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COOLING METHODS OF PHOTOVOLTAIC/THERMAL PANELS. STATE-OF-THE-ART REVIEW

BY

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Abstract. The concept of green energy and sustainability is no longer just an abstract idea intended exclusively for theoretical, numerical and experimental studies, but a “must” of our days. It is a reality that needs to be applied now, not later. Photovoltaic panels are an essential tool in implementing the idea of sustainability, green energy and NZEB (Net Zero Energy Building). Moreover, photovoltaic thermal panels represent the next step, being the main actor in increasing the efficiency of photovoltaic systems. The main challenge is the amount of electrical energy and thermal energy produced by these systems, which leads us to the need to determine the optimal method of cooling the PV. The current working document is intended to be a review of PV cooling methods, how their efficiency is influenced and a preamble for further research on how to optimize photovoltaic / thermal panels integrated in buildings.

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1. Introduction

Energy is an essential element in the development of mankind and the engine that made all the discoveries and innovations of the last decades possible.

It is behind the comfort we enjoy in our everyday life, whether at home, in the office, or when traveling: an optimal temperature in the room, light at any time, appliances that make our lives easier and more beautiful.

Regardless of the activities that people carry out, the type and level of effort (physical or intellectual work), optimal working conditions are necessarily ensured with energy consumption.

Taking into account these aspects, it is natural that the amount of energy consumed recorded globally every year increase.

An energy system based on renewable energy has the ability to provide electricity in an economic, sustainable, long-term, non-polluting way and may serve a population in full demographic expansion.

Renewable energy is also an optimal solution for the problem of global warming. If we talk about our own sources of obtaining energy and combating energy poverty, we still come to the issue of renewable energy (Alami et al., 2022).

Over time, specialized literature has dealt with various methods of cooling photovoltaic panels. These methods of PV cooling also led to different results, the efficiency values varying significantly from one method to another (Bayrack et al., 2020).

Among the studied methods we can list:

- cooling with air blown through the back of the PV (Mah et al., 2019, Mahdavi et al., 2019);
- air jet cooling of PV installed in buildings (Guohui, 2009, Nada et al., 2018);
- water cooling through pipes glued to the back of the panel (flowing or static) (Moharram et al., 2013, Ahmed et al., 2019, Odeh et al., 2009);
- cooling the PV by immersing the rear part in a container with liquid (water or oil) (Valiente-Blanco, 2022, Mehrotra et al., 2014);
- PV cooling by spraying water on the surface exposed to the sun (Hadipour et al., 2021, Ocłoń et al., 2020);
- PV cooling by applying a thin layer of water on the surface exposed to the sun (Bahaidarah et al., 2013);

It is known that photovoltaic panels cooled by different techniques are more efficiency than panels without cooling (Odeh et al., 2009). Studies shows that a photovoltaic panel has a maximum efficiency at a temperature of 25 °C,

which means that the ambient temperature in the immediate vicinity must be between 22 °C and 27 °C (Siecker et al., 2014, Armstrong et al., 2010).

According to the experimental studies (Siecker et al., 2014, Armstrong et al., 2010), the photovoltaic panel temperature is higher that the ambient temperature between 8 AM and 5 PM, in the winter, and starting with 7 AM, until 9 PM in the summer. The heating of photovoltaic panels is due to the fact that only 15%-24% of the solar radiation is converted into electricity and the rest of it is converted into heat (this is the reason why this amount of energy transformed into heat can be used in the green energy's domain in the sustainability concept). Within that period the solar radiation level rises until 1 PM – 3 PM, but the production of the photovoltaic panel does not reach the maximum level because of the temperature.

Moreover, for a photovoltaic system mounted on the roof, a phenomenon that is characterized by two components occurs:

The heat absorbed by the photovoltaic panels is transmitted to the roof, back to the lower part of the panels and from here it is transferred to the surrounding environment.

This phenomenon determines a double heating of the photovoltaic panels: solar radiation and heat radiated by the roof.

A high temperature of the photovoltaic panels leads to a small increase of the short-circuit current (ISC) and an important decrease of the open circuit voltage (VOC). The negative effect of heating the photovoltaic cell also extends to its efficiency, which decreases proportionally with increasing temperature.

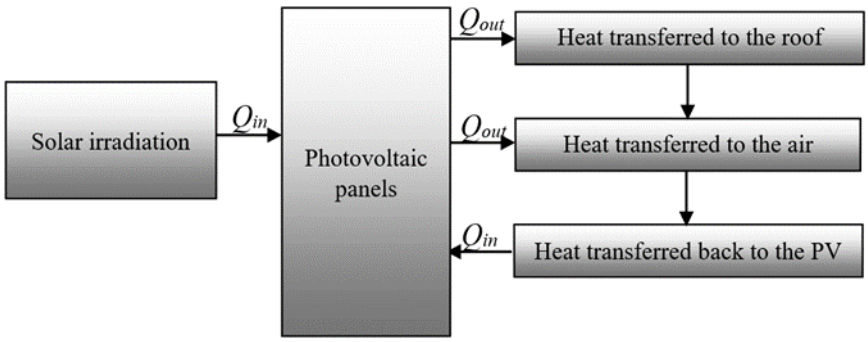


Fig. 1 – Heat transfer balance of a PV panel mounted on the roof.



Fig. 2 – Photovoltaic Panel integrated in green roofs (www.andalsolar.com).

Specialized studies have demonstrated that green roofs that integrate photovoltaic panels have multiple benefits (Fig. 2).

First, green roofs (especially those provided with a layer of vegetation) have the great advantage of regulating the environmental temperature and humidity level (www.andalsolar.com);

Secondly, the photovoltaic panels integrated within the green roofs benefit from a constant ambient temperature, which leads to passive temperature regulation (www.andalsolar.com).

Their working temperature will be in the allowed range of the optimal working temperature (23°C – 28°C), which leads to the maximization of electricity production.

Thirdly, the exchange of thermal energy between the green roofs, the environment and the photovoltaic panels is an exchange that comes to the advantage of PV, in the sense that the PV will transfer heat, unlike roofs made of standard materials whose temperature increases significantly and which, in turn, will conduct to an increase in PV's temperature.

Finally, a last advantage of green roofs is a constant level of humidity, which leads to a low level of dust, dirt and other small waste.

This last property of green roofs is an integral part of the entire heat exchange mechanism between the three components (roof, PV and ambient environment).

This automatically leads to a high level of cleanliness of the PV, their high efficiency, higher energy production and, automatically, a decrease in the maintenance costs associated with their cleaning.

Table 1 presents the relationship between the values of the air temperature around a photovoltaic system placed on a roof made of traditional materials and a system integrated in a green roof.

For a better observation of the influence of green roofs, the data on roofs with different thicknesses were analyzed.

In the first case, measurements were made for a PV system placed on a roof with a height of 18 cm (the heating level is lower and the thermal inertia is lower).

In the second case, measurements were made for a PV system placed on a roof with a height of 24 cm, whose heating level is higher, yet the thermal inertia is also higher (Ogaiti, 2015).

Table 1

Ambient temperature depending on regularly / green roofs (Ogaiti, 2015)

Type of roof Ambiental temperature	Regular roof	Green roof
T_{amb} for 18 cm height [°C]	28.7	27.6
T_{amb} for 24 cm height [°C]	29.5	27.5

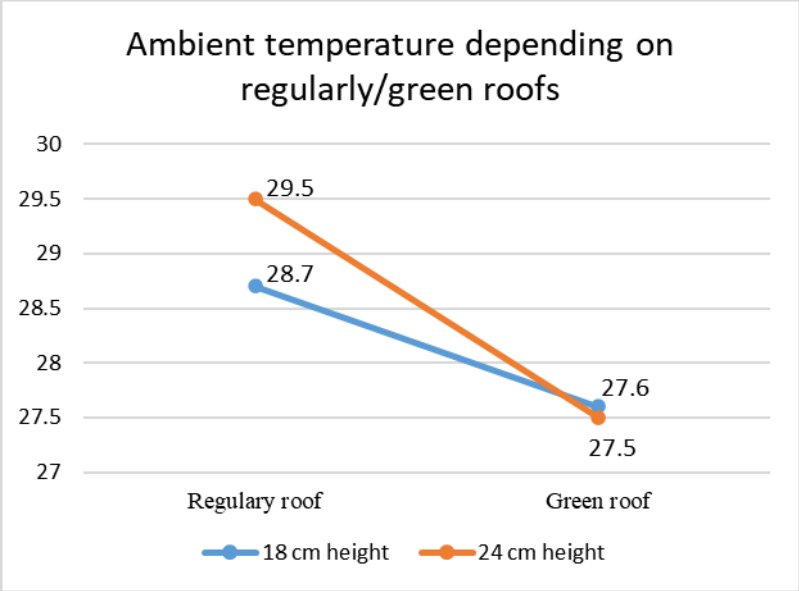


Fig. 3 - Ambient temperature depending on regularly / green roofs.

2. Theoretical considerations

In order to increase the efficiency of photovoltaic panels, it is necessary to reduce the amount of heat irradiated on their surface or to the backside of the panels.

The specialized literature mentions several solutions to reduce the amount of heat and to increase the overall efficiency:

- systems with glass coating (Alami et al., 2022) (Fig. 4);

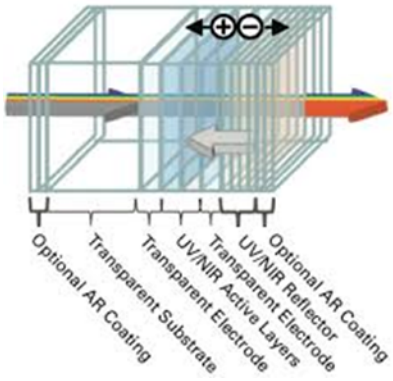


Fig. 4 - System with glass coating. (Lunt et al., 2011).

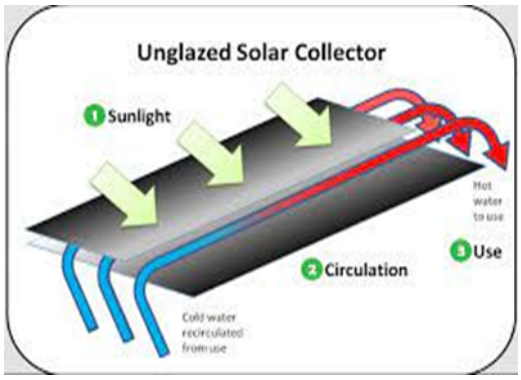


Fig. 5 - System with glass coating (Pros and Cons, 2020).

- use of unglazed units (Pesaran et al., 1994, Pros and Cons, 2020, Wei Hong Li, 2011) - this PV cooling technique was studied and developed more than 20 years ago, as the attached bibliography shows (Fig. 5);

- a different arrangement of water channels (Ostler et al., 2021, Wang et al., 2019) (Fig. 6);

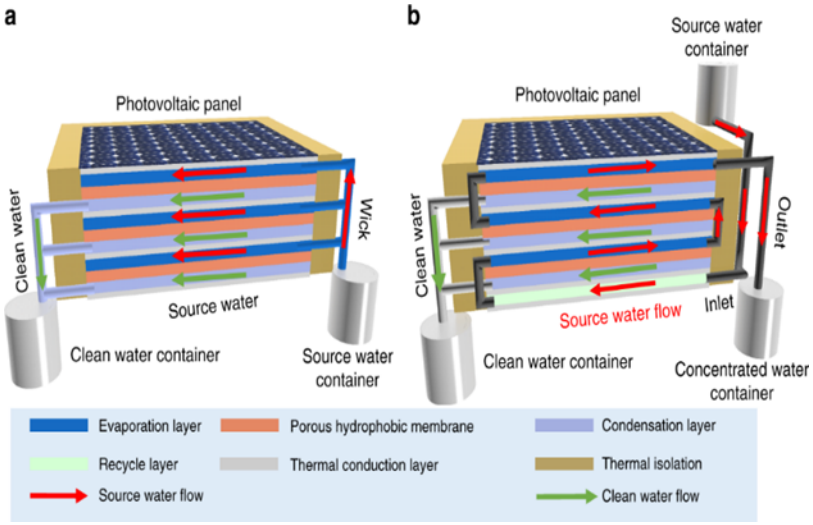


Fig. 6 - PV cooling with water channels (Wang et al., 2019).

- adoption of collectors completely or partially covered with solar modules (Tamm, Jha et al., 2022) (Fig. 7);

- use of semi-transparent solar panels (Vourdoubas et al., 2016) (Fig. 8);

- use of phase change materials (Shaito et al., 2021, Awad et al., 2022, Sarikarin et al., 2018) (Fig. 9).



Fig. 7 – PV completely/partially covered with solar modules (Tamm).



Fig. 8 – Semi-transparent solar panels. (Vourdoubas, 2016).

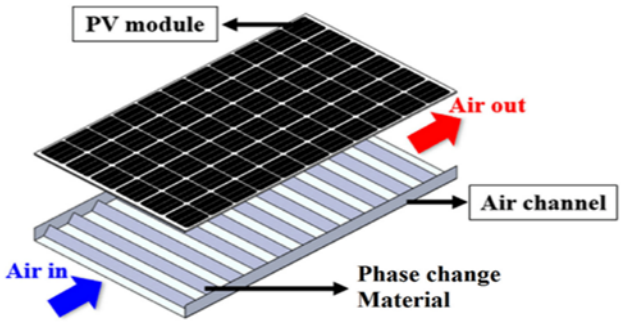


Fig. 9 - Photovoltaic panels using phase change materials (Awad et al.,2022).

There are two types of water–cooling system:

1. Indirect water-cooling system (Fakouriyan et al., 2018);
2. Direct water-cooling system (Someshwar et al., 2021).

In addition to the water cooling method presented above, there is also the air cooling method used to clean a photovoltaic panel; it consists in mechanically brushing surfaces, a method that was presented by Al-Housani (Al-Housani et al., 2019).

The method consists in brushing the surface of the photovoltaic panels by using dedicated tools that are not destroying the protective layer.

The main advantage of the method is that there is no need for any liquid, there is no need for water recovery, cleaning and reutilization. This can be used in areas with very small amounts or no water. It can also be used with minimal

expenses, without the need for an investment in the process of using and recovering household water.

The main disadvantage of the method consists in cleaning without any liquid solutions for cooling. Thus, regardless of the low degree of hardness, the damage of the first protective layer and, after a while, the damage of the photovoltaic panels may occur.

The connection between the power generation and temperature of a photovoltaic panel is well documented in scientific literature (Dubey et al., 2013).

Other studies showed that the temperature of a photovoltaic cell directly influences the power of the cell (Dubey et al., 2013).

During the experiments the solar irradiance (W/m2) incidence on the horizontal surface was measured using the solar meter. The temperature of the module was measured using a contactless infrared digital thermometer and a k-type thermocouple temperature data logger. Two different multimeters were used to measure voltage and current respectively.

This experiment showed once again the interdependence between the value of the temperature of the photovoltaic panel and the amount of electricity produced by it.

In other words, the efficiency of a photovoltaic panel increases as the temperature of the panel decreases, a high temperature (over 32°C-35°C) leading to a low yield and, therefore, to a decrease in productivity.

One of the techniques of indirect water cooling is the removal of the heat from a source without direct contact with water. This involves replacing an evaporator or water-cooled radiator by the traditional air-cooled radiator (Zhang et al., 2022). In addition, the classic indirect liquid cooling system is usually equipped with a cooling plate and water blocking mechanisms (Zheng et al., 2022). Meanwhile, recent research in this area has tended to focus on micro channel radiators and their increased efficiency as a result of their superior heat transfer properties compared to traditional indirect water-cooling systems.

The difference between direct water cooling and indirect water cooling lies in how that interacts with the electronic components (direct contact). The direct contact with the electronic components has the advantage that the cooling has an immediately effect on the temperature, while the degradation is accelerated (Ehsan et al., 2018).

The main advantage of using liquids in the cooling process is the adaptability to the shape of the photovoltaic panel; that is able to form a layer whose thickness is directly proportional to the volume of liquid and no additional adaptations are necessary (metal or plastic casing, guided sustained fluid etc.)

Due to latent heat transfer, this system comprises a phase-change phenomena that results in a uniform temperature profile on the surface of the heat source. Due to the absence of a hermetically sealed enclosure, it also runs at atmospheric pressure, which results in a low-maintenance heat exchange process.

However, further precautions must be taken to avoid fluid loss and degassing of the air and moisture infiltration system:

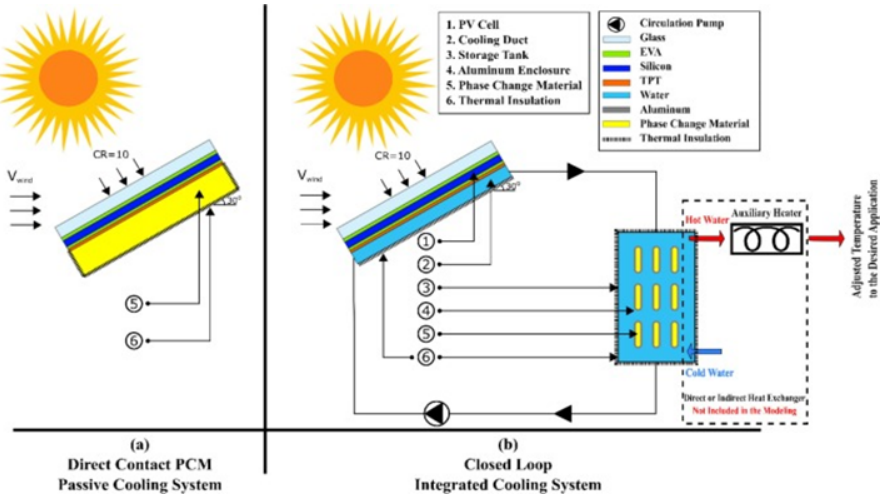


Fig. 10 – Direct water-cooling systems (Nasef et al., 2019).

Another research studied the effects of cooling on PV module performance in the tropical region, which were investigated experimentally (Nasef et al., 2019, Ehsan et al., 2018). The results indicated that under water cooling condition, the temperature decreased maximally by 24.1°C. This leads to a percentage increase of 10.06% of the open circuit voltage, the maximum power delivered by the PV module also increases by 9.83% and this effectively increases the conversion efficiency of the PV module by 9.83%. The cooling arrangement maintains the temperature to a certain limit, between 30.6°C and 34.5°C, thereby preventing the long-term thermal degradation of the PV module. The result of this work further corroborated the results of works done from other regions.

According to the literature reviewed (Ehsan et al., 2018), in the temperate region irradiance value is not as high as in the tropical region, yet the PV module performs better compared to the tropical region due to the low thermal characteristics. Therefore, in the case of large solar farms, cooling mechanisms should be employed to ensure optimal performance.

3. Cooling methods. Experimental and numerical review

3.1. Active cooling techniques applied to the Photovoltaic Panel (Habeeb et al., 2018, Pathak et al., 2022)

3.1.1. Cooling photovoltaic panels with heat pipes (Fig. 12)

The first technique consisted of four heat pipes attached to the back of the PV, pipes that were inserted into the flowing water (Habeeb et al., 2018).

In this experiment, for the cooling of the photovoltaic modules, a water flow of 5 l/h was used in the first phase, after which the water flow was increased to a value of 15 l/h.

The flow rate of 5 l/h was applied at the beginning of the warm season, in May. The value of 15 l/h of the water flow was reached progressively, directly proportional to the increase in ambient temperature (Fig. 12).



Fig. 11 – Direct water-cooling systems. (Habeeb et al., 2018).



Fig. 12 – Direct water-cooling systems. (Mahmood et al., 2022).

The first method, based on four cooling pipes that were immersed in water, led to a cooling of the PV by 53%.

3.1.2. Cooling photovoltaic panels immersing them in water or attaching pipes to the back of the PV in a vessel with **liquid, no flowing** (Fig. 13)

Cooling method with PV immersed in water or a film of water located behind the panel, but without it being recirculated through a pipe system (the heat taken by the water from the PV is, in turn, taken by a metal surface) can be used in that case in building facades (Habeeb et al., 2018-Mayameen et al., 2020).

The method has the advantage that it takes less space (the space required for PV cooling is small) and the design reduces the solar radiation incoming to the building.

The heat taken by the metal component can be used for the internal use of the building and the photovoltaic panels represent, in turn, a thermal barrier.

In the second case, a 48% drop in PV temperature resulted, after it was immersed in ethylene glycol.

3.1.3. Cooling photovoltaic panels that are **immersed in oil**

The method of cooling photovoltaic panels using an oil pool is not a new one and is based on the high thermal inertia of the oil (Mayameen et. Al., 2020). The oil has low temperature and the solution was adopted due to the high capacity of the oil to take over the heat of the environment.

The third process consisted in immersing the PV in engine oil. A 25% higher cooling efficiency of the modules was recorded.

3.1.4. Cooling photovoltaic panels with pipes, **pipes filled with water** glued to the back (Fig. 14).

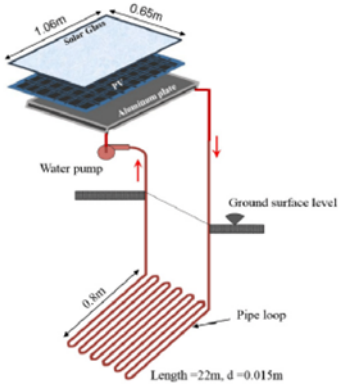


Fig. 13 - Cooling photovoltaic with filled with water (Mayameen et al., 2020).

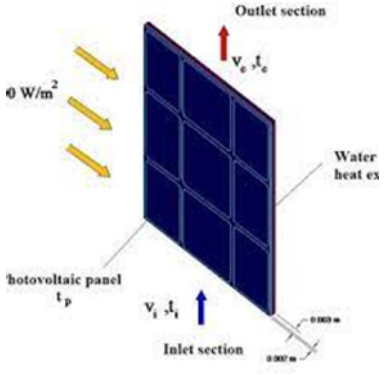


Fig. 14 - Cooling photovoltaic with pipes film heat exchange. (Hudişteanu et al. 2021, Hudişteanu et al., 2015).

The method consisted in gluing four **pipes filled with liquid** to the back of the PV; the liquid had the role of cooling the pipes and the PV (Basri et al., 2022, Mayameen et al., 2020, Hudişteanu et al., 2021, Hammad et al. 2021).

This method has the advantage that it takes little space and the photovoltaic panels can be embedded in buildings.

Additionally, the volume of the liquid behind the photovoltaic panel increases the heat absorption capacity, heat that will be eliminated during the night.

The disadvantage of the method is given by the limited cooling capacity of the system and the fact that this amount of heat stored in the volume of the liquid is lost without being used.

This case consisted in the application of a continuous line of water passing through four pipes glued to the back of the PV. The cooling efficiency is only 13% higher than for the no cooled PV system.

3.1.5. **The water film heat exchanger** (Fig. 15)

The method consists in applying on the back of the photovoltaic panel of an assembly consisting of two metal plates, with a space between them, which is filled with water (Hudişteanu et al., 2021, Hudişteanu et al., 2015).

The last method is considered to be the best cooling method and the results are the best: a PV cooling of 58% compared to the nominal value.

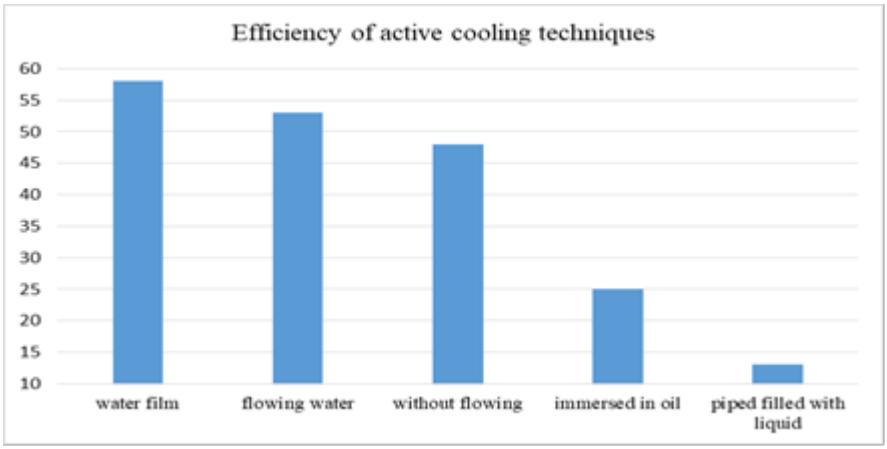


Fig. 15 – Direct water-cooling systems method (Habeeb et al., 2018 - Pathak et al., 2022).

The advantage of the last method (water film cooling) (Hudişteanu et al., 2021, Hudişteanu et al., 2015, Pathak et al., 2022) is given by the relatively simple assembly, the small space occupied by the photovoltaic panels (they can be used in embedded buildings) and that the absorbed heat from the water film can be used for the internal needs of the building.

According to the studies carried out on this cooling method, the amount of heat taken from the photovoltaic system depends on the thickness of the water film and the speed in crossing the PV surface.

Four cases were studied, corresponding to four different values of water film thickness: d=3mm, d=5mm, d=7mm and d=10mm. For each individual case, six values of the water film speed (0,001 m/s, 0,002 m/s, 0,003 m/s, 0,004 m/s, 0,005 m/s and 0,01 m/s) were studied and the results were presented in graphic form.

From a value point of view, the cooling method with the water film seems to the highest in efficiency, therefore this method was analyzed from the point of view of the dependence between the speed of the water film and the thickness of the water layer.

Within this active method of cooling the photovoltaic panels, the most efficient ratio between the water speed and the thickness of the water film can be identified both through numerical analysis and experimentally.

The results of this analysis may be used in the study of water-cooled thermal photovoltaic panels (water film method) embedded in buildings, for example to find the amount of water needed to cool a photovoltaic system embedded in a twenty-floor building.

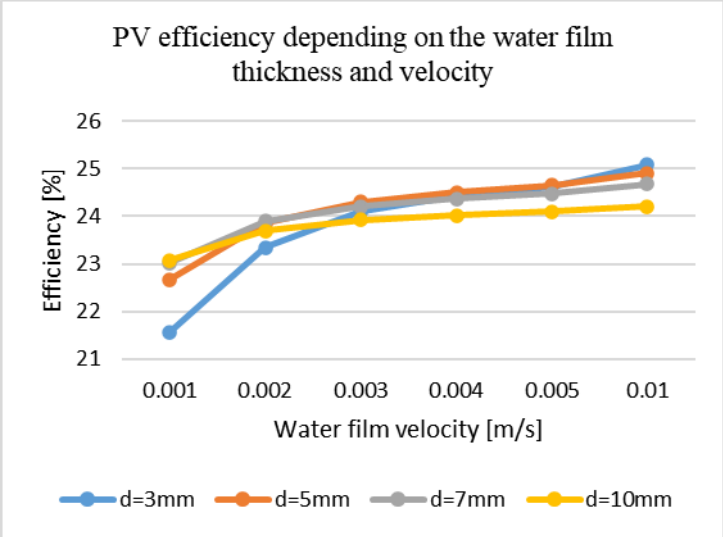


Fig. 16 – The relationship between the water speed and the thickness of the water film (Habeeb et al., 2018; Pathak et al., 2022).

Table 2

The relationship between the water velocity and the thickness of the film

V[m/s]	Efficiency for [%]			
	d=3mm	d=5mm	d=7mm	d=10mm
0.001	21.57	22.67	23.02	23.08
0.002	23.34	23.86	23.89	23.69
0.003	24.1	24.3	24.21	23.92
0.004	24.42	24.5	24.36	24.01
0.005	24.62	24.65	24.47	24.1
0.01	**25.08**	24.91	24.68	24.21

The photovoltaic panels cooling technique with liquids are worth studying due to the buoyancy of liquids and their ability to transfer energy through evaporation. Oil also has the ability to absorb a large amount of heat due to its physio-chemical properties: high caloric inertia.

The data from the table no. 2 were derived experimentally and represent the increase in the efficiency of a photovoltaic panel depending on the thickness of the water film and the speed of the water (Hudişteanu et al., 2022, Hudişteanu et al., 2015, Pathak et al., 2022).

Four values were established for the thickness of the water film (values that were calculated, in the first phase, theoretically and for which it was

demonstrated that they lead to the most efficient models) and for each value of the thickness of the water film, six values of the liquid speed were applied, according to the table (Hudișteanu et al., 2022).

The conclusion of the experiment is that for a 3 mm thick water film, at a liquid speed of 0.01 m/s, the increase in the efficiency of the photovoltaic panel is the higher value.

4. Conclusions

The specialized literature, through theoretical and experimental studies, has demonstrated the fact that there is a close connection between the working temperature of a photovoltaic panel and its efficiency.

The analysis over recent literature regarding the PV cooling emphasized that the lowest temperature (the highest PV cooling efficiency) was obtained by the active cooling of the photovoltaic panels using heat pipes immersed in water.

For maximum efficiency, the temperature of the photovoltaic panels must be kept at a value between 22ºC and 27 ºC, a value that can be obtained by cooling them. This working temperature is obtained by passive or active cooling, air jet cooling, water spraying or even water cooling in direct contact with the elements of the photovoltaic panel.

Thermal photovoltaic panels are those panels that, through the cooling method, release heat to the environment that cools it, heat that can be used in different forms.

As stated at the beginning of this work, thermal photovoltaic panels represent the next step in streamlining photovoltaic systems, these panels having at least three main advantages:

First, cooling the photovoltaic panel (decrease the temperature) will lead to increased efficiency (and directly proportional to the efficiency increased the electricity production), which will generate better coverage of the energy needs.

The phenomenon of cooling the photovoltaic system with water will result in a significant amount of thermal energy (heated water), thermal energy that can be used to heat the building or as a heat exchanger for domestic hot water.

When the thermal energy will be recovered from photovoltaic panels, its use will lead to a reduction in heating costs and will bring the building one step closer to “zero consumption”.

Finally, such a water-cooled photovoltaic system can be a very good building insulation system, which will behave like active insulation.

In the cold period of the year, the photovoltaic system will contribute to the thermal insulation of the building, being a thermal barrier against low temperatures, but also a barrier against the wind.

In the warm period of the year, the system can be a thermal factor of stability and regulation of the ambient temperature, especially in urban areas, where the temperature reaches very high values due to concrete/brick buildings.

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METODE DE RĂCIRE A PANOURILOR FOTOVOLTAICE TERMICE. STADIUL ACTUAL AL CUNOAŞTERII

(Rezumat)

Panourile fotovoltaice reprezintă un instrument esențial în implementarea ideii de sustenabilitate și energie verde. Mai mult decât atât, panourile fotovoltaice termice reprezintă următorul pas în dezvoltarea clădirilor de tip NZEB (Net Zero Energy Building), fiind principalul actor în creșterea eficienței sistemelor fotovoltaice. Principala provocare o reprezintă cantitatea de energie electrică și cantitatea de energie termică produsă de aceste sisteme, ceea ce ne conduce la necesitatea de a determina metoda optimă de răcire a PV/T. De asemenea o trecere în revistă a metodelor de răcire, a modului în care eficiența PV/T este influențată de tipul metodei ne ajută să facem o atentă analiză și să identificăm cea mai bună variantă (varianta optimă) pentru implementarea sistemului cu panouri fotovoltaice termice integrate în fațada clădirilor. PV/T integrate în fațada clădiri sunt parte activă din anvelopa clădirii (cu rol de reglare a temperaturii), dar și cu aport suplimentar de căldură (apa încălzită a sistemului de răcire) pentru preîncălzirea apei calde menajere sau încălzirea spaţiilor interioare.