % for the case of the examined PVT system with nanofluids and a copper serpentine heat exchanger. The economy of the proposed nanofluid cooling was not considered. Study [73] analyzed various studies with respect to the increase of electrical efficiency with nano-cooled PV panels. Depending from the nanofluid type such as TiO_2/water,ZnO/water,Al_2O_3/water and CuO/water, the efficiency improvement ranges from about 6 to over 22 %, depending from the nanofluid concentration as well as type of nanofluid. In some specific studies, such as nanofluids in combination with cotton wick, the electrical efficiency was reduced from 7 to 9 %) with the addition of nanofluids when compared to the cotton wick. The study should focus more on specific applications with a better evaluation of overall referent and nano-enhanced system performance parameters. A bohemite/deionized water nanofluid was examined for the thermal management of small sized PV cells (5Wp, Si-poly). The experiments were conducted in laboratory conditions, Figure 46 with a solar irradiation level of 1,000 W/m^2 and weight nanofluid concentrations ranging from 0.01 to 0.5 %, [74]. The nanofluid flow rate was variated up to 400 ml/min.

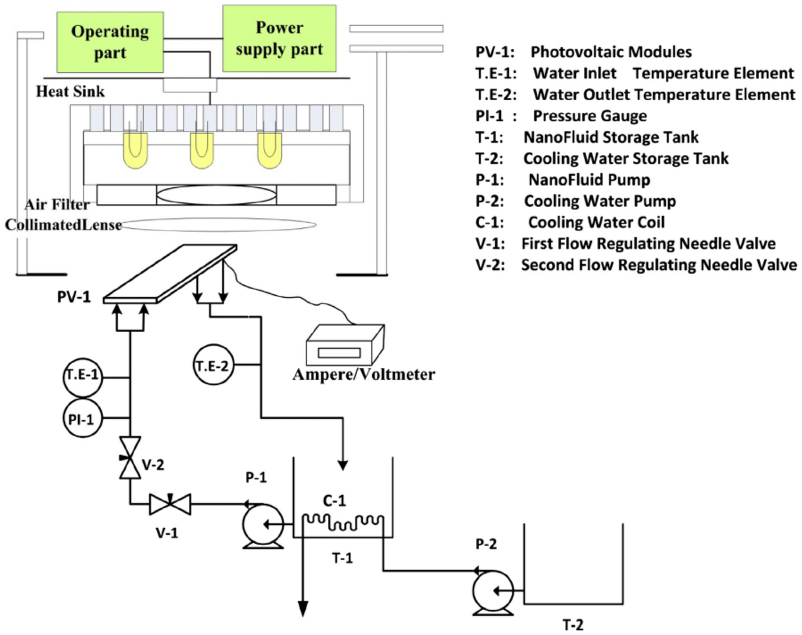


Fig. 46. Schematic of the PV panel cooled by nanofluids in laboratory conditions, [74]

The helical and spiral channels were tested and their impact on the effectiveness of the cooling approach. The highest improvement of the PV panel performance (power output) ranged from about 20 up to 37 %, with a reduction of the PV panel working temperature ranging from 18 to 24 °C. The best performance improvement was found for the helical channel configuration. It must be emphasized that the results were produced on a small sized PV cell, while the results on a large sized PV panel could be different, thus in that sense, further investigation should be conducted. The economy of the proposed cooling setup is also missing.

4.5. Summary and discussion

According to the analyzed and discussed existing active cooling approaches for the thermal management of PV panels, the overall performance improvement ranges from about 5 up to 30 %, Table 2, depending from the specific applied cooling approach. The reduction of the PV panel working temperature can be expected from 10 up to 30 °C. The results can vary according to PV panel size and specific PV technology; however, the previously indicated numbers are realistic expectations for the specific cooling approaches. In general, the economy of the active cooling approaches was weakly discussed in the existing research literature as well as for the environmental evaluation.

Table 2. Expected average performance improvement of PV panel for active cooling approaches

Direct water	10 up to 30 %
Indirect water	10 to 20 %
Air forced	5 to 10 %
Nanofluids	6 up to 20 %

Direct cooling approaches with water as the coolant are the most effective since the best performance improvement can be ensured (usually from 10 up to 30 %) and the highest reduction in the PV panel temperature is achieved (usually from 15 to 30 °C). However, direct cooling requires operational energy, which means that the net values related to the performance improvement would have to be lower than specified in Table 2. In some cases, the performance improvement can even be negative or not economically feasible due to the high operational energy needed. The critical issue with direct water cooling is the evaporation rate, as water evaporation exists and can usually go to dozens of liters per day. The evaporation strongly depends from the specific climate and general surrounding circumstances, but it strongly affects the overall economy and feasibility as water is a limited resource in some geographical locations. Feasible direct water cooling systems are possible in real circumstances proven in a recent study [48], but should be carefully designed and optimized for each specific case.

Indirect cooling systems mainly use water as the coolant and the main applications are in the case of PVT systems. As there is no direct contact between the fluid (water) and PV panel, the performance improvement is lower than in the case of direct water cooling. The performance improvement usually ranges from 10 up to 20 %, while the reduction in PV panel temperature ranges from about 10 to 15 °C. Operational energy is required for PVT systems as it is the case for direct water cooling, however, an evaporation effect is not present, which is the main advantage when improving the overall feasibility of the examined system. The main task of the PVT cooling system is to secure improvement in thermal and electrical efficiency, which contributes to the overall economy of the cooling strategies when compared to the case of direct PV panel cooling.

Air forced cooling of PV panels can ensure a performance improvement in a range of about 5 up to 10 %, with a maximal decrease in PV panel temperature by up to 10 °C. Air based cooling configurations are simpler when compared to water based, but the performance improvement is lower, since air has weaker thermal characteristics. Moreover, these systems also require operational energy for blower fans, which has a significant effect on the overall economic feasibility when taking into account the limited increase in the overall performance. Overall, air-based cooling techniques have the lowest increase in performance due to cooling, as air is not a suitable coolant.

Finally, cooling with nanofluids ensures quite a wide range of performance improvement, which depends from the specific type and concentration of used nanofluid. The performance improvement related to the nanofluids for the thermal management of PVs can range from about 6 to over 20 % in some cases, with an average temperature reduction of the PV panel ranging between 10 to 20 °C. The main problem with nanofluids is their high unit cost, toxicity as well as demanding preparation procedure that has a strong impact on the properties and long term stability of the nanofluids. Higher weight concentrations of nanoparticles in the nanofluids lead to general higher performance improvements based on the existing research findings. In some cases, the addition of nanofluids can even reduce the overall performance. The economic and environmental suitability of the nanofluids is weakly addressed in the existing research literature.

5. Conclusions and future field directions

The cooling approaches for the thermal management of PV panels can ensure the performance improvement and lifetime of the PV systems. According to the herein discussed selected research studies, the cooling approaches can be generally passive and active ones. The expected performance improvement for the passive cooling approaches ranges from about 3 to 15 % and is followed by a reduction in the PV panel temperature ranging from 5 to 15 °C. Passive cooling approaches are less effective in general, however, simpler and easier for maintenance without requirements for operational energy. Active cooling approaches can ensure a performance improvement from 5 up to 30 %, with decrease in the PV panel temperature from about 10 to 25 °C. Various passive and active cooling strategies have been discussed in this work with the further general observations being highlighted:

- Further design improvements are needed both in the case of passive and active cooling approaches. The optimization of specific cooling strategies is needed for specific climate circumstances and PV system setups. Special care should be directed towards a more advanced design of PVT systems, since both electrical and thermal output can be ensured,
- More efficient auxiliary equipment should be considered for active cooling approaches in order to minimize the required operational energy,
- Investigations of novel and economically more acceptable PCM materials should be provided taking into account a reduction in unit costs and increased durability. Moreover, more intense research work should be focused towards the numerical modelling of PV-PCM cooling systems,
- Environmental evaluations of various cooling strategies should be provided since it is

currently not well addressed in the existing research literature. Special care should be directed towards environmental evaluations, especially for cooling approaches that involve the application of the nanomaterials,

- The economic evaluation is weakly elaborated in existing literature where the more comprehensive approach is needed in that sense in order to determine an economic suitability of the cooling strategies. The effect of the climate conditions on the economy of different cooling systems for PV panels should be also investigated in detail,
- There is a necessity for the consideration of hybrid cooling approaches, i.e. during the design stage for a specific cooling approach to consider and enable both passive and active cooling approaches. The main focus should be to provide a flexible cooling system in order to maximize performance, reduce operational costs and ensure the regular cleaning of the PV systems,
- Radiative cooling approaches should be investigated in more detail regarding the development of cheap and durable coatings,
- Experimental approaches should be conducted for passive cooling strategies that involve a modification in the architecture of convectional and market available PV panels in order to investigate a realistic performance improvement,
- The introduction of smart and IoT supported technologies should also be considered since it allows the opportunity for further advancements in the optimization and minimization of operational energy for various working regimes.

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