ANALYSIS OF THE COOLING EFFECT ON THE EFFICIENCY OF THE PHOTOVOLTAIC PANELS

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Abstract. The paper presents the analysis of the cooling of a photovoltaic (PV) panel integrated on the facade of buildings, in vertical position, for different orientations: South, South-East and South-West. The effect of the cooling of PV panel is presented comparatively for the basic case, the case of the PV location apparently on the building facade, without the possibility of ventilation on its rear area and also for the integration in the ventilated facade of the building. Finally, the optimal solutions for obtaining passive cooling by using air and heat sinks or active cooling by using water film exchanger are evaluated. The study aims to evaluate the efficiency of PV panels according to climatic conditions and does not concern the operation of the entire photovoltaic system.

Keywords: BIPV, passive cooling, active cooling, conversion efficiency.

1. Introduction

Photovoltaic conversion has important advantages, considering that the energy source is renewable and free, and the processes of electricity production do not have a negative impact on the environment (CO₂ and NOₓ emissions, waste, noise etc.). The generation of electricity is done without the use of moving parts, determining reduced maintenance costs. The energy produced is consumed locally, which results in low power losses [1]. The Building Integrated Photovoltaics (BIPV) concept consists in placing PV panels on the roof or facades of buildings [2]. The integration is justified if the main advantages of the local production and consumption of electricity are analysed, which imply reduced energy losses and the possibility of complex use of electricity and heat. By increasing energy generation and reducing consumer losses, a reduction in CO₂ and NOₓ emissions and environmental protection are achieved, maintaining the same comfort conditions for occupants.

One of the main problems concerning the operation of photovoltaic panels is the significant increase of their operating temperature which causes an important drop of
conversion efficiency [3-5]. The decrease of the efficiency and of the produced power related to the increase of the temperature have values between -0.46...-0.50%/°C and -0.47...-0.50%/°C, respectively [6, 7].

As the power of a photovoltaic cell is influenced by the temperature and radiation levels, the standard test conditions (STC) parameters were defined: \( t_{\text{cell}} = 25^\circ \text{C}, \ G = 1000 \ \text{W/m}^2, \ \text{AM1.5} \). In STC the PV panels produce the Watt-peak power [Wp], but a real concern is that in regular operation, at 1000 W/m\(^2\), the photovoltaic panels can reach temperatures of 80…90°C [8], leading to a significant decrease of the efficiency.

Experimental tests on monocrystalline or polycrystalline photovoltaic panels, that show the decrease of the efficiency as the operating temperature increases and the necessity of cooling solutions are current concerns in the literature [6, 7]. Most of the studies on the cooling of photovoltaic panels [9-11] are also focused on the usage of the thermal energy extracted as a result of this process, so that the recovery time of the investment is less than of the stand-alone photovoltaic systems.

The simultaneous conversion of solar energy into electric and thermal energy using photovoltaic-thermal panels is known in the literature as PVT (Photovoltaic-Thermal System) [9]. A particular feature of this solution is the BIPVT concept, which implies the integration of photovoltaic-thermal panels into buildings [10, 11]. The generation of two of the most used types of energy is performed in such conditions in which the operation of each of the two systems is beneficial to the other, with priority to the production of electricity and ensuring the efficiency of photovoltaic conversion. The PVT concept is commercialized as hybrid photovoltaic solar panels, passive cooling solutions with polymeric films or ventilated cooling systems [12].

This study presents the performance analysis of a photovoltaic panel integrated in the facade of a building, for different locations in Romania: Bucharest, Cluj-Napoca, Iasi and Timisoara. The four large cities have different climatic conditions, in a national context, being located on variable latitudes and longitudes. The study aims to evaluate the performance of photovoltaic panels according to climatic conditions and does not concern the operation of the entire photovoltaic system.

### 2. Numerical modelling

The numerical simulation was performed in the TRNSYS modelling environment, and the purpose of the study is to determine the energy efficiency of the photovoltaic panel under the conditions of integration in double skin façade (DSF) and its temperature reduction. The model is created by using the following blocks: climatic data, photovoltaic panel model, conversion elements of the units of measurement and units for calculating and displaying the output quantities.

There are analysed the operating parameters of a photovoltaic (PV) panel, integrated on the facade of a building, at a height of 10 m above the ground, while the results are...
reported to the surface area [W/m²] and [kWh/m²]. The photovoltaic panel consists of 36 solar cells connected in series.

The PV panel is modelled using Type 94 of TRNSYS software, recommended in modelling monocrystalline or polycrystalline silicon modules. For a more realistic analysis, the four parameters model is used [13, 14], which takes into account both series and shunt resistances, \( R_s \) and \( R_{sh} \).

The value for the output current of the PV cell is determined with the following expression, Eq. 1:

\[
I = I_{ph} - I_D \left( \exp \frac{q(V + R_s I)}{nKT_{cell}} - 1 \right) - \frac{(V + R_s I)}{R_{sh}} \quad (A)
\]

For the same hypothesis, the open circuit voltage of the cell can be determined using Eq. 2:

\[
V_{oc} \approx \frac{nKT_{cell}}{q} \ln \left( \frac{I_{ph}}{I_D} + 1 \right) \quad (V)
\]

Where, 
- \( I \) - current produced by PV cell [A];
- \( I_{ph} \) - photocurrent produced by PV cell [A];
- \( I_D \) - reverse saturation current of diode [A];
- \( q \) - electric charge of electron [C];
- \( V \) - voltage on diode terminal [V];
- \( R_s \) – series resistance [Ω];
- \( n \) - ideality factor;
- \( K \) - Boltzmann constant, \( K = 1.38 \times 10^{-23} \) [J K\(^{-1}\)];
- \( T_{cell} \) - operating temperature of PV cell [°C];
- \( R_{sh} \) - shunt resistance [Ω];
- \( V_{oc} \) - open circuit voltage [V].

The PV panel cooling is achieved by using some of the most widespread solutions in the literature: heat sink [8] and water film changer [15], attached to the back of the panel. The efficiency is determined in the conditions of cooling the photovoltaic panel to a temperature as close as possible to the nominal one, of 25 °C. In order to obtain more intuitive results, a standard PV panel of 100 Wp is analysed. Table 1 shows the dimensional characteristics and parameters of the analysed photovoltaic panel [16].
Table 1

| PV panel parameters | Input data | Output data |
|---------------------|------------|-------------|
| Surface of PV: $S_{PV} = 0.89 \, \text{m}^2$; | - PV orientation: | - PV panel efficiency; |
| Short-circuit current: $I_{sc} = 6.5 \, \text{A}$; | - S, S-E, S-W; | |
| Open-circuit voltage: $V_{oc} = 21.6 \, \text{V}$; | - PV position: - horizontal, vertical; | - maximum power, current and voltage generated; |
| Maximum power: $P_{mp} = 100.3 \, \text{W}$ | - climatic conditions: Bucharest, Cluj-Napoca, Iasi and Timisoara (TMY); | - operating temperature of PV panel; |
| Current at $P_{mp}$: $I_{mp} = 5.9 \, \text{A}$; | - | |
| Voltage at $P_{mp}$: $V_{mp} = 17.0 \, \text{V}$; | - | |
| $t_{NOCT} = 47 \, ^\circ\text{C}$; | - reference temperature: $t_{ref} = 25 \, ^\circ\text{C}$; | - interval: annual, monthly and daily. |
| Reference solar radiation: $G = 1000 \, \text{W/m}^2$. | - | - power generated by PV panel. |

Studied cases

The four locations analysed in the study represent the biggest cities of Romania and have slightly different climatic conditions according to the following coordinates:
- Bucharest (44°26'10.1"N, 26°06'03.4"E);
- Cluj-Napoca (46°46'16.6"N, 23°35'24.1"E);
- Iasi (47°09'06.9"N, 27°35'13.1"E);
- Timisoara (45°45'23.9"N, 21°13'43.2"E).

The study analysed the power produced by the photovoltaic panel for each of the four locations, for three different orientations in vertical position (South, South-East and South-West), for annual, monthly and daily study intervals.

The cooling effect of the photovoltaic panel is presented comparatively for the basic case (when the PV panel is positioned apparently on the building façade, without the possibility of ventilation in its rear area) and for the solution of integration in the ventilated façade of the building. In the end, the optimal passive cooling (air and heat sink) and active cooling (water film exchanger) are analysed.

3. Results

The influence of cooling is shown in Figure 1. The annual variation of the average operating temperature of the photovoltaic panel is presented, in a vertical-South position, for Bucharest climatic conditions. The climatic conditions used in modelling are according to the typical meteorological year, according to TRNSYS database [16]. Each simulation is realized by using a time step of 1 hour.
Fig. 1 - Evolution of the operating temperature of the photovoltaic panel during the year, vertical-South position, Bucharest: a) without ventilated facade; b) integrated in ventilated facade c) with heat sink; d) with water film heat exchanger.

**Case 1 – Bucharest**

The cooling effect of the photovoltaic panel is presented in Figure 2, which shows the electricity production obtained for one given year for each of the integration solutions proposed for Bucharest. Figure 3 shows the increase of the percentage of annual energy produced, compared to the base case.

![Graph showing energy production with different cooling solutions](image)

**Fig. 2 - Bucharest – Energy produced one given year per surface unit according to orientation and cooling solution.**
Fig. 3 - Bucharest – Additional energy produced one given year depending on the orientation and cooling solution, relative to the base case.

The cooling effect of the solutions proposed during the year, for Bucharest in the vertical position of the photovoltaic panel, can be tracked in Figure 4.

For Bucharest case, it is found that for the vertical integration of the photovoltaic panel, significant amounts of additional energy are obtained, if cooling is achieved between May and September.

Fig. 4 - Bucharest – The effect of cooling solutions on the monthly electricity production for the vertical position of the PV: a) South; b) South-East; c) South-West.
Case 2 – Cluj-Napoca

Figure 5 shows the electricity production obtained annually for each of the integration solutions proposed for Cluj-Napoca. Figure 6 shows the increase of the percentage of annual energy produced, compared to the base case.

Fig. 5 - Cluj-Napoca – Energy produced one given year per surface unit according to orientation and cooling solution.

Fig. 6 - Cluj-Napoca – Additional energy produced one given year depending on the orientation and cooling solution, relative to the base case.

The cooling effect of the solutions proposed during the year, for Cluj-Napoca in the vertical position of the photovoltaic panel are presented in Figure 7.
In the case of Cluj-Napoca, it is found that for the vertical integration of the photovoltaic panel, significant amounts of additional energy are obtained if cooling is performed between July and October.

**Case 3 – Iasi**

Figure 8 shows the electricity production obtained annually for each of the integration solutions proposed for Iasi. Figure 9 shows the increase of the percentage of annual energy produced, compared to the base case.
The cooling effect of the solutions proposed during the year, for Iasi in the vertical position of the photovoltaic panel, can be observed in Figure 10.

In the case of Iasi, it is found that for the vertical position of the photovoltaic panel in buildings, significant amounts of additional energy are obtained if cooling is performed between April and September.
Case 4 – Timisoara

Figure 11 shows the electricity production obtained annually for each of the integration solutions proposed for Timisoara. Figure 12 shows the increase of the percentage of annual energy produced, compared to the base case.

![Diagram showing energy production and increase in percentage for Timisoara cases](image1)

Fig. 11 - Timisoara – Energy produced one given year per surface unit according to orientation and cooling solution.

![Diagram showing increase in energy produced for Timisoara cases](image2)

Fig. 12 - Timisoara – Additional energy produced one given year depending on the orientation and cooling solution, relative to the base case.

The cooling effect of the solutions proposed during the year, for the locality of Timisoara and the vertical position of the photovoltaic panel, can be observed in Figure 13.
In the case of Timisoara, it is observed that for the vertical position of the photovoltaic panel in the buildings, important amounts of additional energy are obtained if the cooling is carried out between May and September.

**Highlighting the effect of cooling on the day with maximum production**

The maximum daily power produced when the cooling is achieved by water film heat exchanger is presented for the case of Iasi, Vertical-South-East, August. For the day with maximum energy production, the parameters of the photovoltaic panel in the basic case are comparatively presented, Figure 14.a, in the situation of simple integration in the ventilated facade of the building, Figure 14.b, and in the situation of using the optimal variant of water film heat exchanger, Figure 14.c.
Fig. 14 - The evolution of the temperature and power produced by PV panel during the maximum day, for the vertical-South-East position in Iasi: a) basic case; b) integration in DSF; c) water film heat exchanger.

It is observed that the integration of the photovoltaic panel in the ventilated facade and the use of the water film heat exchanger determines the reduction of the operating temperature and the increase of the produced power, in the same external conditions, Figure 15.

Fig. 15 - Daily analysis of PV electricity production - comparison between the optimal water film heat exchanger solution and simple integration in the ventilated façade.
For a decrease in efficiency of \(-0.45\%/\degree C\), according to [8], cooling may result in an increase of generated power according to Figure 15 and Figure 16.

According to Figure 15 and Table 2, if the temperature reduction of the photovoltaic panel is applied by using the water film heat exchanger between 08:00 and 15:00, the efficiency of the panel is increased, up to values of 12.38%. Consequently, the electrical power produced by the photovoltaic panel in similar sunny conditions is higher than that obtained under normal operating conditions. The energy increase over the cooling interval is approximately 47.7 Wh/m\(^2\), which represents an increase of 8.2% compared to the conditions of its integration in the ventilated facade.

![Fig. 16 - Daily analysis of PV panel electricity production - comparison between the optimal water film heat exchanger solution and the base case.](image)

**Table 2**

The parameters of the PV panel in optimized conditions for Iasi - August

| Interval | \( G_{med} \) | \( T_{base} \) | \( P_{base} \) | \( \eta_{base} \) | \( T_{DSF} \) | \( P_{DSF} \) | \( \eta_{DSF} \) | \( T_{opt} \) | \( P_{opt} \) | \( \eta_{opt} \) |
|----------|-------------|--------------|---------------|-----------------|-------------|-------------|----------------|-------------|-------------|----------------|
| 06-07    | 22.1        | 16.9         | 2.4           | 10.73           | 13.4        | 2.4          | 10.90          | 16.88       | 2.4          | 10.90         |
| 07-08    | 426.0       | 33.7         | 48.4          | 11.37           | 26.7        | 50.0         | 11.73          | 20.00       | 50.0         | 11.73         |
| 08-09    | 657.6       | 45.0         | 71.8          | 10.92           | 35.7        | 74.9         | 11.39          | 20.00       | 80.2         | 12.20         |
| 09-10    | 780.5       | 52.6         | 82.6          | 10.58           | 41.7        | 86.8         | 11.13          | 21.56       | 95.3         | 12.21         |
| 10-11    | 774.0       | 55.0         | 81.3          | 10.51           | 43.7        | 85.7         | 11.08          | 22.57       | 94.9         | 12.26         |
| 11-12    | 753.3       | 56.7         | 78.9          | 10.48           | 45.0        | 83.3         | 11.06          | 23.25       | 92.7         | 12.30         |
| 12-13    | 638.3       | 54.6         | 67.9          | 10.64           | 43.3        | 71.5         | 11.20          | 22.39       | 79.0         | 12.38         |
| 13-14    | 469.1       | 49.8         | 51.0          | 10.88           | 39.6        | 53.5         | 11.41          | 20.44       | 58.2         | 12.41         |
| 14-15    | 274.4       | 43.6         | 30.3          | 11.06           | 34.6        | 31.6         | 11.52          | 20.00       | 33.7         | 12.28         |
| 15-16    | 108.9       | 38.0         | 11.9          | 10.92           | 30.2        | 12.3         | 11.32          | 20.00       | 12.9         | 11.84         |
| 16-17    | 98.9        | 37.9         | 10.8          | 10.88           | 30.0        | 11.2         | 11.28          | 20.00       | 11.7         | 11.79         |
| 17-18    | 82.3        | 36.8         | 8.9           | 10.82           | 29.2        | 9.2          | 11.21          | 20.00       | 9.2          | 11.21         |
| 18-19    | 45.5        | 33.9         | 4.8           | 10.60           | 26.9        | 5.0          | 10.95          | 20.00       | 5.0          | 10.95         |
| TOTAL    | -           | -            | 551           | -               | 577         | -            | 625            | -           | -            | -             |
where, $G_{med}$ - average intensity of solar radiation in the time interval [W/m²];
$T_{opt}$ - average cell temperature under cooling conditions [°C];
$\eta_{base}$ – effective conversion yield (simple integration in façade) [%];
$\eta_{base}$ – effective conversion yield (integration in DSF) [%];
$\eta_{opt}$ - optimized conversion yield (integration in DSF and water cooling) [%];
$P_{add}$ - the electrical power produced additionally by PV panel after cooling [W/m²].

Table 2 presents the values of the parameters of the photovoltaic panel in the cooling conditions, for Iasi, August and the vertical-South-East position of PV panel. The determined quantities represent the averages calculated on the study time intervals. Table 3 shows the raise of power generated and efficiency of the PV panel when water cooling is achieved compared to the basic case or simple integration into the DSF.

**Table 3**

*The effect of the water cooling of the PV panel for Iasi - August*

| $P_{add}$ [W/m²] compared to base | $\Delta \eta$ [%] compared to DSF |
|-----------------------------------|----------------------------------|
| 1,56 | 3,23 | 7,08 |
| 8,44 | 5,31 | 11,75 |
| 12,73 | 8,49 | 15,41 |
| 13,52 | 9,14 | 16,62 |
| 13,76 | 9,37 | 17,43 |
| 11,13 | 7,51 | 16,40 |
| 7,19 | 4,71 | 14,08 |
| 3,36 | 2,08 | 11,09 |
| 0,90 | 0,56 | 4,58 |
| 0,90 | 0,50 | 4,52 |
| 74,1 | 47,7 | 13,28 |

**Comparative analysis of the cooling effect for the four locations**

The productivity of photovoltaic panels depending on location and orientation is presented in Tables 4-6.

**Table 4**

*The energy produced annually by PV panel integrated in the double-glazed ventilated façade*

| Orientation          | Vertical-S | Vertical-SE | Vertical-SW |
|----------------------|------------|-------------|-------------|
| Bucharest            | 90 %       | 87,9 %      | 87,5 %      |
| Cluj-Napoca          | 100 %      | 94,4 %      | 94 %        |
| Iasi                 | 89 %       | 85,2 %      | 85,9 %      |
| Timisoara            | 92,1 %     | 88,2 %      | 88,1 %      |
### Table 5

*The energy produced annually by the PV panel integrated in the DSF and heat sink*

| Orientation          | Vertical-S | Vertical-SE | Vertical-SW |
|----------------------|------------|-------------|-------------|
| Bucharest            | 90.5 %     | 88.1 %      | 88.2 %      |
| Cluj-Napoca          | 100 %      | 94.2 %      | 94.5 %      |
| Iasi                 | 89.2 %     | 85.2 %      | 86.4 %      |
| Timisoara            | 92.4 %     | 88.2 %      | 88.9 %      |

### Table 6

*The energy produced annually by the PV panel integrated in DSF and water film heat exchanger*

| Orientation         | Vertical-S | Vertical-SE | Vertical-SW |
|---------------------|------------|-------------|-------------|
| Bucharest           | 90.9 %     | 88.3 %      | 89 %        |
| Cluj-Napoca         | 100 %      | 94 %        | 94.9 %      |
| Iasi                | 89.4 %     | 85.3 %      | 87.1 %      |
| Timisoara           | 92.7 %     | 88.3 %      | 89.6 %      |

### 4. Conclusions

Taking into account that in large urban centres, the available horizontal area is limited, both at the level of buildings and on the ground, it is considered appropriate to place the vertical photovoltaic systems in the facades of buildings. For this position, the influence of the orientation of the photovoltaic panels on the energy produced annually, monthly and daily was determined. The analysis of the results regarding the integration of photovoltaic panels in buildings, for the four locations, highlighted a series of relevant data. The maximum energy output is obtained for the South orientation of the photovoltaic panel. Under these conditions, the maximum energy production is recorded for the building integration of the PV panels in Cluj-Napoca.

The annual analysis shows that the influence of the PV panel orientation has the same tendency for all the studied locations. The values range from 107.9...126.5 kWh/m²/year, with maximums recorded for Cluj-Napoca for all orientations (118.9...126.5 kWh/m²/year) and minimums for Iasi (107.9...112.7 kWh/m²/year).

Regarding the average efficiency of the photovoltaic panel, it varies between 11.54% and 11.66% for the annual analysis interval. The average efficiency, for the months of maximum production, is lower than the annual one, being located in the range 11.17...11.47%, while the values for the maximum day is even lower, of 10.82%...11.66%. These values are directly dependent on the intensity of solar radiation and negatively influenced by the operating temperatures of the photovoltaic panel.

One way to improve the efficiency of PV panel, during hot days and with increased input of solar radiation, is to reduce its operating temperature. Water cooling has the advantage of obtaining the best efficiency, the performance increase being between 5.60
... 8.47%, compared to the case of apparent integration on the building facade. However, the energy used to make the liquid flow needs to be accounted and it will be studied in further researches. This solution can be capitalized on by producing hot water for consumption. There is the possibility of using water from the cold-water supply system, being a cheap energy source with optimal parameters for an efficient heat exchange with the photovoltaic panel. Thus, the so-called hybrid PV/T (photovoltaic/thermal) systems can be obtained, using the excess heat extracted from the PV panel to preheat the domestic hot water. In the case of hybrid systems, the aim must always be to obtain the optimum efficiency for the photovoltaic panel, and to extract the excess heat by achieving the lowest possible energy consumption.

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