Effect of cooling on power generated by photovoltaic panels

S V Hudișteanu1,*, N C Cherecheș1, C G Popovici1, M Verdeș1, V Ciocan1, M C Balan1, F E Țurcanu1 and I C Scurtu2
1Gheorghe Asachi Technical University of Iași, Faculty of Civil Engineering and Building Services, Romania
2Naval Academy Mircea cel Batran Constanta, Romania

* E-mail: sebastian.hudisteanu@tuiasi.ro

Abstract. The paper presents a numerical analysis of the operation of photovoltaic (PV) panels integrated in fixed position on the roofs or facades of the buildings. Knowing that the efficiency of photovoltaic panels is temperature-dependent, and due to fixed PV panel position, the possibility of improving the conversion is analysed from the point of view of the temperature of the PV cells. The model is simulated using TRNSYS software and the main functioning parameters assessed are the operating temperature of the cells, open circuit voltage, maximum power generated and conversion efficiency. The solution proposed for cooling consists in using water heat exchangers attached to the backside of the photovoltaic panel. The results highlight the direct dependence of the photovoltaic efficiency with the temperature of the panel for different positions in the same geographical location. The energy gain during the cooling interval is about 26.9 Wh/m² (vertical), 81.9 Wh/m² (inclined) and 81.7 Wh/m² (horizontal), which represents an increase of 5.8%, 9.3% and 9.2% respectively, compared to the normal operating conditions.

1. Introduction

Photovoltaic cells are made of several semiconductor materials, but the vast majority of solar cells (95%) are made of silicon (Si). It is one of the most widespread chemical elements in the Earth's crust, representing approximately 25% of it. Therefore, it is available in sufficient quantities, being accessible at a reasonable price [1]. Also, the processing of the material is not aggressive to the environment.

Advantages of using photovoltaic panels:
• direct conversion of solar radiation into electricity;
• no moving elements (no noise);
• long life.

Disadvantages:
• dependence on climatic conditions (clouds, dust etc.);
• diurnal variation of solar radiation;
• dropping of the operating parameters when the temperature of the cells is rising.

When photons from solar radiation strike a photovoltaic cell, they can be reflected, transmitted or absorbed. Only the absorbed photons with a certain level of energy can generate electricity, figure 1. Almost all the solar energy captured by photovoltaic panels not converted into electricity, about 80%, is converted into heat [2].

The performance of photovoltaic panels is known to be temperature-dependent [3]. There are studies regarding the dependence of the conversion efficiency to the cell temperature [4].
A linear variation tendency of the temperature-power dependence, figure 2, is noticed in most studies [5]. Thus, when a temperature increase occurs, the efficiency of converting the energy of solar radiation into electricity decreases. As a guideline value, a reduction of the efficiency of the photovoltaic panels by 0.3 ... 0.5% can be considered [6] (0.45% according to [1]), for each degree of temperature increase. The reduction of the efficiency and of the maximum power produced by the photovoltaic panel occurs due to the decrease of open-circuit voltage, $V_{oc}$, by 0.30 ... 0.50 %/°C, when the operating temperature of the cells increases.

The improvement of the performance of the photovoltaic panels can be achieved by controlling the operating temperature of the cells, while the control of the other parameters implied is more challenging to attain. For example, in the particular case of the placement of photovoltaic panels on the buildings on vertical, inclined or horizontal non-orientable surfaces, the solar radiation becomes an uncontrollable parameter.

Various methods and relationships for determining the dependence between the conversion efficiency of photovoltaic modules and their temperature are presented in the literature [4, 7]. Both the open-circuit voltage ($V_{oc}$) and the fill factor (FF) are influenced negatively by the temperature, while a small increase of the short-circuit current ($I_{sc}$) is registered [7]. This linear correlation has the following form:

$$\eta_c = \eta_{ref} [1 - \beta_{ref} (t_c - t_{ref})]$$  

where, $\eta_{ref}$ - electrical efficiency at the reference temperature ($t_{ref}$);
$t_{ref}$ - reference temperature of 25 °C;
$\beta_{ref}$ - temperature coefficient. It is mainly a material property, having values of about 0.004 K$^{-1}$ for crystalline silicon modules [8].

As the power of a photovoltaic cell varies depending on the temperature and radiation changes, the standard conditions parameters (STC) have been defined ($t_{ref} = 25$ °C, $G = 1000$ W/m$^2$, AM1.5), which produce the so-called Watt-peak [Wp] power [9].

The experimental tests [10, 11] and numerical analysis [12, 13] on monocrystalline or polycrystalline photovoltaic panels are current concerns in the literature [1, 14, 15]. Those researches express the necessity of cooling solutions due to the reduction of the conversion efficiency when the operating temperature of PV panels raises. There are various ways of cooling the photovoltaic panels, but the most wide-spread solutions consist in air cooling [16] and water cooling [17].

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) [18, 19]. A particular feature of this solution is the BIPVT (Building Integrated Photovoltaic-Thermal System) concept, which implies the integration of photovoltaic panels into buildings [20, 21]. The generation of two of the most used types of energy is performed under the 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.

Different technologies to improve the efficiency of photovoltaic panels by passive cooling, using air, are studied in the literature [1, 15, 22-23]. The characteristic values for two photovoltaic cells were compared through experimental tests, under different conditions [24]. This system consists of a network of rectangular fins made of aluminium, being thermally coupled to the photovoltaic cell through a thermal conductive paste. There was an increase in the heat extracted from the photovoltaic cell and a decrease in its temperature, with values between 5 °C and 9 °C. Also, the integration of photovoltaic panels in the building’s envelope, as the exterior glazing of the double-skin facades, is considered a viable solution [25-27].

The use of water as a cooling agent for photovoltaic panels is a solution analysed in different studies [28-31]. The hybrid photovoltaic panels studied in literature have attached a water coil with the role of both cooling the PV panel and solar collector. A solution for the cooling of the photovoltaic panels by using water as a heat transfer agent is presented in [28]. This study presents a hybrid photovoltaic panel with an attached functionally graded material backside, with a serpentine inside for water circulation. Besides its primary role of PV panel cooler, this circuit is also used as a solar collector. An example of such a system is presented in [32]. The modelling of heat transfer in the case of photovoltaic-thermal systems under variable atmospheric conditions is studied in [33, 34]. The water-cooling techniques are placed in the category of active cooling solutions and are superior to air cooling, but more expensive.

Also, newer solutions like nanofluids [35], phase change materials [32, 36, 37] or heat pipes [38] are developing fast and emphasizes the real concerns in cooling the photovoltaic panels in order to obtain higher efficiencies.

Most of the studies on the cooling of photovoltaic panels [18, 21, 39-40] are also focused on using the thermal energy extracted in this process, resulting shorter recovery time of the investments comparing to classical stand-alone photovoltaic systems [12]. Since the efficiency of the photovoltaic panels is lower than the solar thermal, it is opportune to use hybrid systems that ensure optimized operation of the whole assembly [24].

The main aim of the proposed work is to determine the quantitative advantages of using a water heat exchanger for cooling the PV panels and to calculate the additional generated power and the required water flow rate [1].

2. Problem description
The main objective of this work is to determine through numerical modelling the operating parameters reported for a 1 m$^2$ surface of a photovoltaic panel integrated on the roof or in the facade of a building.
The photovoltaic panel consists of 72 solar cells connected in series, being placed in different positions in the same temperate climate area – Constanta, Romania.

The analysis aims to determine the efficiency of PV panel both in normal operation and cooling conditions. The cooling of PV panel is performed by using a heat exchanger, attached to the backside of the panel. In order to achieve high efficiencies, the photovoltaic panel is cooled to a temperature close to the nominal one of $t_{ref} = 25$ °C.

The heat exchanger must allow the heat to be dissipated from the rear area of the photovoltaic panel. The contact zone between heat exchanger and the photovoltaic panel must be made of a material with a high thermal conductivity (copper or aluminium).

3. Numerical simulation
The external conditions considered are those for a typical day of summer (July) in Constanta, Romania (44.1598° N, 28.6348° E) [41]. The photovoltaic panel is analysed in three main positions: vertical-south, inclined-south and horizontal, while the intensity of the solar radiation is considered to be variable during a day.

The numerical simulation was conducted using TRNSYS software. The model presented in figure 3 has the following blocks for: climatic data, polycrystalline photovoltaic panel, elements of conversion of the measurement units, tracking and output data.

![Figure 3. Numerical modelling of the photovoltaic panel with the TRNSYS software.](image)

The recommended unit for the PV panel modelling is Type 94. This block which is used in simulations is appropriate for both monocrystalline or polycrystalline silicon PV modules. The four parameters model [42] used for a more realistic PV panel functioning and evaluation is described by the following equations which are taking into account both series ($R_s$) and shunt ($R_{sh}$) resistances [6, 43]. The current, $I$, generated by PV cell is determined using Eq. 2:

$$I = I_{ph} - I_D \left( \frac{q(V+R_s)}{nKT_{cell}} - 1 \right) - \frac{(V+R_D)}{R_{sh}}$$

The open-circuit voltage ($V_{oc}$) of the cell is calculated using Eq. 3:

$$V_{oc} = \frac{nKT_{cell}}{q} \ln \left( \frac{I_{ph}}{I_D} + 1 \right)$$
The operating parameters of the polycrystalline PV panel studied SPR-P17-330-COM [44] are presented in table 1.

| Parameter                                                                 | Value       |
|---------------------------------------------------------------------------|-------------|
| short-circuit current                                                     | $I_{sc} = 8.47$ A |
| open circuit voltage                                                      | $V_{oc} = 50.9$ V |
| current at the maximum power point                                        | $I_{max} = 7.88$ A |
| voltage at maximum power point                                            | $V_{max} = 41.9$ V |
| operating temperature of the panel under nominal conditions               | $T_{NOCT} = 47 ^\circ$C |
| net module area                                                           | $S = 2.06$ m$^2$ |

The input data required for the numerical model are presented in table 2.

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| PV panel orientation       | South (for vertical and inclined positions) |
| PV panel position          | Vertical (on the façade of the building), inclined and horizontal |
| climatic conditions        | typical day of July according to the Typical Meteorological Year (TMY) of Constanța, Romania |
| solar radiation intensity  | variable                                   |

The output data from simulations:
- the operating temperature of the photovoltaic panel;
- current intensity, voltage and electrical power produced by PV panel;
- PV panel efficiency.

4. Results

Figures 4-6 show the values resulted from the simulations, under the conditions described above, for a typical day of production. On the left-hand axis there can be determined the amount of solar radiation [W/m$^2$] and the power generated by the photovoltaic panel on its maximum operating point [W/m$^2$]. On the right-hand axis, the values of the outdoor temperature as well as the operating temperature of the photovoltaic panel [‘C] are available.

Figure 4. Daily variation of climatic parameters and PV panel output for the vertical position
During the typical day of summer, the temperature of the PV panel has a proportionate variation with the intensity of the solar radiation and with the temperature of the outside air. The power produced by the PV panel is also dependent on the intensity of the solar radiation, but inversely proportional to the temperature of the cells.

\[ \eta = \frac{P_{mp}}{G \cdot S} \text{ [\%]} \]

**Figure 5.** Daily variation of climatic parameters and PV panel output for the inclined position

**Figure 6.** Daily variation of climatic parameters and PV panel output for the horizontal position

Under these conditions the photovoltaic panel operates according to the parameters presented in table 3. The conversion efficiency has values below 16\%, with a maximum around 15.96\%.
The photovoltaic efficiency is directly influenced by the intensity of the solar radiation but also by the temperature of the panel, which reaches values up to 48.8 °C for solar radiation of 847.4 W/m². In order to decrease the operating temperature and to improve the conversion efficiency of the photovoltaic panel, a cooling down to the operating temperature toward the STC of \( t_{ref} = 25 \) °C is analysed. Considering the values of the parameters in table 3, it is recommended that the cooling of the photovoltaic panel must be done between 08:00 and 15:00.

The energy balance of the PV panel is performed in order to determine the necessary heat extraction in order to achieve the standard operating temperature of the photovoltaic panel after cooling [46]. The energy balance is achieved for hourly intervals where the intensity of the solar radiation is high and the conversion efficiency can be improved by reducing the panel temperature. Knowing the specific heat capacity of the components of a PV panel [33], there are determined specific heat of the entire panel and the thermal energy extracted under the same environmental conditions in order to maintain the PV panel at \( t_{ref} = 25 \) °C.

### Table 3. PV panel parameters under normal operating conditions

| Hour [h] | Intensity of solar radiation [W/m²] V / I / H | Temperature of PV panel [°C] V / I / H | Efficiency in normal conditions [%] V / I / H | Electric power generated [W/m²] V / I / H |
|----------|--------------------------------------------|----------------------------------------|-----------------------------------------------|------------------------------------------|
| 5.00     | 20.6 / 31.4 / 45.0                         | 23.0 / 23.2 / 23.5                     | 14.65 / 14.92 / 15.15                         | 3.0 / 4.7 / 6.8                          |
| 6.00     | 51.9 / 84.0 / 119.0                        | 24.3 / 25.0 / 25.8                     | 15.22 / 15.49 / 15.67                         | 7.9 / 13.0 / 18.6                        |
| 7.00     | 100.7 / 272.6 / 357.0                      | 26.4 / 30.1 / 32.0                     | 15.57 / 15.94 / 15.96                         | 15.7 / 43.4 / 57.0                       |
| 8.00     | 195.4 / 481.8 / 541.0                      | 30.0 / 36.3 / 37.6                     | 15.82 / 15.89 / 15.86                         | 30.9 / 76.6 / 85.8                       |
| 9.00     | 318.9 / 652.5 / 674.0                      | 34.1 / 41.4 / 41.9                     | 15.90 / 15.73 / 15.71                         | 50.7 / 102.6 / 105.9                     |
| 10.00    | 437.5 / 837.2 / 822.0                      | 38.0 / 46.8 / 46.5                     | 15.86 / 15.49 / 15.51                         | 69.4 / 129.7 / 127.5                     |
| 11.00    | 471.0 / 855.3 / 820.0                      | 39.8 / 48.3 / 47.5                     | 15.82 / 15.44 / 15.49                         | 74.5 / 132.1 / 127.0                     |
| 12.00    | 461.8 / 847.4 / 820.0                      | 40.3 / 48.8 / 48.2                     | 15.81 / 15.44 / 15.47                         | 73.0 / 130.8 / 126.9                     |
| 13.00    | 423.5 / 776.4 / 755.0                      | 40.1 / 47.8 / 47.4                     | 15.82 / 15.51 / 15.54                         | 67.0 / 120.4 / 117.3                     |
| 14.00    | 353.9 / 698.0 / 705.0                      | 38.8 / 46.4 / 46.5                     | 15.82 / 15.60 / 15.59                         | 56.0 / 108.9 / 109.9                     |
| 15.00    | 244.7 / 542.4 / 587.0                      | 36.5 / 43.1 / 44.1                     | 15.77 / 15.74 / 15.71                         | 38.6 / 85.4 / 92.2                      |
| 16.00    | 121.3 / 347.3 / 424.0                      | 33.6 / 38.6 / 40.3                     | 15.52 / 15.82 / 15.81                         | 18.8 / 55.0 / 67.0                      |
| 17.00    | 76.0 / 156.7 / 240.0                       | 32.0 / 33.8 / 35.6                     | 15.28 / 15.64 / 15.79                         | 11.6 / 24.5 / 37.9                      |
| 18.00    | 36.1 / 41.5 / 122.0                       | 30.4 / 30.5 / 32.3                     | 14.84 / 14.93 / 15.55                         | 5.4 / 6.2 / 19.0                        |
| 19.00    | 10.8 / 15.9 / 18.0                        | 28.9 / 29.1 / 29.1                     | 14.04 / 14.31 / 14.39                         | 1.5 / 2.3 / 2.6                         |

Thus, the analysed PV panel has an approximate weight of 20.3 kg and an average specific heat capacity of 594.3 J/kgK.

In table 5 the values of the parameters of the photovoltaic panel are presented under cooling conditions. The parameters are determined as the average calculated on the hourly intervals.

Because the efficiency of a photovoltaic cell is also influenced by the solar radiation levels, it is noticed that when \( G \) is below 1000 W/m², even if \( t_{ref} = 25 \)°C, the efficiency is less than the one for STC.
Table 5. PV panel parameters under cooling conditions

| Hourly interval | \( t_{\text{cell}} \) [°C] | \( t_{\text{ref}} \) [°C] | \( \eta_{\text{eff}} \) [%] | \( \eta_{\text{opt}} \) [%] | \( P_{\text{sup}} \) [W/m\(^2\)] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 8.00-9.00       | 30.0            | 36.3            | 37.6            | 15.82           | 15.89           | 15.86           | 15.68           | 16.70           | 16.75           | 0.7             | 3.9             | 4.9             |
| 9.00-10.00      | 34.1            | 41.4            | 41.9            | 15.90           | 15.73           | 15.71           | 16.55           | 16.89           | 16.90           | 2.1             | 7.6             | 8.0             |
| 10.00-11.00     | 38.0            | 46.8            | 46.5            | 15.86           | 15.49           | 15.51           | 16.79           | 17.01           | 17.01           | 4.1             | 12.7            | 12.3            |
| 11.00-12.00     | 39.8            | 48.3            | 47.5            | 25              | 15.82           | 15.44           | 15.49           | 16.88           | 17.06           | 17.06           | 5.0             | 13.9            | 12.9            |
| 12.00-13.00     | 40.3            | 48.8            | 48.2            | 15.81           | 15.44           | 15.47           | 16.90           | 17.09           | 17.09           | 5.0             | 14.0            | 13.3            |
| 13.00-14.00     | 40.1            | 47.8            | 47.4            | 15.82           | 15.51           | 15.54           | 16.89           | 17.11           | 17.10           | 4.5             | 12.4            | 11.8            |
| 14.00-15.00     | 38.8            | 46.4            | 46.5            | 15.82           | 15.60           | 15.59           | 16.81           | 17.10           | 17.10           | 3.5             | 10.5            | 10.7            |

Where: \( t_{\text{cell}} \) – cell temperature in normal operating conditions - without cooling; \( \eta_{\text{eff}}, \eta_{\text{opt}} \) – conversion efficiencies before and after optimization (cooling); \( P_{\text{sup}} \) – additional power produced by PV panel in cooling conditions.

Figure 7. The power generated by PV panel in normal conditions vs cooling conditions – vertical

Considering that the efficiency is decreasing by 0.45% for each degree above the standard temperature of 25 °C [1], the cooling is determining a power increase according to figures 7-9.

According to table 5, when the temperature of the photovoltaic panel is reduced to 25 °C in 08:00 - 15:00 interval, the conversion efficiency reaches up to 17.11% (13.00-14.00).
Consequently, the electrical power produced by the photovoltaic panel under similar conditions of solar radiation is higher than that obtained under normal operating conditions. The energy gain during the cooling interval, 08:00 - 15:00, is about 26.9 Wh/m² (vertical), 81.9 Wh/m² (inclined) and 81.7 Wh/m² (horizontal), which represents an increase of 5.8%, 9.3% and 9.2% respectively, compared to the normal operating conditions.

Considering that temperature of the supply water is maximum 15 °C for selected location during summer, the following flow rates would be necessary for obtaining the cooling of 1 m² of PV panel towards $t_{ref}$, table 6.

These results show that it can be obtained a large quantity of water at approximate 25 °C, that can be used as a preheated thermal agent in buildings with hot water requirements [46] or guided to be used as conventional clean water for toilets.
### Table 6. Average flow rates necessary for cooling 1 m² of PV panel for interval 8.00-15.00

|                        | Vertical | Inclined | Horizontal |
|------------------------|----------|----------|------------|
| Flow rate for cooling [l/min] | 36.7     | 56.7     | 58.3       |
| Flow rate for cooling [m³/day] | 2.2      | 3.4      | 3.5        |

5. Conclusions

Cooling of photovoltaic panels is an advantageous solution for improving their conversion efficiency. The reduction of the operating temperature achieved by using water as a heat transfer agent has many advantages, being a cheap source with optimal parameters for extracting the excess of heat stored in the mass of the photovoltaic panel. The preheating of the cold water available in the water supply system would be useful in further processes in buildings with hot water requirements, such as hotels, laundries and hospitals or industrial.

The use of a heat exchanger and a storage system for the extracted thermal energy determines a superior efficiency of the whole assembly evaluated globally, compared to the stand-alone photovoltaic system. In the case of PV/T systems, the highest efficiency of the photovoltaic panel must always be a priority and the extraction of the thermal energy must be done with the lowest auxiliary consumption possible. In further numerical and experimental studies there will be analyzed other possibilities to improve the performance of these systems, in the conditions of their integration in buildings.

The energy gain during the cooling interval is about 26.9 Wh/m² (vertical), 81.9 Wh/m² (inclined) and 81.7 Wh/m² (horizontal), which represents an increase of 5.8%, 9.3% and 9.2% respectively, compared to the normal operating conditions.

The results underline the direct dependence of the photovoltaic efficiency with the operating temperature of the panel for different positions of PV panel, also highlighting the necessity of a particular analysis for each system implemented, depending on its location, position and time of the year.

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