Filip Grubišić-Čabo
Sandro Nižetić
Tina Giuseppe Marco

ISSN 1333-1124
eISSN 1849-1391

PHOTOVOLTAIC PANELS: A REVIEW OF THE COOLING TECHNIQUES

Summary

In this paper, current advances in cooling techniques and temperature control of photovoltaic (PV) panels in general, are analyzed and discussed. Namely, it is well known that a decrease in the panel temperature will lead to an increase in electrical efficiency, so in recent years different cooling techniques have been proposed and tested experimentally. The efficiency drops with the rise in temperature, with a magnitude of approximately 0.5 %/°C. Several cooling techniques have been tried, mostly based on active water and air cooling, as these are the simplest techniques. Other cooling techniques include conductive cooling, phase-change material cooling, etc. Increase in electrical efficiency depends on cooling techniques, type and size of the module, geographical position and the season of the year, and usually corresponds with a rise of 3-5 % in overall efficiency. Finally, a perspective on the other cooling techniques for PV panels will be also elaborated on and discussed in this paper.

Key words: cooling techniques, photovoltaics, electrical efficiency, renewable energy.

1. Introduction

Renewable energy sources are becoming more and more popular, regarding the pollution and non-sustainability of common energy sources. With increasing human population, a question arises, what is going to be the next reliable energy source after the disappearance of fossil fuels? One of most abundant resources is solar energy, which manifests itself directly, as solar irradiance, or indirectly as wind energy and biomass energy. When it comes to the efficiency of energy transformation, a couple of things need to be distinguished. There are two distinct types of energy that can be produced: electrical energy and thermal energy. Electrical energy, mostly because of its ability to be easily transferred to work, is more valuable than thermal energy. The most efficient way to obtain electrical energy is from direct solar irradiance via photovoltaic cells (PV cell). Although the overall efficiency of PV cells ranges from about 5 % - 20 %, it is still higher than the total indirect efficiency when it comes to wind and biomass efficiency. However, it has been shown that the overall efficiency of photovoltaic cells drops drastically with an increase in temperature. The rate of decrease ranges from 0.25 % to 0.5 % per degree Celsius, depending on the cell material used. Especially for concentrated PV cells, which use concentrated sunlight to produce larger amounts of power, and reduce the cost of generally expensive PV equipment, it has been observed that high temperatures greatly decrease the working life of the whole PV system. Cooling mechanisms have already been proposed [1-4] and the development of cooling techniques continues [5]. It has been shown that a sizable amount of power can be gained, up to a total of 5 % [6], by utilization of a cooling system. Nevertheless, a large amount of irradiated energy (up to 87 %) converts into heat. More recent developments have been concentrated on harnessing that waste heat into useful thermal energy. Generally, hybrid elements that harness both electrical and thermal solar energy are called photovoltaic-thermal units (PV/T unit). These units usually have a higher overall efficiency but lower specific efficiencies, when compared with stand-alone photovoltaic and solar collectors [7]. They save significantly on costs, and take up less space in operation. The objective of this paper is to compare different cooling techniques and propose the most efficient and propulsive one.

2. Cooling techniques for PV panel

Cooling techniques for heat applications were proposed early on in PV exploitation, as mentioned in [8]. The main advantage of cooling is evident: higher electrical output. However, cooling requires a separate system which will remove heat to some extent. The construction and maintenance of that system can be expensive and there is a possibility that the cost of system maintenance could outweigh the benefits of the improved electrical yield. Hence, overall electrical gain can be discussed in most of the studies made for example [1-7]. Two types of cooling can be distinguished: active cooling, which consumes energy (pump, fan, etc.,) and passive cooling, which uses natural convection/conduction to enable heat extraction.

2.1 Passive cooling techniques

When it comes to passive cooling techniques, they can be divided into three main groups: air passive cooling, water passive cooling, and conductive cooling. Conductive cooling mostly ends up with air passive cooling, but an important difference is that the prevailing mechanism of heat transfer from PV cells is conductive in nature. Cuce et al. [9] worked on an experimental study on polycrystalline PV cells in controlled conditions. Two PV cells were used: one with aluminum fins as a heat sink, with thermal grease applied and one without a heat sink. Illumination was varied from 200 to 800 W/m^2. A relative increase in electric efficiency of 9 % has been gained via usage of passive cooling with a heat sink. R. M. Hernandez et al. [10] has shown that the depth of flow channel beneath PV cells has significant influence on passive cooling, for larger PV surface (1.95 m^2). It has been shown that, for a length-to-depth ratio of 0.085, the PV module heats up by 5-6 °C when compared with a PV module on a regular mount. It has been noted that the temperature difference rises with the increase of insolation. In other words, passive flow channels can have the reverse effect on PV module cooling.

A special type of passive conductive cooling is phase change material cooling, PCM. Although this can’t be viewed as cooling in the strict sense, it has the result of maintaining the same temperature. It can still be counted as a passive technique mainly because of the fact that no additional work is needed to take away the heat - it is dissipated mostly conductively. In the [11] authors has showed that, with the right type of PCM material, a decrease of 15 °C relative to reference PV cell can be achieved, for a period of 5 hours, at insolation of 1 000 W/m^2. PV modules with nominal power of 65W were used, with 50 mm of PCM material from the back, with vertical aluminum fins to enhance conduction. The power gain was higher by 9.7 % than that from a reference PV module. Maiti et al. [12] used a V-through reflective panel to gain concentration of 2 suns, Fig.1. A PV panel of 0.133 m^2 surface was used, with 10 W of nominal power. Using 5.5 kg of PCM material mixed with turning shavings decreased the maximum temperature from 85 °C to 65 °C. The rise in efficiency was about 55 %. However, 5.5 kg of PCM material for 0.133 m^2 of surface under 2 suns is significantly higher mass of material than in [11]. The global potential of PCM is observed in [13].

Fig. 1 PCM, [12]

Water passive cooling is somewhat more efficient, mainly because of the higher thermal capacity of water. Several studies have been made with front and back cooling. Rosa-Clot et al. [14] used a submerged technique to cool down the mono-crystalline PV module in water. The effect had limited success: the temperature was maintained at 30 °C which in turn yielded a relative efficiency increase of 20 %, but insolation intensity dropped with depth. However, at a depth of 4 cm, relative efficiency is increased by 11 %.

Fig. 2 Thermosyphon effect used on PV/T system, [15]

El-Seesy et al. [15] made an attempt to cool down the PV cell with a thermosyphon effect, Fig.2. A polycrystalline silicon module, with a total area of 0.260 m^2 was used, along with a copper sheet and tubing installed on the back of the module, and a thermosyphon water system with a water capacity of 80 liters. The increase of relative efficiency gained was 19 %. Chandrasekar et al. [16] used the capillary effect to cool down the back of a monocrystalline PV module, 0.36 m^2 of surface. The capillary effect was produced via cotton wick structures wrapped spirally at the back of the module, and immersed in fluid. Nano fluid capillary cooling was also tried, but it failed to enhance the cooling effect when compared with water. The maximum increase in efficiency goes up to 10.4 % when compared to a non-cooled module. Similar results were achieved in [17]. Han et al. [18] compared immersion in different cooling fluids. The immersion takes place in isolation liquid, de-ionized water and three different organic liquids. The irradiance was augmented to 10, 20 and 30 suns, where 1 sun is 1000 W/m^2. The relative efficiency increase goes up to 15 %. Several things need to be taken into account. Mainly, the fact that the cell is relatively small when compared to the amount of liquid and its casing. On the other hand, a concentration of 30 suns requires a sizeable amount of cooling, which can obviously be done with passive liquid cooling. For a better understanding, temperature measurements should be conducted, which is omitted in [18]. A more important conclusion is that the PV cell remains unchanged after 180 days of immersion. Abdulgafar et al. [19] compared different efficiencies of 0.12 W and 15 cm^2 polycrystalline PV cell immersed in different depths of deionized water. Highest overall power was gained at lowest depth of 1 cm. However, highest efficiency of 22 % was gained at depth of 6 cm. This was due to the fact that pyrometer used for detecting solar irradiance was also immersed in water to same depth. With decrease in irradiance, relative efficiency rises, although the output power is much smaller than that of a non-immersed PV cell. Also, the amount of water used for cooling greatly overcomes the mass of PV cell hence it cannot be easily compared with large-scale PV systems.

2.2 Heat pipe cooling

Heat pipe cooling is combination of phase change cooling together with convection of cooling medium. On one side cooling medium evaporates and expands (or rises, depending of the variant) taking up heat. On the other side medium condensates and releases the heat into the surrounding. The medium travels back as liquid via capillary tubes and evaporates, thus completing the cycle. Gang et al. [20] have shown a relation between a number of heat pipes and electrical efficiency. Also, they achieved fairly stable PV-T panel temperature with water cooled heat pipes, at peak insolation rates of about 800 W/m^2. The surface of the panel is around 1.0 m^2, while total amount of circulating water was around 200 L.

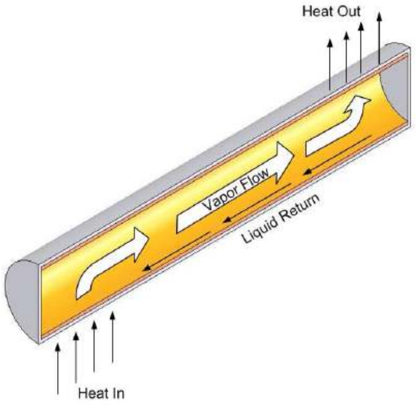

Fig. 3 Heat pipe mechanism, [21]

Maximum temperature of water reached up to 48 °C. Anderson et al. [21] used heat pipe to cool down PV cell of 1 cm^2 which is illuminated with waste heat of 40 W/cm^2, Fig.3. Maximum temperature difference of cell with ambient air was 43 °C. Tang et al. [22] used heat pipe to cool down a PV panel of 0.0625 m^2. Absolute increase in efficiency was measured. The increase in efficiency was 2.6 % and decrease in temperature was by 4.7 °C, at highest illumination. Maximum increase in power yield was 8.4 %. The size of heat pipe must be taken into account for this case. Heat pipe size is approximately the same as the size of the cell. The use of this type of cooling on large scale models is questionable, although it can easily be used on concentrated PV cells, as advised in [21]. Authors in [22] have also used water to passively cool down the condensing side of heat pipe. The efficiency increase was, in case with water cooling, 3 %. Nowee et al. [23] used a set of heat pipes to cool down monocrystalline PV module of 0.150 m^2. At the condenser end of heat pipes, water boxes have been placed, to act as heat storage and to enhance cooling of heat pipes. A decrease of approximately 13 °C of rear side temperature was observed for summer and spring measurements. An average increase of 1.2 W was achieved, which roughly corresponds with relative increase in efficiency of about 6 %. It ought to be noted that this is realistic application of heat pipe for PV cooling.

2.3 Active cooling methods

Active cooling methods can be considered as those methods that continuously consume power in order to cool the PV module. Most of the methods used are based on air or water cooling. Hence, main consumption system is pump or fan needed for maintaining fluid circulation. In general, active cooling methods result in more produced power and more accessible thermal energy, but when power consumption is taken into account, question arises if cooling system can support itself. When concentrated PV cells are used, active cooling system can easily be applied, mainly because of fluid-to-cell mass ratio and the ability to use less cooling fluid. Thus, less power is needed to maintain the system. Teo et al. [24] cooled four polycrystalline PV modules of 55W nominal power, from back side. The surface of PV module is 0.78 m^2. Special flow channel was manufactured and CFD analysis was used to optimize its shape. Total efficiency gain was around 1 %, depending of the irradiation. Optimal air flow beneath the panel is 0.055 kg/s, although no ambient temperature was given. This information is therefore reliable only for this specific case. Nevertheless, this information can be valuable when trying to evaluate the amount of air needed to cool down standard PV module. Farhana et al [25] used polycrystalline PV cell of 0.924 m^2 to examine air cooling effect. Two cells have been compared, one with and the other without cooling. The cooling cell has aluminum casing on the back side, which acts as flow channel. The work omits information about mass flow of the cooling air. Instead, fan specification was given. From it, mass flow can be approximated to 0.035 kg/s. Results show a maximum relative efficiency increase of 8.9 % and a decrease in temperature of maximum 12 °C. Authors in [10] have showed that, for air mass flow of 0.74 m^3/s, total efficiency can be maintained above 13.5 % at peak insolation of 970 W/m^2, and an overall increase in efficiency is about 2 %, Fig.4. At certain regimes, temperature decrease of 15 °C has been achieved.

Fig. 4 Forced air cooling [10]

Arcuri et al [26] cooled a polycrystalline PV panel of 1 m^2. Cooling was provided on back side of panel, through specially constructed flow duct. Flow duct consists of aluminum sheet 1 mm thick at the back of the plate, and wooden casing around it. Mean air mass flow of about 0.016 kg/s was established. Mass flow is established via helical fan of 3.6 W power consumption. Mean increase in total efficiency was about 0.6 %, depending of the insolation and part of the year.

As for water cooling, 2 distinct techniques can be applied: front side and back side cooling. Hosseini et al. [27] created a thin water film at front side of a monocrystalline PV panel and gained total efficiency increase of about 1 %. Total area of panel was 0.44 m^2 and maximum water flow was around 1 lit/min. The pump used consumes 0.25 hP. A decrease in temperature of 20 °C was reached. There is no mentioning of amount of heat taken off by evaporation, which should be taken into account when cooling is done from the front side. Du et al. [28] used concentrated monocrystalline PV cell of 0.152 m^2. The concentration was at the intensity of 8.5 suns. Cooling technique used was back side cooling via 2 aluminum pipes on aluminum mounting. Peak efficiency gain was 0.8 % for mass flow of 0.035 kg/s of water. Peak PV temperature was around 60 °C. Bahaidarah et al. [29] cooled a mono-crystalline PV module with an area of 1.24 m^2 from back side, via closed casing through which a flow of water is established, Fig.5. Water pump consumes 0.5 hP of power. Maximum mass flow is 0.06 kg/s. Maximum increase in efficiency, when compared with non-cooled module is total of 2.8 %, and decrease of module temperature is 10 °C. Considering the size of the panel, the rise in efficiency is significant.

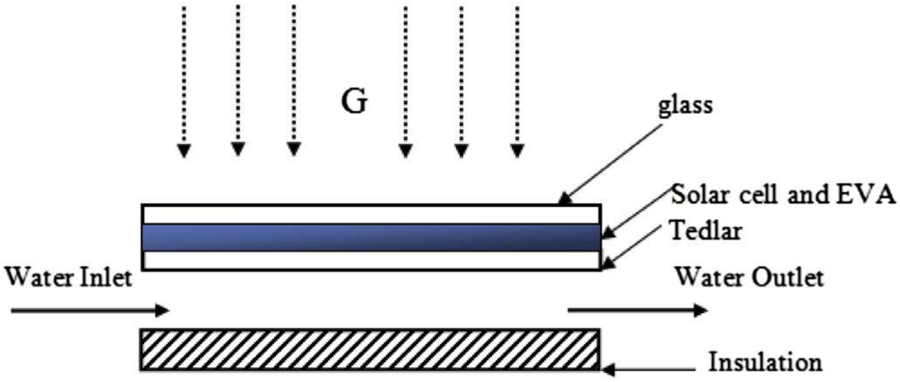

Fig. 5 Water cooling technique as used in [29]

Dorobantu et al. [30] cooled a PV cell of about 0.56 m^2 on front side by washing it with 0.03 kg/s of water. Increase in efficiency was not measured. Instead, increase in power yield is given, and it reaches up to 4 W. Decrease in temperature was 12.5 °C and 8 °C on back and front side respectively. Pump consumption was not mentioned, it is only emphasized that increased power yield is enough to cover the pumping cost. Moharram et al. [31] used monocrystalline PV panel of 1.25 m^2 surface, and cooled it with a water flow on the front side of the panel. The pump used consumes around 1 hP of power. Flow of the water is fixed at 0.48 kg/s. The cooling was conducted in intervals of 5 minutes, with 15 minute pauses and it was proven that cooling rate is about 2 °C/min. Total increase in efficiency, as a result of cooling, was about 1.5 %. According to [31], optimal temperature for cooling start should be 45 °C. Also, the mechanism keeps the front of the panel clean, which is important for dusty regions such as Sahara or Middle East. Sun et al. [32] cooled a concentrated mono-crystalline PV cell array of 0.014 m^2, illuminated by 9.1 suns. Cooling liquid used was dimethyl silicon oil. Mass flow was varied from 0.19 to 0.95 kg/s. Cell temperature was maintained in interval of 20 °C to 32 °C, depending of mass flow. Overall efficiency was kept between 12.5 % and 13.74 %, depending of the time of the year. That efficiency is fairly close to efficiency of non-concentrated cell array, which is 13.94 %. Hence, there was very little drop in efficiency due to higher concentration of sunlight. Also, no significant cell degradation was observed after 270 days of direct immersion. Smith et al. [6] measured an increase in power yield for concentrated cells by cooling the front side with spraying water. Monocrystalline PV panels were used, without panel specifications. Another group of panels was also measured as a test group. Concentration factor was omitted. Water flow was at maximum 0.116 kg/s. Net power gain for regular water cooling was 4.6 %, when pump consumption is taken into account. When ice water was used (2.5 °C at the entrance), largest power improvement was 24 %. When light concentration and ice water cooling was combined, power increase was 43 % greater than that of the control group. Tina et al. [33] cooled the polycrystalline PV panel of 1.27 m^2 with water flow at the front of the PV module. The water flow was at maximum 0.0167 kg/s, and depth of closed water box was 25 mm. It was proven that front side cooling is inefficient for small irradiation intensity. Optical losses overcome thermal drift caused by heating effect. In contrast, for high irradiation, front side cooling reduces thermal drift which gives greater power yield regardless of optical losses through water layer. For high irradiation, [33] shows that efficiency can be raised by total of around 1.2 % for previously described cooling technique. In [34], a cooling technique from both front and back side is tried out. Water flow is varied and its maximum value was 0.0625 kg/s. Water is applied in jet form, which enhances the cooling effect, according to [35]. Results are showing a relative increase in efficiency of 14.8 %, 19.1 %, and 20.4 % for back side, front side and simultaneous back-and-front cooling. Also, relation of type of flow with heat dissipation is discussed in [36]. It was shown that high velocity fluid fluxes (jets) have a capability to drastically take away the heat from the PV cell. The downside is the need for high pressures in the system.

2.4 Nanofluids cooling

Nanofluids are considered to be dispersed mixtures of cooling fluid and solid nanoparticles. Most of the particles used are metal oxides, per example Al_2O_3 or CuO particles. Weight percentage of dispersed particles is around 0.1-2.0 %. The particles have Brownian motion through cooling fluid. Main advantages of Nano fluids are greater thermal conductivity (therefore connectivity) and somewhat greater heat capacity [37]. Main disadvantage is pumping process and overall change in flow regime, i.e. characteristic turbulent flow occurs at different speeds and geometries, when compared with regular fluids. Xu and Kleinstreuer [38] made a numerical model for water and Nano fluid cooling of silicon PV cells and showed the cooling potential of Nano fluid to be somewhat greater than that of water. Electrical efficiency seems to maintain higher values even at increased temperatures, when PV panel is cooled with Nano fluids. The efficiency difference between water and Nano fluid cooling is significant during higher outlet fluid temperatures, and it can be up to 1 % of total efficiency. Karami and Rahimi [39] used Boehmite nanofluid to conduct cooling of polycrystalline module of 0.059 m^2. Cooling was made on the back side of the module, via cooling ducts of two different shapes. It was shown that small percentage of nanofluid in cooling water enhances temperature difference of module surface. For a concentration of 0.1 % wt. of Nano fluid, and fluid flow of 0.006 kg/s, a decrease in temperature of about 4.5 °C was observed, when compared with water cooling. Strong influence of flow channel shape on cooling intensity was observed. It was proven that nanofluid cooling efficiency mainly depends of nanofluid content and local flow regime. Sardarabadi et al. [40] used copper tubing to cool down a 40W polycrystalline PV module from back side. Cooling fluid was water and two Nano fluids with silica particles. Content of particles was 1.0 % and 3.0 % of weight respectively. Maximum fluid flow was 0.011 kg/s. It was shown that nanofluid with 3.0 % wt. of particles enhances the efficiency by nearly 1.5 %, when compared with water cooling. Presumed surface of 40 W PV module is 0.35 m^2.

2.5 Thermoelectric cooling

The basics of thermoelectric cooling lie in phenomena of Peltier effect. The Peltier effect occurs at an electrified junction as a heat flow in specific direction. On one side of the junction it produces heating, and on the other, cooling effect. The heating/cooling intensity depends on the temperature difference and voltage/current intensity. Cooling effect consumes electricity. Najafi and Woodbury [41] modelled a PV cell cooling with Peltiere element. It was shown that implementation of thermoelectric cooling can be viable for high concentration PV cells. Only in specific cell working regimes enough extra power can be produced to maintain cell cooling.

3. Discussion

With so many different cooling techniques tried, if one wants to compare cooling effect, one needs to define universal value that describes the cooling. Since very few works made complete measurements and calculations of gained power, relative and total increase in efficiency, and complete description of cooling method, it is difficult to compare the gained results. If maximum power gain is taken into account, and divided with effective surface of the PV cell, a specific power gain per surface can be defined for each experiment. Unfortunately, experiments without those information's can't be taken into consideration. Also, this way of comparing is only qualitative, because in several works, crucial information's are missing and can only be logically deduced (i.e. the effective area deduced approximately from total area, etc.).

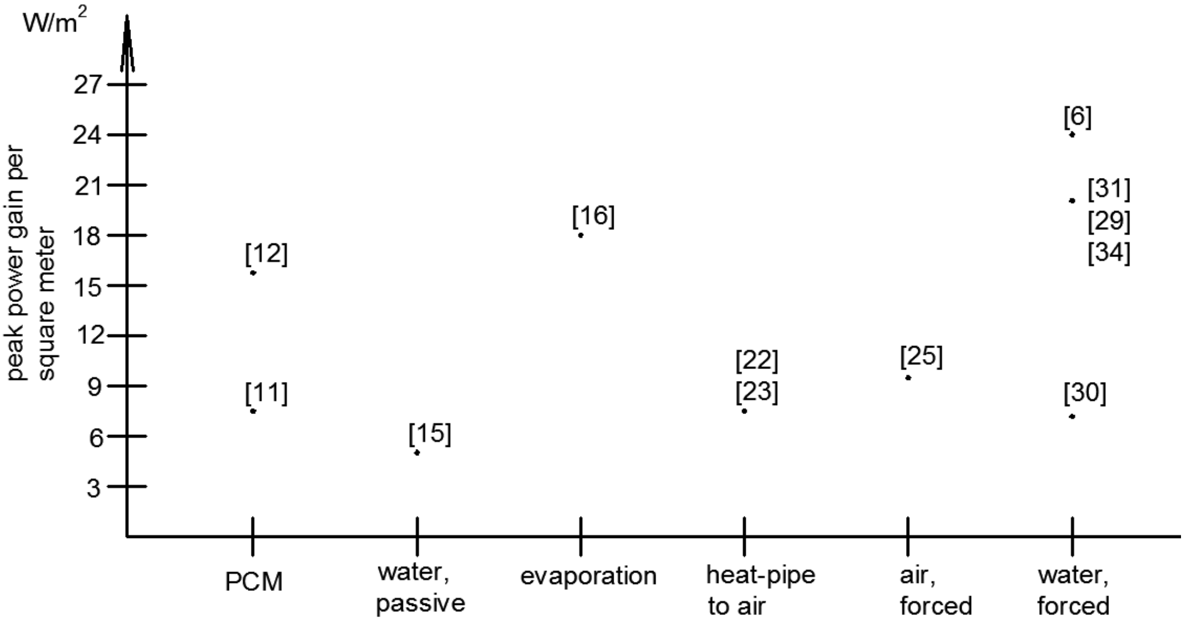

Fig. 6 Highest electricity gain for most common cooling techniques used

It is seen from Figure 6 that most additional power can be gained by active water cooling. Forced air cooling gives lower efficiency when compared with water cooling, as shown in [25]. Evaporation is second best option, but it consumes water. Also, technique in [31] is partially efficient due to evaporation of water on the front side of the cell, as in [34]. For PCM techniques, [12] proves that, with enhancement in PCM conductivity, good results in cooling and efficiency gain can be achieved. Highest cooling effect occurred at [6]. In this case, the temperature of cooling water needs to be taken into account (temperature of water inlet was about 2 to 3 °C). Of course, other factors, such as fluid mass flow (main difference between [29], and [30] [31] [34]) or properties of PCM material (as in [11] and [12]) need to be observed if true comparison is to be made. The usage of active water techniques provides thermal energy in form of hot water. In next two best solutions, such as evaporation and PCM material, thermal energy literally can't be applied. Concentrated PV cells need to be cooled either way. Water cooling can be proposed as the best type of cooling, after considering the information from Fig. 6.

4. A perspective

Many works emphasize the utilization of waste heat for domestic hot water. Although hot water (and heat in general) production is important, main purpose of PV cells is electrical energy production. When exergy is compared, the exergy of electrical energy is significantly greater than exergy of produced thermal energy [33]. Produced hot water almost never reaches the temperatures above 65 °C, due to significant decrease in PV electrical efficiency, except in concentrated PV systems [43]. Hybrid PV/T technology is a necessity, mainly because of space optimization and compactness of design. The system should focus on gaining more electrical energy, because of its higher quality. For that reason it is important to define optimal working temperature and to establish a control process by which outlet water temperature can be varied. One serious issue is definitely the mismatch of energy needs - most thermal energy is needed in winter, when there is a lack of it. For that purposes, concentrated PV cells can be used, mainly because of the higher ratio of water-to-cell mass. In summer, large amount of heat needs to be taken away. A PCM material can be used to capture additional heat at peak loads. When considering nanofluid cooling, a separate circulation system needs to be taken into account, if cooling water is to be used for domestic needs. Since nanofluid cooling can enhance electrical efficiency by up to additional 1 %, it can be considered as a good solution for large PV/T systems, where the introduction of additional circulation system could be economically viable.

5. Conclusions

Different cooling techniques have been examined and compared. It was shown that active cooling techniques, as expected, have higher efficiency than passive ones. In several cases, however, passive cooling can replace active cooling, in order to save the installation costs. Such specific cases are mainly usage of PCM material and usage of small concentrated PV cells. Also, when pumping costs are taken into account, especially for back side cooling, passive techniques can sometimes yield more power gain than active ones. If PV/T system is to be used, active cooling system is the best solution which will enable the usage of waste heat. It was shown that active water cooling is the best choice when increasing electrical efficiency is the main goal. Therefore, research aim in the future should be implementation of effective active water cooling of PV panel. Additional solar panel at the water outlet can be proposed to increase water outlet temperature, thus increasing overall efficiency. For reducing pumping costs, front surface cooling is proposed as more economical solution, especially in hot climate conditions. One obvious drawback of front side cooling could be water evaporation, which would require continuous replenishment of evaporated water.

REFERENCES

[1] Krauter, S., Increased electrical yield via water flow over the front of photovoltaic panels, *Solar Energy Materials & Solar Cells* 82 (2004)

[2] Royne, A., Dey, C. J., Mills, D. R., Cooling of photovoltaic cells under concentrated illumination: a critical review, *Solar Energy Materials & Solar Cells 86* (2005) 451–483

[3] Kumar, R., Rosen, M. A., A critical review of photovoltaic–thermal solar collectors for air heating, *Applied Energy* 88 (2011) 3603–3614

[4] Daghigh, R., Ruslan, M. H., Sopian, K., Advances in liquid based photovoltaic/thermal (PV/T) collectors, *Renewable and Sustainable Energy Reviews* 15 (2011) 4156–4170

[5] Makki, A., Omer, S., Sabir, H., Advancements in hybrid photovoltaic systems for enhanced solar cells performance, *Renewable and Sustainable Energy Reviews* 41(2015) 658–684

[6] Smith, K. et al., Water Cooling Method to Improve the Performance of Field Mounted, Insulated, and Concentrating Photovoltaic Modules, *Journal of Solar Energy Engineering,* August 2014, Vol. 136 / 034503 1-4

[7] He, W., Zhang, Y., Ji, J., Comparative experiment study on photovoltaic and thermal solar system under natural circulation of water, *Applied Thermal Engineering* 31 (2011) 3369-3376

[8] Tripanagnostopoulos, Y., Tonui, Y.K., Improved PV/T solar collectors with heat extraction by forced or natural air circulation, *Renewable Energy* 32 (2007) 623–637

[9] Cuce, E., Bali, T., and Sekucoglu, S. A., Effects of passive cooling on performance of silicon photovoltaic cells, *International Journal of Low-Carbon Technologies* 2011, 6, 299–308

[10] Mazón-Hernández, R. et al. Improving the Electrical Parameters of a Photovoltaic Panel by Means of an Induced or Forced Air Stream, *International Journal of Photoenergy*, 2013.

[11] Hassan, A., Phase Change Materials for Thermal Regulation of Building Integrated Photovoltaics, *Doctoral Thesis*, Dublin Institute of Technology, 2010.

[12] Maiti, S.,et al., Self-regulation of photovoltaic module temperature in V-trough using a metal–wax composite phase change matrix, *Solar Energy* 85 (2011) 1805–1816

[13] Smith, C. J., et al., Global analysis of photovoltaic energy output enhanced by phase change material cooling, *Applied Energy* 126 (2014) 21–28

[14] Rosa-Clot, M., et al., Submerged photovoltaic solar panel: SP2, *Renewable Energy* 35 (2010) 1862–1865

[15] El-Seesy, I. E., Khalil, T., Ahmed, M. T., Experimental Investigations and Developing of Photovoltaic/Thermal System, *World Applied Sciences Journal* 19(9), 1342-1347, 2012.

[16] Chandrasekar, M., et al., Passive cooling of standalone flat PV module with cotton wick structures, *Energy Conversion and Managemen*t 71 (2013) 43–50

[17] Alami, A. H., Effects of evaporative cooling on efficiency of photovoltaic modules, *Energy Conversion and Management* 77 (2014) 668–679

[18] Han, X., Wang, Y., Zhu, L., The Performance and Long-term Stability of Silicon Concentrator Solar Cells Immersed in Dielectric Liquids, *Energy Conversion and Management* 66 (2013) 189–198

[19] Abdulgafar, S. A., Omar, S. O., Yousif, K. M., Improving The Efficiency Of Polycrystalline Solar Panel Via Water Immersion Method, *International Journal of Innovative Research in Science, Engineering and Technology, Vol. 3, Issue 1, January 2014.*

[20] Gang, P., Huide, F., Huijuan, Z., Jie, J.; Performance Study and Parametric Analysis of a Novel Heat Pipe PV/T System, *Energy 37 (2012) 384e395*

[21] Anderson, W. G., et al., Heat Pipe Cooling of Concentrating Photovoltaic (CPV) Systems*, Conference Record of the IEEE Photovoltaic Specialists Conference*, 2008.

[22] Tang, X., Quan, Z., Zhao, Y., Experimental Investigation of Solar Panel Cooling by a Novel Micro Heat Pipe Array, *Energy and Power Engineering*, 2010, 2, 171-174

[23] Moradgholi, M., Nowee, S. M., Abrishamchi, I., Application of heat pipe in an experimental investigation on a novel photovoltaic/thermal (PV/T) system, *Solar Energy* 107 (2014) 82–88

[24] Teo, H.G., Lee, P.S., Hawlader M.N.A., An active cooling system for photovoltaic modules, *Applied Energy 90 (2012) 309–315*

[25] Farhana, Z., et al., Experimental Investigation of Photovoltaic Modules Cooling System, *IEEE Symposium on Computers & Informatics* 2012.

[26] Arcuri, N., Reda, F., De Simone, M., Energy and thermo-fluid-dynamics evaluations of photovoltaic panels cooled by water and air, *Solar Energy* 105 (2014) 147–156

[27] Hosseini, R., Hosseini, N., Khorasanizadeh, H.; An Experimental Study of Combining a Photovoltaic System with a Heating System, *World Renewable Energy Congress, 2011 - Sweeden,*

[28] Du, B., Hu, E., Kolhe, M.; Performance Analysis of Water Cooled Concentrated Photovoltaic (CPV) System, *Renewable and Sustainable Energy Reviews 16 (2012) 6732–6736*

[29] Bahaidarah, H., Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions, *Energy* 59 (2013) 445-453

[30] Dorobanțu, L., Experimental Assessment of PV Panels Front Water Cooling Strategy, *Renewable Energy and Power Quality Conference* 2013

[31] Moharram, K. A., et al., Enhancing the performance of photovoltaic panels by water cooling, *Ain Shams Engineering Journal*, May 2013.

[32] Sun, Y. at al. Direct liquid-immersion cooling of concentrator silicon solar cells in a linear concentrating photovoltaic receiver, *Energy 65 (2014) 264-271*

[33] Tina, G. M., Rosa-Clot, M., Rosa-Clot, P., TESPI: Thermal Electric Solar Panel Integration, *Solar Energy* 85 (2011) 2433–2442

[34] Nižetić, S., Čoko, D., Yadav, A., Grubišić-Čabo, F. Water spray cooling technique applied on a photovoltaic panel: The performance response, Energy Conversion and Management 108 (2016) 287-296.

[35] Rahimi, M. et al., Design of a self-adjusted jet impingement system for cooling of photovoltaic cells, *Energy Conversion and Management* 83 (2014) 48–57

[36] Røyne, A.: Cooling Devices for Densely Packed, High Concentration PV Arrays, *MrSc thesis, University of Sydney, March 2005.*

[37] Al-Shamani, A. N., et al., Nanofluids for improved efficiency in cooling solar collectors – A review, *Renewable and Sustainable Energy Reviews* 38 (2014) 348–367

[38] Xu, Z., Kleinstreuer, C.; Concentration Photovoltaic–thermal Energy Co-generation System using Nanofluids for Cooling and Heating, *Energy Conversion and Management 87 (2014) 504–512*

[39] Karami, N., Rahimi, M., Heat transfer enhancement in a PV cell using Boehmite nanofluid, *Energy Conversion and Management* 86 (2014) 275–285

[40] Sardarabadi, M., Passandideh-Fard, M., Heris, S. Z., Experimental investigation of the effects of silica/water nanofluid on PV/T (photovoltaic thermal units), *Energy* 66 (2014) 264-272

[41] Najafi, H., Woodbury, K. A., Optimization of a cooling system based on Peltier effect for photovoltaic cells, *Solar Energy* 91 (2013) 152–160

[42] Arcuri, N., Reda, F., De Simone, M., Energy and thermo-fluid-dynamics evaluations of photovoltaic panels cooled by water and air, *Solar Energy* 105 (2014) 147–156

[43] Darwish, A., Immersion Cooling of Photovoltaic Cells in Highly Concentrated Solar Beams, (2011). UNLV Theses/Dissertations/Professional Papers/Capstones. Paper 1081.

Submitted: 24.8.2015

Accepted: 20.4.2016

Filip Grubišić-Čabo
Sandro Nižetić
Faculty of Electrical Engineering,
Mechanical Engineering and Naval
Architecture, University of Split, Croatia

Giuseppe Marco Tina
University of Catania, Italy