Prototyping and economic assessment of a novel automatic cooling system for existing photovoltaic solar systems to increase their efficiency

André F. A. Castanheira

Abstract—This paper presents a closed-loop water cooling kit to be assembled in already built photovoltaic (PV) solar power plants, especially in hot regions, to increase its electrical energy production. The cooling kit was designed to minimize cost and the amount of water required, minimizing load losses in the hydraulic circuit to reduce pump power and water tank size. To estimate the increase of production for different locations and ambient conditions, an analytical model was developed and validated through experimental tests, capable of predicting with sufficient accuracy the PV temperature of a cooled and non-cooled panel based on meteorological data. In Lisbon (Portugal), a prototype of the cooling kit was installed in 5kW of an existing 20kW PV power plant. Experimental results evaluated how cooling/heating thermal time constants and water ON/OFF cycles in each array of panels affects PVs’ efficiency. Experiments showed to be possible to increase up to 17% of energy production in Lisbon region. A detailed feasibility study and economic analysis was done indicating that the cooling system can be paid in 2 years with an additional revenue of 17000USD in the next 20-years. Therefore, it was concluded that the system is economically viable even for different world locations.

Index Terms—Photovoltaic systems, temperature, efficiency, water-cooling system prototype.

I. INTRODUCTION

This paper focuses on a solution to increase the efficiency of photovoltaic (PV) panels through an active closed loop water cooling system. By cooling the panel, it is possible to increase the output voltage, increased its energy produced. Although there has been some analysis in cooling systems of PV using water [1]-[10], there are few available complete descriptions of experimental prototypes and its economics feasibility analysis based on the experimental tests and on theoretical model simulation.

Solar energy is a clean, inexhaustible, renewable source of energy that is growing since the last century and it is now one of major targets of investment and research [11]. Photovoltaics have been growing exponentially for more than two decades, evolved from a pure niche market of small scale applications towards becoming one of the main sources of energy [12]-[15]. Consequently, the cost of solar PV declined significantly due to improvements in technology and economies of scale, and in a few years the price will become competitive with conventional energy sources.

Since PV parks cannot increase their capacity by installing more PV panels without a change in their current contract, one way to increase their production is by increasing the efficiency of the panels. The performance of a PV module is strongly dependent on its operating temperature [16]. Most of the energy absorbed by the panel is converted to heat which is lost in a conventional PV and so provides no value. The negative effect of high operation temperatures on conversion efficiency at crystalline silicon-based solar cells is well known in the literature [17]. The voltage is highly dependent on the temperature and an increase in temperature will decrease the voltage, and therefore, the output power.

To ensure maximum production, new techniques have been created to inspect parks and avoid problems, as for example, dead panels, hotspots, etc. [18]

In this work, it was constructed a prototype installed in 5kW of a 20kW PV power plant, which cools the panels with a closed loop water system. A simple analytical model that estimates the new PV module temperature after its cooling, is developed and validated through the experimental tests to be used in the estimation of increase of energy production for different ambient conditions. With this estimated temperature, it is possible to estimate the new produced energy and compare it with a non-cooling PV panel. With this model, a program is developed, to make an economic evaluation of the PV cooling system for any region, having as input only the meteorological data.

II. CONCEPT OF THE COOLING SYSTEM

The cooling system consists in a closed-loop water cooling system which lowers the PV surface temperature to increase its efficiency and uses a set of valves to optimize the water flow. The main purpose is to cool the PVs with a uniform water layer to lower its surface temperature and to create a refractive layer to decrease the solar radiation reflected by the glass layer (refractive index: 1.3 to water and 1.5 to glass [1]).

The water is stored in a tank which can be at ambient temperature or buried, to reduce the water temperature coming from the PV panels. The water is then pumped into a main channel which will be spread to different strings of PVs. Each PV string has its own controlled valve. Using sprinklers, the water is spread along the PVs at a low pressure and speed to create a uniform layer of water. Finally, the water is collected
at the bottom of the PV strings and carried to the water tank, where it is processed and cleaned.

The main characteristics of this water cooling system concept are based on the following:

- The reduction of the water pump fatigue:
  To reduce the water pump fatigue, the pump operates at only one speed and with the minimum required start/stop operations. To achieve this, a set of controlled valves (v1 to v5 in Fig. 1) is installed and only one operates at one time. With this, the water pump flow remains constant.

- The optimization of the water flow:
  From previous studies [19], it was verified that the thermal constant of the PV cooling is much higher than heating one. Using the difference between thermal constants, it is advantageous to use a cyclic cooling process which cools only one string at one time, as seen in Fig. 2. With this process, the water pump can be dimensioned for only one string, reducing the investment and operating costs of the system.

III. IMPLEMENTATION OF THE COOLING SYSTEM

A prototype of the water cooling system was installed on a string of 5kW (25 panels) of a 20kW PV solar power plant located in Bobadela, Lisbon, Portugal. The solar power plant consists of four 5kW PV strings: three strings of mono-crystalline silicon PVs and one of poly-crystalline PVs as shown in Fig. 3. For the experimental tests, two strings of mono-crystalline PVs were chosen, one to be the reference (string 1) and the other to be cooled with the developed prototype of the cooling system (string 2). The mono-crystalline panels present a rated power of 190W and the characteristics are on Table I. Note that the maximum power of the panel decreases with the temperature, -0.45 %/ºC.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Operating Cell</td>
<td>45±2ºC</td>
</tr>
<tr>
<td>Temperature (NOTC)</td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient of Pmax</td>
<td>-0.45 %/ºC</td>
</tr>
<tr>
<td>Temperature Coefficient of Voc</td>
<td>-0.34 %/ºC</td>
</tr>
<tr>
<td>Temperature Coefficient of Isc</td>
<td>0.050 %/ºC</td>
</tr>
</tbody>
</table>

The schematic of the prototype cooling system is shown in Fig. 4. The PV panels are installed in a rooftop with an inclination of 33º along the strings array, Fig. 5.

Experimental tests were done with only one string (String 2 in Fig. 3) with twenty-five panels, where the cooling time during which the sprinklers are working is controlled by an electric valve. Different water cycle ratios ON/OFF are tested to analyze the impact in the increase of efficiency and in the water and electricity water pump consumption. This ON/OFF cycle corresponds to the time the panel is being cooled (ON) or not (OFF).

The water is storage in a 150L water tank (Fig. 6) and it is pumped through a manual valve and a controlled valve into the two arrays of PVs of string 2. The escape valve simulates the presence of other PV strings being cooled, when the controlled value is closed, maintaining the water pump flow. Using sprinklers, the water is spread along the PVs with a low pressure to assure a uniform distribution along the panel and to reduce the water leakage, Fig. 7. Finally, in Fig. 8, the water collecting system can be seen, made of PVC gutters connected to the water tank. Due to the rooftop inclination, the water flows to the tank by gravity.
The major issue found in this system is related to the water losses in the process in form of water evaporation. In peak hours and with excessive wind speeds, the water evaporation losses may be significant.

IV. EXPERIMENTAL TESTS

A series of experimental tests were carried out, with different ON/OFF cycles, to study the optimization of the cooling system and associated costs. Two temperature probes were placed, one on the cooled panel and the other on a panel of the non-cooled reference string.

For the 11th of August of 2016, the temperature profiles for the strings with and without the cooling system are shown in Fig. 9a), with different ON/OFF cycles for different hours. In this day, the temperature difference between the cooled and non-cooled panels reach up to 22°C. Effect of the decrease of temperature on the cooled panel resulted in an increase of power. In Fig. 9b) is shown the power output from the cooled and non-cooled string, showing an increase up to 15% in that day. Note that the largest difference occurs between 11:30h and 15:30h, precisely when the ambient temperature and irradiancy are typically higher.

Over time, it has also been found that water ultimately cleans dust and dirt from the panels, resulting in increased power even when the system is not running. In Fig. 10, it can be verified that, even with the cooling system not running, due to the water...
cleaning from the previous day, the panels already presented an increase of 5% of power. When the cooling system is ON, the power increases up to 15%. During the whole experiment (3 months of experiments), a maximum increase of 17% was measured. In Fig. 11 are presented the experimental results for the increase of efficiency for different ON/OFF cycles measured during the 3 months of experiments.

A. PV panel temperature

Usually PV panel temperature can be estimated by a simplified model, which relates the ambient temperature, $T_{amb}$ and the irradiance, $G$. This model consists of admitting that the temperature of the module is equal to the sum of $T_{amb}$ with the product of a constant by $G$ (Ross constant) [20], eq.(1).

$$T_{pv} = T_{amb} + kG$$  \(1\)

It is possible to rearrange it, eq.(2), where NOCT (Nominal Operation Cell Temperature) is given by the panel manufacturer in its datasheet. This variable represents the temperature reached by the cell in normal operating conditions, defined by $T_{amb} = 20^\circ C$ and $G = 800W/m^2$.

$$T_{pv} = T_{amb} + \frac{G\cdot(NOCT - 20)}{800}$$  \(2\)

B. Cooled PV Panel Temperature

To simulate the ON/OFF water cycles and to obtain the optimal cycle of the prototype, the following solution was proposed: by an analysis of the experimental results of the cooled panel temperature (Fig. 12), it was concluded that these could be described by exponential transient curves. These curves enable the calculus of the heating and cooling thermal constants.

The following equations were then deduced, where each parameter is shown in Table II. Eq.(3) translates the cooling curve of the panel, and eq.(4) its heating. Through these equations, the behavior of the panel temperature was simulated, Fig. 12.

$$T_{cooling} = \left(T_{PV_{cool}} - T_{PV_{cool}}\right)\cdot e^{-\frac{t}{\tau_{ON}}} + T_{PV_{cool}}$$  \(3\)

$$T_{heating} = \left(T_{PV_{cool}} - T_{PV_{cool}}\right)\cdot (1 - e^{-\frac{t}{\tau_{OFF}}}) + T_{PV_{cool}}$$  \(4\)

V. ANALYTICAL MODEL AND ITS VALIDATION

The thermoelectric model of the panels is needed to estimate the increase of power due to the water cooling system for a whole year and for different locations. Therefore, an analytical model capable of predicting the PV temperature with and without the cooling system was built and adjusted to the experimental results.

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**Fig. 10.** Power output comparison between the cooled string (red) and the reference one (black), 11-August-2016.

**Fig. 11.** Correlation between increase of electrical efficiency and the ON/OFF cycles.

The experimental tests were performed between 9am and 5pm. The ambient temperature varied between 21 and 37 ºC and the irradiance between 500 and 1100 $W/m^2$. As expected, the longer the water circulates the higher the efficiency is.

One fact verified during the experiments was the influence of the wind in the closed water cycle. The water that falls on the panel eventually leaves the circuit and is thus lost. Evaporation is the most critical part to estimate since it depends mostly on the wind, which is always changing. After several tests with different ON/OFF cycles it was verified that these losses can vary between 10 and 25 litters/h for a range of wind speeds up to 6 m/s.

**Fig. 12.** Example of experimental and theoretical PV temperature for a ON/OFF cooling cycle.
To validate the analytical model, comparison between the experimental and estimated temperature was done. In Fig. 13 is presented the experimental and estimated results for the PV temperature, with a different ON/OFF cycle every hour, on 9th of August of 2016. The theoretical model is capable of predicting the behavior of the PV temperature for different cycles of ON/OFF and for different ambient temperatures and solar radiances.

The experimental tests showed that a minimum of 2 minutes is required with the system switched ON so that the panel is completely cooled.

VI. ECONOMIC ANALYSIS

The different scenarios for economic analysis will be based on the initial investment costs, the operating costs and the income obtained by the surplus of energy produced. Two case studies were analyzed for a PV power plant with 5 strings, each one with 25 panels, located in: a) Lisbon, Portugal and b) Barreiras, Brazil.

A. Fixed Costs

The fixed costs of the water cooling system were considered the same for both case studies. Using the same cost of materials as the ones used in the prototype installed in the RESUL park, one can calculate the total fixed costs for each case studied, Table III.

The material costs depend on the number of strings to be cooled. This value decreases, per string, as more strings are considered.

B. Case study: Portugal, Lisbon data - 2015

In the first case study, it was considered a solar power plant located in Lisbon, Portugal. To compute the total energy produced, with and without the cooling system, data provided by the Instituto Superior Técnico, University of Lisbon, meteorological institute with the hourly average ambient temperature and solar irradiation was considered for the whole year of 2015.

1) Variable costs

For the variable costs the following considerations were made.

- The system operates whenever the panel temperature exceeds 30°C;
- Water losses are 15 liters per hour;
- The tariff of energy sold to the grid, produced by the panels, is 0.266 USD/kWh;
- The energy purchased from the grid to supply the pump is 0.174 USD/kWh;
- The water price is 1.614 USD/m³.

Using the developed thermoelectric model to predict the temperature of the solar panel with and without the cooling system, it was found that the pump would be connected 1912h per year. Therefore, the water and energy annually cost spent by the pump are 43 USD and 82 USD, respectively.

These costs are independent from the number of existing strings, because only one string is cooled at a time.

2) Annual revenue

Table IV shows the revenue results for water cooling system installed in Lisbon, Portugal in 2015. All calculations made are based on a panel without a routine cleaning, which can be considered as the typical operation of panels, due to accumulation of dirt and dust. It was considered a water tank.
installed at ambient temperature.

Since the system is to be assembled in parks already built, and due to the lifetime of PV parks of 25 years, the calculations were performed for a period of 20 years. Fig. 14 shows the financial return after this period of around 17000USD.

Table IV – Annual revenue for Lisbon, 2015. With a tank mounted at ambient temperature.

<table>
<thead>
<tr>
<th>Number of strings</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy production of non-cooled park</td>
<td>MWh</td>
<td>MWh</td>
<td>MWh</td>
<td>MWh</td>
<td>MWh</td>
</tr>
<tr>
<td>Increase of energy</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Annual income increase</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
</tr>
<tr>
<td>Annual water and energy costs</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
</tr>
<tr>
<td>Annual revenue</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
</tr>
</tbody>
</table>

Fig. 14. Financial return after 20 years for case study of Lisbon, Portugal, 2015.

Additionally, there is the case in which the tank is buried underground, and therefore the water temperature is lower and remains almost constant along the year. In the particular case of Lisbon, it was verified that the increase in energy is almost the same, however, this was not observed for regions with a higher ambient temperature.

To maximize profit, it is necessary to calculate the optimal number of strings that should be cooled by one water pump. Fig. 16 shows from which number of strings it compensates to use a second pump, i.e., two independent strings with different cooling systems. For this case, one pump refrigerating 5 strings still has a higher revenue than two pumps cooling 5 strings (one pump cooling 2 strings and the other 3 strings).

Table V – Annual revenue for Barreiras, Brazil, 2016. With a tank mounted at ambient temperature.

<table>
<thead>
<tr>
<th>Number of strings</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy production of non-cooled park</td>
<td>MWh</td>
<td>MWh</td>
<td>MWh</td>
<td>MWh</td>
<td>MWh</td>
</tr>
<tr>
<td>Increase of energy</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Annual income increase</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
</tr>
<tr>
<td>Annual water and energy costs</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
</tr>
<tr>
<td>Annual revenue</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
<td>USD</td>
</tr>
</tbody>
</table>

Fig. 16. Optimal number of strings for one pump (case study of Lisbon, Portugal, 2015).

C. Case study: Barreiras, Brazil, 2016

Considering other locations for the system, it was chosen Barreiras, Bahia, Brazil, due to its different ambient temperature and solar irradiations range.

1) Variable costs

All considerations, purchase and sale tariffs were considered the same as in the previous case. For meteorological data of this location, it was found that the pump would be connected 3628h. Therefore, the water and energy annually cost spend by the pump are 83 USD and 147 USD, respectively.

2) Annual revenue

Table V shows the revenue results for water cooling system installed in Barreiras, Brazil in 2016. The calculations were done considering the tank installed at ambient temperature.

Fig. 16 shows the financial return after this period. In this case the financial return would be higher (from 17000USD to 21000USD), which was already expected. The high temperatures reduce the efficiency of the panel, which makes this cooling system more profitable.
In another case, it was considered that the water tank is buried and it is assumed that the water temperature in the tank is 20°C. This configuration allows the cooling temperature to be lower than the previous case and thus has a higher energy gain. The results, are presented in Table VI and Fig. 17.

Table VI – Annual revenue for Barreiras, Brazil, 2016. With a tank buried underground.

<table>
<thead>
<tr>
<th>Number of strings</th>
<th>Energy production of non-cooled park</th>
<th>Increase of energy</th>
<th>Annual income increase</th>
<th>Annual water and energy costs</th>
<th>Annual revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWh MWh MWh MWh MWh</td>
<td>% % % % %</td>
<td>USD USD USD USD USD USD</td>
<td>USD USD USD USD USD USD USD</td>
<td>USD USD USD USD USD USD USD</td>
</tr>
<tr>
<td>1</td>
<td>8.09 16.21 24.28 32.38 40.48</td>
<td>22.42 21.27 20.04 18.91 17.87</td>
<td>482 914 1292 1626 1921</td>
<td>240 240 240 240 240</td>
<td>242 674 1052 1386 1681</td>
</tr>
<tr>
<td>2</td>
<td>16.21 24.28 32.38 40.48</td>
<td>21.27 20.04 18.91 17.87</td>
<td>914 1292 1626 1921</td>
<td>240 240 240 240 240</td>
<td>674 1052 1386 1681</td>
</tr>
<tr>
<td>3</td>
<td>24.28 32.38 40.48</td>
<td>20.04 18.91 17.87</td>
<td>1292 1626 1921</td>
<td>240 240 240 240 240</td>
<td>1052 1386 1681</td>
</tr>
<tr>
<td>4</td>
<td>32.38 40.48</td>
<td>18.91 17.87</td>
<td>1626 1921</td>
<td>240 240 240 240 240</td>
<td>1386 1681</td>
</tr>
<tr>
<td>5</td>
<td>40.48</td>
<td>17.87</td>
<td>1921</td>
<td>240 240 240 240 240</td>
<td>1681</td>
</tr>
</tbody>
</table>

This is the most interesting case for an economic analysis. It is observed that there is a financial return after 1 year and during the PV lifetime it is expected a profit of approximately 32000USD, with 5 strings.

VII. CONCLUSIONS

In the present work, a closed loop water cooling system for photovoltaic (PV) panels is fully designed and implemented with the purpose of increasing their efficiency, by lowering the modules temperatures.

The built system was installed in 5kW of a 20kW solar power plant installed in Lisbon. This consists in a closed loop water cooling system, with an optimized water flow to reduce the water pump fatigue and with an optimized ON/OFF cycle to reduce the operation costs, while maximizing its revenue.

Experimental tests were carried to analyze the influence of the water flow, cooling and heating thermal constants and water cycles (ON/OFF) in the panels temperature and, consequently, in the increase of the PV efficiency. After obtaining the temperature data, a theoretical thermoelectric model was developed to simulate the temperature of the panel when cooled, under different ambient conditions and water ON/OFF cycles. The model can predict the PV cooled temperature with available data from meteorological institutes, with sufficient accuracy.

With the developed model, two case studies were analyzed: for the system installed in Lisbon, Portugal, and installed in Barreiras, Brazil. Results shows that the cooling system is paid after 2 years and have a 20-years revenue of 17000USD, for the case of Lisbon, and it is paid in 1 year and with a 20-years revenue of around 32000USD. Therefore, it was concluded that the system is economically viable even for different world locations.

REFERENCES


