Development and economic assessment of an automatic cooling system prototype for a 20kW PV solar park to augment its energy efficiency

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This dissertation is lovingly dedicated to my mother.
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Resumo
A energia proveniente de sistemas fotovoltaicos é cada vez maior e é por isso importante que haja um aproveitamento máximo da mesma. Um dos maiores problemas associados é a diminuição de rendimento associado à elevada temperatura. Ao longo do tempo têm sido testados novos materiais e a eficiência das células fotovoltaicas “tradicionais” são cada vez maiores, mas o pico de produção é durante o período das 12h-14h, precisamente quando a temperatura também é mais elevada.

Como resposta a este problema atual, foi desenhado e construído um protótipo de refrigeração a água que visa reduzir a temperatura do painel e por sua vez aumentar a produção de energia do mesmo. Este sistema é constituído por um tanque, bomba hidráulica e tubagens, em que a água cobre a superfície total do painel e retorna ao tanque realizando assim um ciclo fechado.

De forma a testar o funcionamento do sistema proposto são realizadas experiências em condições reais, assim como simulações em diferentes condições, as quais permitem validar o funcionamento do mesmo. É proposto um modelo teórico de forma a simular outros cenários em diferentes regiões do globo. Por fim é feita uma avaliação econômica a fim de certificar o projeto e verificar a viabilidade de outros locais.

Palavras-chave: sistemas fotovoltaicos, temperatura, rendimento, protótipo de refrigeração
Abstract

The energy from photovoltaic systems is increasing and it is therefore important that there is a maximum use of it. One of the major problems associated is the decrease in yield associated with high temperature. Over time, new materials have been tested and developed and the efficiency of "traditional" photovoltaic cells is increasing, but the peak of production is during the period from 12h to 14h, precisely when the temperature is also higher.

In response to this actual problem, a water-cooling prototype was designed and built to reduce the panel temperature and in turn increase the power output of the panel. This system consists of a tank, hydraulic pump and pipes, performing a closed water cycle, in which covers the entire surface of the panel and returns to the water tank.

In order to test the operation of the proposed system experiments are carried out under real conditions, as well as simulations under different conditions, which allow to validate the operation of the same. A theoretical model is proposed in order to simulate other scenarios in different regions of the globe. Finally, an economic evaluation is performed in order to certify the project and verify the viability of other sites.

Keywords: photovoltaic systems, temperature, efficiency, water-cooling prototype
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Nomenclature

Greek symbols

\[\Delta T\] Temperature variance.
\[\epsilon\] Band gap energy.
\[\gamma\] Constant.
\[\tau_{OFF}\] Heating thermal time constant of the panel.
\[\tau_{ON}\] Cooling thermal time constant of the panel.

Roman symbols

\[A\] Area.
\[B\] Constant.
\[V_T\] Thermal voltage.
\[C_{pump}\] Pump electricity cost.
\[C_{water}\] Water cost.
\[D\] Diffusivity of the minority carrier given for silicon as a function of doping.
\[N_D\] Doping.
\[E_{G0}\] Band gap energy linearly extrapolated to absolute zero.
\[C_{pump}\] Value of cost of energy sold to the grid.
\[FF\] Fill factor.
\[P_m\] Irradiance.
\[h\] Constant.
\[I\] Current.
\[I_0\] Diode maximum reverse saturation current.
\[I_D\] Current that closes through the diode.
$I_{SC}$ Short-circuit current.

$I_s$ Current generated by the beam of light radiation.

$K$ Boltzmann constant.

$k$ Constant.

$L$ Minority carrier diffusion length.

$m$ Diode ideal factor.

$m_e$ Effective masses of electrons.

$m_h$ Effective masses of holes.

$n_i$ Intrinsic carrier concentration given for silicon.

$N_s$ Number of cells in series.

$P_m$ Maximum output power.

$PV$ Photovoltaic.

$q$ Electron electric charge.

$q$ Electronic charge.

$R_1$ Annual revenue for case of a conventional pump.

$R_2$ Annual revenue for case of a solar pump.

$T$ Temperature.

$T_c$ Cell temperature.

$T_{amb}$ Ambient temperature.

$T_{cooling}$ Panel temperature when it is being cooled.

$T_{heating}$ Panel temperature when it is heating up.

$t_{OFF}$ Time that the panel is not being cooled.

$t_{ON}$ Time that the panel is being cooled.

$T_{PV\,cool}$ Final panel temperature when cooled.

$T_{PV\,n\,cool}$ Theoretical panel temperature.

$V$ Voltage at cell terminals.

$V_{oc}$ Open-circuit voltage.

**Superscripts**

$r$ Reference values.
Chapter 1

Introduction

The purpose of this work is to assemble, do the experimental evaluation and study the economic viability of a prototype of an automatic cooling system to improve energy efficiency of photovoltaic panels in a 20 kW solar park, which is located in the company facilities (Resul S.A.).

The aim is to cool the solar panels, using water as refrigerator, to increase their efficiency. With the increase of temperature in solar cells the output voltage decreases which in turn decreases the output power. Thus, decreasing the temperatures allows the panels to produce more energy for the same available area.

At the end of this process it is necessary to check the viability of the system, i.e., one must take into account whether the panels efficiency gain outweighs the water losses; and the electricity expenditure associated with the operation of the hydraulic pump.

1.1 Motivation

Although there has been some analysis in cooling systems of PV using water [1, 2, 3, 4, 5, 6, 7, 8] there are few available complete descriptions of experimental prototypes and its economics feasibility analysis based on the experimental tests and on theoretical model simulation.

The performance of PV (photovoltaic) module is strongly dependent on its operating temperature. Most of the energy absorbed by the panel is converted to heat which is lost in a conventional PV with no value. The negative effect of high operation temperatures on conversion efficiency at crystalline silicon-based solar cells is well known in the literature. The voltage is highly dependent on the temperature and an increase in temperature will decrease the voltage, and therefore, the output power. Besides this, cleaning a PV panel can increase the power output up to 5% in normal conditions. This has special importance during the months of summer, when the radiation is at its maximum, but the output power of a panel can stagnate due to its temperature increase.

1.2 Objectives

Thesis objectives consists of the following points:
• The study of the energy efficiency enhancement system installation of a 20 kW PV park located in Resul;

• Experimental validation of the photovoltaic panels' thermal model;

• Economic feasibility study of the energy efficiency enhancement system for 20 kW park;

• Implementation of an optimization energy efficiency algorithm based on the provided atmospheric conditions;

1.3 Thesis Outline

The present dissertation is divided in 7 chapters. For a better understanding, the structure is presented in the Table 1.1 where the content of each chapter is described.

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   - Theoretical simulations and its validation. |
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| Chapter 7 | - Conclusions and suggestions for future work. |
Chapter 2

State-of-the-art

Solar energy is a clean, inexhaustible, renewable source of energy that is growing since the last century and it is now a major target of investment and research [9]. The sun emits more energy to earth in 20 minutes than all that is consumed by the world population in one year.

Photovoltaics has been growing exponentially, as can be seen in Figure 2.1, for more than two decades. Photovoltaics (PV) has evolved from a pure niche market of small scale applications towards becoming one of the main sources of energy [10, 11, 12, 13]. As a consequence, the cost of solar PV declined significantly due to improvements in technology and economies of scale, and in few years the price will become competitive with conventional energy sources.

![Cumulative capacity in megawatts [MWp] grouped by region](image)

Figure 2.1: Worldwide growth of photovoltaics.

Currently, in Europe, Solar PV contributes 7.9% and 7.0% to the respective annual domestic con-
sumption in Italy and Germany [14]. According to International Energy Agency (IEA), the sun could be the world’s largest source of electricity by 2050, ahead of fossil fuels, wind, hydro and nuclear [15].

Portugal is one of the European countries with the largest annual global index of solar radiation - \(1650 \pm 150 \text{ kWh/m}^2\) and with an annual average of 2500 hours of sunshine, Figure 2.2.

![Global horizontal irradiation - Portugal](https://solaris.data/solaris.info/)

Figure 2.2: Global horizontal irradiation - Portugal [9].

Given this, Portugal has a huge capacity to produce solar energy, especially in locations such as Alentejo and Algarve. Currently the most important photovoltaic plant in the country is located in the district of Beja, in Amareleja, and has 46,41 MW, enough to feed 30,000 homes.

The main problem of the installed parks is the low efficiency of the solar cells. Currently, the domestic photovoltaic cells are of the order conversion efficiency of 16% (mean value – 10%). There are solar cells with efficiencies up to 46% [16], but their high cost limits the production exclusively for use in space industry. However these values are determined based on tests done in controlled environments laboratories (irradiance=1000 W/m\(^2\) and ambient temperature=25\(^\circ\)C), which are difficult to obtain in natural environment. The negative effect in high operating temperature on conversion efficiency at crystalline silicon-based solar cells is well known [17].

This thesis is a continuation of a previous work [18] which was done in IST rooftop, Figure 2.3, but never implemented in a PV park.
2.1 Boosting PV efficiency

There are several ways of obtaining the maximum possible output power from a PV panel. This can be made by changing its position, cleaning or cooling it, among other techniques.

2.1.1 PV Panel - Cleaning

Accumulation of dirt or particles on the surface of solar photovoltaic panel obstruct or reflect light energy from reaching the solar cells and this is a major problem since the light obstruction materials pose as external resistances that reduce solar photovoltaic performance. Although the PVs routine cleaning are important to ensure the proper functioning of the panel, these are not as regular as they should. The cooling system proposed in this thesis also performs this work.

An experiment was done by comparing a clean panel and a panel covered with talcum, dust, sand and moss. According to Figure 2.4, the output power of the 50 W solar panel (with irradiance=310 W/m²) decreased between 9-31%, due to the effects of presence of talcum, between 60-70%, due to dust, between 70-80%, due to sand, and between 77-83% due to moss [19].
To overcome these problems, a proper maintenance operation for the solar panels would be necessary. Particles like dust and sand can be reduced naturally when washed away by rain, but for moss proper cleaning would be required.

2.1.2 PV Panel - Position

Fixed Orientation

To intercept the maximum sunlight, a PV panel must be positioned so that the incoming sunlight arrive at the panel vertically. If not, it does not produce as much power as it could. In many applications, fixed installations or installations where tilt angle can be adjusted manually are used. In such cases maximum power production can be achieved if the optimal values of tilt and azimuth angles can be determined, depending on it’s location.

Several papers show that there are models that correlate tilt angle and orientation with mean global irradiance and its variance on tilted surfaces, [20] [21]. Mehleri et al. work uses both well-established mathematical models and data collected from the area where the PV panels will be installed (Athens, Greece in this case). Kacira et al. did also a mathematical model to estimate the total solar radiation on the tilted PV surface. The optimum tilt angles were determined by searching for the values of angles for which the total radiation on the PV surface was maximum for the period studied. Figure 2.5 shows that the angle changes throughout the year with its minimum value in June and maximum value in December.
Unfixed Orientation

Other form of choosing position are solar trackers, Figure 2.6. Solar tracker is a device that orients a payload toward the sun. It is common to see in solar panels, parabolic troughs, fresnel reflectors, etc.

For flat-panel PV system, trackers are used to minimize the angle of incidence between the incoming sunlight and a photovoltaic panel. This increases the amount of energy produced from a fixed amount of installed power generating capacity. This increase can be as much as 30%, depending on the geographic location. Other advantage is that solar trackers generate more electricity in roughly the same amount of space needed for fixed tilt systems, making them ideal for optimizing land usage.

On the other hand, they are slightly more expensive than their stationary counterparts, due to the more complex technology and moving parts necessary for their operation. Even with the advancements in reliability there is generally more maintenance required than a traditional fixed rack, [22] [23].
2.1.3 PV Panel - Cooling

In the past years studies were developed that demonstrate the efficiency that can be gained by cooling the panels using different methods.

Front Surface Water Cooling

Just like the work proposed in this thesis, similar experiments have been referred. Krater et al. [2] made a comparison in terms of efficiency, using two PV panels, one with a cooling system and the other without. It was used a method of reducing reflection with a thin (1 mm) film of water running over the face of the panel. Yet water has some good properties for reducing the optical loss as with a refractive index of 1.3, it is a viable intermediary between glass and air, which have refractive indexes of 1.5 and 1.0, respectively. It was also mentioned “solar radiation hitting a glass encapsulated or laminated PV-module at a perpendicular incidence angle yields a reflection loss in the range of 4–5%”.

In this study was concluded that water reduces reflection by 2-3.6% and decreases cell temperatures up to 22°C, as depicted in Figure 2.7, and so a system like this can have a net-gain of 8-9% even when subtracting the power needed to run the pump. K.A. Moharram et al[1] concluded the possibility to cool and clean the PV panels using the proposed cooling system in hot and dusty regions.

Figure 2.7: Comparison of cell temperatures between a conventional PV module vs. a PV module with water flow [1].

Back Surface Water Cooling

Bahaidarah et al. [3] made a performance evaluation of a PV module by back surface water cooling. The experimental setup was a hybrid system composed of a PV module combined with a solar thermal collector in it’s back surface.
This study concluded that solar thermal collector underside of the PV panel captures the waste heat from the panel, producing hot water and increasing electrical power, and so there is an increasing in the overall power produced. In this active cooling technique, the operating temperature of the module dropped to about 20% and there was an increase of 9% in the electrical efficiency. Lastly energy collection (electrical plus heating) with the hybrid PV system is higher (nearly 4 times) than the PV only system. Brogren and Karisson [24] proved that circulating water over the cell at the backside is the most effective way to cool it.

**Floating solar park**

Currently under construction is a 6.3 MW floating solar park in Europe, on the Queen Elizabeth II reservoir at Walton-on-Thames, UK. Since there is water covering the back of the panels, it will allow these PV cells have lower temperatures and thus greater efficiency, [25] [26].
Phase-change materials

Besides active cooling measures, like fluid cooling, there are passive cooling measures based on the latent heat of fusion (phase-change materials, PCM). However, one of the major disadvantages using PCM for operating temperature control is the usually low thermal conductivity. To investigate this process, Japs et al. [27] made a comparison in terms of efficiency between two PV modules, one with an integrated layer of conventional PCM and another with improved PCM (called PCM+, which has a higher thermal conductivity) as depicted in Figure 2.10. In addition, an identical bare module was also used as a reference. The result was that the modules equipped with PCM+ layer showed a more favorable temperature development during the morning hours compared to a regular module or a PCM module.

![Figure 2.10: Krater’s experiment with three different layers [22].](image)

This experience had a total duration of one month. Although the paper does not demonstrate efficiency values, they conclude that the module with PCM+ layer is most appropriate in comparison to the other PCM module. In spite of the results (especially during the morning) were promising, as the study was done in terms of energy prices, they conclude that the results were negative in terms of profitability. Currently this type of configuration is not feasible. Nevertheless this technology still have challenges and stimulating opportunities for future research, [4].

Transparent silicon overlay

Shanhui Fan et al. [28] have developed a transparent silicon overlay that can increase the efficiency of solar cells by keeping them cool. The solution is based on a thin, patterned silica material laid on top of a traditional solar cell.

The cover collects and then radiates heat directly into space, without interfering with incoming photons. It collects and then radiates heat as infrared electromagnetic waves, which can easily travel through the atmosphere. The coating allowed visible light to pass through so it won’t interfere with the solar cell’s light collecting ability and improves on the heat dissipation of the silicon cells.

According to the study results, this material can cool the underlying absorber by as much as 23°C, [29].
Chapter 3

Photovoltaic system

Silicon cells can be constituted of monocrystalline, polycrystalline or amorphous silicon crystals.

Multicrystalline cells have lower production costs, although they also achieve lower electric efficiency values than monocrystalline cells. This is because the uniformity of the molecular structure resulting from the use of a single crystal is ideal for enhancing the photovoltaic effect; the discontinuities of the molecular structure of the polycrystalline silicon make the movement of electrons difficult, which reduces the output power [30].

3.1 The photovoltaic effect

The photovoltaic effect corresponds to the creation of a voltage or electric current in a material after its exposure to sunlight. The basic working principle of silicon cells is simple. When a photon of solar radiation containing enough energy strikes an electron from the valence band, it moves to the conduction band, leaving a hole in its place, which behaves as a positive charge. Through the process of silicon doping, it is possible to create two layers in the cell, thus having a layer with an excess of positive charges and another with an excess of negative charges. In the region where the two materials meet, an electric field is created that separates the cargo carriers that reach it. By connecting the terminals to a circuit that is externally closed through a load, an electric current DC will circulate.

PV panels are composed of photovoltaic modules which in turn consist of silicon solar cells, as seen in Figure 3.1.
Silicon is the second most abundant element in the earth’s crust and is a semiconductor material, however it needs a doping process in order to become a good conductor. The doping process leads to each silicon cell of the photovoltaic modules being composed of a thin layer of material of type N (material with free negative charges - electrons) and another with material of type P (material with free positive charges), which when attached create an electric field in the region of the so-called PN junction. Thus, when photons strike the cell and collide with the electrons, they provide them with energy and these, due to the presence of the electric field at the junction, are driven from the P (positive electric charge) layer to the N (negative electric charge) layer. Over time there is a natural tendency of the electrons injected into the N layer to invert the direction of the electric field in order to achieve a balance between the number of electrons travelling to the N joint, but this number is gradually smaller, as the amount of energy required to move the electrons will increase.

Through this process, the open circuit voltage is generated at the terminals of the cell as well as a circulating current in case an electric receiver is connected to these terminals. This is responsible for the decrease in the number of injected electrons in the P zone, thus contributing to the electric field inversion, which is why the voltage to the cell terminals decreases as the current increases. The value of the current that is generated depends on the intensity of the incident light.

The creation of Maximum Power Point Tracking (MPPT) systems, which allow the regulation of PV power and the energy flow between the panel and the load, is justified by the need to maximize PV performance. Thus, in order to take advantage of their capacities in total, these systems use electronic power converters, which allow to extract at each instant the maximum possible power. In order to obtain higher generation powers, the PVS are constructed through the association of modules in series and in parallel.

### 3.2 Temperature dependence of the energy bandgap

Energy band gap is usually referred to the energy difference between the conduction band and the valence band. The conduction band is the outermost energy band where the free electrons lie and below that there is the valence band, Figure 3.2. An electron residing in the valence band cannot jump to the
conduction band until and unless it is provided the amount of energy needed for the electron to cross the energy barrier between those bands, which is called the band gap energy. As soon as the electron is provided energy equal or greater than the band gap energy, it can go to the conduction band, become a free electron which is the main reason for the high conductivity of metals.

Figure 3.2: Semiconductor band structure [Wikipedia].

The energy bandgap of semiconductors tends to decrease as the temperature is increased. This behaviour can be better understood if one considers that the interatomic spacing increases when the amplitude of the atomic vibrations increases due to the increased thermal energy. This effect is quantified by the linear expansion coefficient of a material. An increased interatomic spacing decreases the potential seen by the electrons in the material, which in turn reduces the size of the energy bandgap. A direct modulation of the interatomic distance, such as by applying high compressive (tensile) stress, also causes an increase (decrease) of the bandgap.

The temperature dependence of the energy bandgap has been experimentally determined yielding the following expression for $E_g$ as a function of the temperature $T$:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$  \hspace{1cm} (3.1)

where $E_g(0)$, $\alpha$ and $\beta$ are the fitting parameters. These fitting parameters are listed in Table 3.1.

Table 3.1: Silicon fitting parameters

<table>
<thead>
<tr>
<th>$E_g(0)$ [eV]</th>
<th>$\alpha$ [eV/K]</th>
<th>$\beta$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>1.166</td>
<td>4.73 $\times$ 10^{-4}</td>
</tr>
</tbody>
</table>
3.3 Theoretical model

3.3.1 Establishment of the model

The photovoltaic cells and their operation can be represented by different models, being the most common: the diode and three parameters model, which is simpler, and the diode model and five parameters, which, due to their greater complexity, presents values closer to reality. However, due to the differences in results obtained being practically insignificant, one will present only the simplest model. In terms of a simplified mathematical model, a cell can be described through the equivalent electrical circuit shown in Figure 3.3.

![Figure 3.3: Equivalent electrical circuit of a photovoltaic cell feeding a load Z [31].](image)

The current source $I_s$ represents the electric current generated by the beam of light radiation, consisting of photons, upon reaching the active surface of the cell (photovoltaic effect); This unidirectional current is constant for a given incident radiation. The junction p-n functions as a diode that is traversed by a unidirectional internal current $I_D$, which depends on the voltage $V$ at the terminals of the cell.

The current $I_D$ that closes through the diode is in equation 3.2.

$$I_D = I_0(e^{V_mVT} - 1) \quad (3.2)$$

In which are the terms:

- $I_0$ - Diode maximum reverse saturation current
- $V$ - Voltage at the cell terminals
- $m$ - Diode ideal factor (ideal diode: $m=1$, real diode: $m>1$)
- $V_T$ - Thermal voltage, $V_T = \frac{KT}{q}$
  - $K$: Boltzmann constant ($K = 1,38 \times 10^{-23} \text{ J/}^\circ \text{K}$)
  - $T$: Absolute temperature of the cell in K ($0^\circ = 273,16^\circ \text{K}$)
  - $q$: Electron electric charge (module) ($q = 1,6 \times 10^{-19} \text{c}$)

The current $I$ that closes by the load is therefore, equation 3.3.

$$I = I_s - I_D = I_s - I_0(e^{\frac{V}{V_T}} - 1) \quad (3.3)$$

At this point there are two points of operation of the cell deserve particular attention:
• Short-Circuit, in which:

\[ V = 0 \]

\[ I_D = 0 \]

\[ I = I_s = I_{SC} \]

The short-circuit current \( I_{SC} \) is the maximum value of the load current, equal to the current generated by the photovoltaic effect. Its value is a characteristic of the cell, being a data supplied by the manufacturer for certain incident radiation and temperature conditions.

• Open-Circuit, in which:

\[ I = 0 \]

\[ V_{oc} = mV_Tln(1 + \frac{I_s}{I_0}) \]

The open circuit voltage \( V_{oc} \) is the maximum value of the voltage at the terminals of the cell, which occurs when the cell is empty. Its value is a characteristic of the cell, being supplied in the panel datasheet.

3.3.2 Influence of external factors

The parameters of the model are calculated in Standard Test Conditions (STC), which is an industry-wide standard to indicate the performance of PV modules and specifies a cell temperature of 25° C and an irradiance of 1000 W/m² with an air mass 1.5 (AM1.5) spectrum. However, these are not always verified and it is necessary to analyse the influence of external factors on the different variables of the electric model of the photovoltaic cell. Due to the influence of the meteorological conditions in the parameters of the model it is necessary an adaptation of the equations previously presented in order to obtain values closer to the reality of each moment.

Temperature and irradiance correspond to the factors with the greatest impact on the performance of a PV and on the parameters of the model. For this reason, graphs with an I-V curve are presented in the PV catalogs, where the influence of these same factors on their performance is represented.

The influence of temperature and irradiance on the power of a PV can be seen in Figures 3.4 and 3.5, respectively.
As can be seen, the irradiance has a predominant influence on the maximum current that the panel can provide, and in turn the temperature is responsible for determining the maximum voltage value. It is then verified that the short-circuit current varies linearly with the incident irradiance, being little influenced by the temperature. While the inverse saturation current of the diode is essentially influenced by the temperature at which the cell is present and the characteristics of the material, it is possible to obtain its value from equation 3.4.

$$I_0 = I_0^s \left( \frac{T_c}{T_s} \right)^{\frac{q}{kT}} e^{\frac{q}{kT}}$$

(3.4)

In which parameters have the meaning:

- $\epsilon$ is the band gap energy.
• $N_s$ is the number of cells in series.

• $T_c$ is the cell temperature (in K).

• $r$ corresponds to reference values.

Since $V_{oc}$ depends on $I_0$, it is concluded that this is dependent on the temperature of the cell.

### 3.4 Effect of temperature on a solar cell

Solar cells are sensitive to temperature like all other semiconductor devices. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap. In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the Figures 3.7 and 3.6.

![Figure 3.6: The effect of temperature on relation Power/Voltage](image1)

![Figure 3.7: The effect of temperature on the I-V characteristics of a solar cell](image2)
The open-circuit voltage decreases with temperature because of the temperature dependence of \( I_0 \). The equation for \( I_0 \) from one side of a p-n junction is given by equation 3.5.

\[
I_0 = qA \frac{Dn_i^2}{LN_D}
\]  

(3.5)

In which:

- \( q \) is the electronic charge;
- \( A \) is the area;
- \( D \) is the diffusivity of the minority carrier given for silicon as a function of doping;
- \( L \) is the minority carrier diffusion length;
- \( N_D \) is the doping;
- \( n_i \) is the intrinsic carrier concentration given for silicon.

In the above equation, many of the parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, \( n_i \). The intrinsic carrier concentration depends on the band gap energy (with lower band gaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations). The equation 3.6 shows the intrinsic carrier concentration.

\[
n_i^2 = 4 \left( \frac{2\pi kT}{h^2} \right)^3 \left(m_e^* m_h^* \right)^{3/2} \exp \left( \frac{-E_{G0}}{kT} \right) = BT^3 \exp \left( \frac{-E_{G0}}{kT} \right)
\]  

(3.6)

In which:

- \( T \) is the temperature;
- \( h \) and \( k \) are constants;
- \( m_e \) and \( m_h \) are the effective masses of electrons and holes respectively;
- \( E_{G0} \) is the band gap linearly extrapolated to absolute zero
- \( B \) is a constant which is essentially independent of temperature.

Substituting these equations back into the expression for \( I_0 \), and assuming that the temperature dependencies of the other parameters can be neglected, gives equation 3.7.

\[
I_0 = qA \frac{D}{LN_D} BT^3 \exp \left( \frac{-E_{G0}}{kT} \right) \approx B' T^\gamma \exp \left( \frac{-E_{G0}}{kT} \right)
\]  

(3.7)

where \( B' \) is a temperature independent constant. A constant, \( \gamma \), is used instead of the number 3 to incorporate the possible temperature dependencies of the other material parameters. For silicon solar cells near room temperature, \( I_0 \) approximately doubles for every 10°C increase in temperature.
The impact of $I_0$ on the open-circuit voltage can be calculated by substituting the equation for $I_0$ into the equation for $V_{oc}$ as shown in equation 3.8.

\[
V_{OC} = \frac{kT}{q} \ln \left( \frac{I_{SC}}{I_0} \right) = \frac{kT}{q} \left[ \ln I_{SC} - \ln I_0 \right] = \frac{kT}{q} \ln I_{SC} - \frac{kT}{q} \ln \left[ B' T^{\gamma} \exp \left( -\frac{qV_{G0}}{kT} \right) \right]
\]  

(3.8)

where $E_{G0} = qV_{G0}$. Assuming that $dV_{oc}/dT$ does not depend on $dI_{sc}/dT$, $dV_{oc}/dT$ can be found in equation 3.9.

\[
d\frac{V_{OC}}{dT} = \frac{V_{G0} - V_{OC} + \gamma \frac{kT}{T}}{T} \approx -2,2 mV/°C for Si
\]  

(3.9)

The above equation shows that the temperature sensitivity of a solar cell depends on the open circuit voltage of the solar cell, with higher voltage solar cells being less affected by temperature. For silicon, $E_{G0}$ is 1.2, and using $\gamma$ as 3 gives a reduction in the open-circuit voltage of about $2.2 \text{ mV/°C}$, equation 3.10.

\[
d\frac{V_{OC}}{dT} = \frac{V_{G0} - V_{OC} + \gamma \frac{kT}{T}}{T} \approx -2,2 \text{mV/°C for Si}
\]  

(3.10)

The short-circuit current, $I_{sc}$, increases slightly with temperature, since the band gap energy, $E_G$, decreases and more photons have enough energy to create e-h pairs. However, this is a small effect and the temperature dependence of the short-circuit current from a silicon solar cell is in equation 3.11.

\[
\frac{1}{I_{SC}} \frac{dI_{SC}}{dT} \approx 0,0006 \text{per °C for Si}
\]  

(3.11)

The temperature dependency FF for silicon is approximated by the following equation 3.12.

\[
\frac{1}{FF} \frac{dFF}{dT} \approx \left( \frac{1}{V_{OC}} \frac{dV_{OC}}{dT} - \frac{1}{T} \right) \approx -0.0015 \text{per °C for Si}
\]  

(3.12)

The effect of temperature on the maximum power output, $P_m$, is in equation 3.14.

\[
\frac{1}{P_m} \frac{dP_m}{dT} = \frac{1}{V_{OC}} \frac{dV_{OC}}{dT} + \frac{1}{FF} \frac{dFF}{dT} + \frac{1}{I_{SC}} \frac{dI_{SC}}{dT}
\]  

(3.13)

\[
\frac{1}{P_m} \frac{dP_m}{dT} \approx -(0.004 to 0.005) \text{per °C for Si}
\]  

(3.14)

These results corroborate with the information provided by the manufacturers datasheet.
Chapter 4

Cooling system design

4.1 Concept of the cooling system

The cooling system consists in a closed-loop water cooling system which reduces the PV surface temperature to increase its efficiency and uses a set of valves to optimize the water flow, Figure 4.1. The main purpose is to cool the PVs with a uniform layer of water to lower its surface temperature and to create a refractive layer. With a refractive layer it is possible to decrease the solar radiation reflected by the glass layer (refractive index: 1.3 to water and 1.5 to glass).

The water used by the system is stored in a tank which can be at ambient temperature or buried on the ground, 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:

1. 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 Figure 4.1) is installed and only one operates at one time. With this, the water pump flow remains constant.

2. The optimization of the water flow:

   From previous studies [18], it was verified that the thermal constant of the PV cooling is much higher than the 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 Figure 4.2. With this process, the water pump can be dimensioned for only one string, reducing the investment and operating costs of the system.
4.2 Location

In Figure 4.3 is shown the 20 kW photovoltaic installation installed at the roof of Resul’s office building at Bobadela, Lisbon, Portugal. The already existing PV installation consists of 8 rows of panels, 6 of those of mono-crystalline and 2 of those of polycrystalline type, as shown in Figure 4.4. Each monocrystalline and polycrystalline PV panel has a nominal power of 190 W and 225 W, respectively.

The solar power plant consists of four 5 kW PV strings, each one formed by 2 rows, composed of 25 panels in series.
4.3 Inverters connection

There are 2 inverters in site, each one connected to 2 strings. Each inverter has the information of its strings in a separate log, allowing to compare the data between them individually. With this configuration is possible to compare the power produced by each string.

4.4 Implementation

To minimize the investment, the adequate components had to be bought to build this full-scale water cooling system. After investigation, it was concluded that it was necessary to buy an electrical pump, sprinklers, plastic water resistant sheeting and medium-density fibreboard (for the tank construction), pipe networks like elbows, T-junctions, bends, contractions, expansions, pvc pipes, one controlled valve, two manual valves, and other auxiliary materials.
4.4.1 Hydraulic subsystem

The main purpose was to spray water over the panels in a continuous and uniform way (intended to create a uniform layer so that the refractive index is 1.3) using a closed-loop water circuit, Figure 4.5. The water was stored in a water tank at ambient temperature and, with a pump, was conducted to the upper part of the panels (33° inclination). Through sprinklers, the water was sprayed at low pressure, from the top of the panels. There were three sprinklers in each panel in order to cover the all surface. After going through them, the water was collected at the end of PVs by PVC gutters and went back into the tank (through gravity force). In this case the rooftop was inclined along the PV strings, which helped the circulation of the water back to the tank. The escape valve in Figure 4.5 simulates the presence of other PV strings being cooled, i.e., when the controlled valve is closed, maintaining the water pump flow.

The hydraulic system’s configuration solves different problems, specifically:

- The pump can work in a continuous way, so it doesn’t have to start and stop. This protects it from fast deterioration and avoids the high electric energy consumption during the startup phase. This is important when implementing for a larger PV parks. In these cases, the water will be redirected to different strings for specific time intervals without having to start and stop the pump.

- The controlled valve allows specifying the ON and OFF time intervals as desired. At this point the system is cooling simultaneously two rows (one string). It can increase in size, just by directing the water flow to the nearby PV rows when the system for the first two rows is in OFF state, instead of returning it directly to the water tank.

- The fact that water is always circulating in the circuit minimizes its heating. The manual valve 1 allows to close the circuit at the beginning in case of any problems with the pipes.
Initially water was pumped over one string (String 2) of 25 panels, Figure 4.4, where the time interval during which the sprinklers are turned ON/OFF is controlled by an electric valve. The water ratio will be optimized in order to minimize the consumption of water and keep the panels cooled. Another string (String 1), Figure 4.4, which is located near this circuit, will be used as a reference for checking the difference of power that each string produces when the panels are cooled.

After all is assembled it is possible to see the overall scheme in Figures 4.6 and 4.7.

Figure 4.6: Water-cooling prototype (overall), identifying the sprinklers and PVC gutters.

Figure 4.7: Sprinklers spraying water at the top of the panel.

In order to assemble the sprinklers, a drip irrigation tube was purchased and then equally spaced holes were drilled to screw the sprinklers. Small aluminium plates were also manually made and shaped to attach the tube to the top of the panels.

It is necessary to check if this process is profitable. All the water losses in the process must be taken into consideration: water retained in the pipes, water evaporation in peak hours and the excessive wind that can drive the water out of the panels are the main issues. The power needed to run the water pump should also be taken into account due to the cost of electricity.
4.4.2 Water tank

At the rooftop of Resul company the only available location for the water tank to be installed was an area with a width of 25 cm and a height of 27 cm. This configuration created three major issues:

1. It was not possible to find commercial tanks with those dimensions.
2. The tank must be wide enough to fit the hydraulic pump.
3. Despite its size, the tank should be closed to avoid water contamination and warming up.

This problem was solved by buying waterproof mDF boards with the right dimensions of the site, screws, and building the tank. The materials choice was due to its properties, preventing it from rotting. In order to avoid any leakage, it was also placed a water resistant sheet inside the tank. The final result can be seen in Figures 4.8 and 4.9. The water is stored in a 150 L water tank.

![Figure 4.8: Water tank, without the water resistant sheet.](image1)

![Figure 4.9: Water tank (on site).](image2)
4.4.3 Pump

From a previous work [18], it was concluded that a 250 W pump should meet the requirements for height and water flow. Unfortunately, given the space to install the water tank, the only available pump to cover these requirements was the high consumption 750 W DOC 7 by Lowara. But since this installation’s purpose is to verify the energy increase in the production and not to be energy efficient, that flow was considered unimportant. For ground installations, higher tanks (more than 0.5 m) can be used and cheap, 250 W pumps exist that meet the requirements. Its datasheet is available in the section A.4.

4.4.4 Control panel

The controlled servo-valve operation had to be regulated. For this reason, a control cabinet was introduced into the system, in order to use the asymmetric oscillator RTOAM62301, which allows for controlling the valve’s ON and OFF time periods as desired. This ON/OFF time must be in accordance with the operation of the several strings in parallel. Its datasheet is available in the section A.5.

4.4.5 Water collection system

The water collection system consists of simply large PVC pipes cut in half in the axial direction having an operation as gutters. They were used to collect the water at the bottom of the panels and direct it back to the tank (Figure 4.10). The collection system is essential, since minimum water losses are required to ensure profitability.

![Figure 4.10: PVC gutters to collect water.](image)

4.4.6 Additional enhancements

During the experimental tests it was found that a certain amount of the water was lost between the space between each panel. The solution was to place black, weather-resistant repair tape in the space between the panels.

Another problem noted was the size of the PVC tubes that fit as gutters. These must have a diameter large enough to collect the entire water, as it gains speed when lowering the base of the panel. In addition it must also be able to collect the drips that lie on the bottom of the panel.
In order for the water to have the lowest possible temperature, and also to avoid evaporation, the tank must be closed.

In the long run water needs to be treated in order to guarantee its quality. With the view to avoid this problem, and also so that the tank does not get sediment, filters will be necessary. This point will be further discussed in Chapter 5.

The ultimate goal is to connect an Arduino (or similar) to the electric solenoid valve which receives weather data and thus switch ON/OFF the pump when the panel temperature so justifies. In this way, the entire cooling process would be automated.
Chapter 5

Automatic cooling PV panels:
theoretical and experimental analysis

The prototype built at the rooftop of RESUL company was installed on monocrystalline panels type STP190S - 24/Ad+ from Suntech. The characteristics of the panels can be seen in the appendix in A.1. The most important electrical characteristics are shown in Table 5.1.

<table>
<thead>
<tr>
<th>STC STP190S-24/Ad+</th>
<th>Optimum Operating Voltage (V_{mp})</th>
<th>36,60 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimum Operating Current (I_{mp})</td>
<td>5,20 A</td>
</tr>
<tr>
<td></td>
<td>Open-Circuit Voltage (V_{oc})</td>
<td>45,20 V</td>
</tr>
<tr>
<td></td>
<td>Short-Circuit Current (I_{sc})</td>
<td>5,62 A</td>
</tr>
<tr>
<td></td>
<td>Maximum Power at STC (P_{max})</td>
<td>190 W</td>
</tr>
<tr>
<td></td>
<td>Module Efficiency</td>
<td>14,90%</td>
</tr>
</tbody>
</table>

The monocrystalline panels present a rated power of 190 W and the temperature characteristics are on Table 5.2. Note that the maximum power of the panel decreases with the temperature, -0.45%/°C, i.e., the higher the temperature the lower the efficiency is. Manufacturers make available the Nominal Operating Cell Temperature (NOCT), which represents the temperature reached by the cell under standard operating conditions, defined as T_{amb}=20° C (ambient temperature) and G=800 W/m².

<table>
<thead>
<tr>
<th>Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Operating Cell Temperature (NOTC)</td>
<td>45±2°C</td>
</tr>
<tr>
<td>Temperature Coefficient of P_{max}</td>
<td>-0,45 %/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of V_{oc}</td>
<td>-0,34 %/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of I_{sc}</td>
<td>0,05 %/°C</td>
</tr>
</tbody>
</table>
5.1 Experimental tests

To monitor and measure the panels (module) temperature, two temperature sensors were used, whose operating characteristics are shown in Figure 5.3. These sensors were placed in two different strings, the first in one panel of a cooled string (Figure 5.1) and the other in a panel of a non-cooled string to be the reference.

The sensors used for this operation were the TK-4023 temperature loggers by Tinytag, shown in Figure 5.2.

These sensors come with a temperature probe, which allows fast response monitoring in difficult to access areas. They have a reading range from -40 to 125° C, and specifically for the temperature range of interest, they have an accuracy of 0.4° C, Figure 5.3.

In addition to the data received by the sensors, it was also provided data by the inverters. From the different information that the inverter provides, what was interesting was the average power production,
in intervals of 10 minutes. This information allows one to make a direct and accurate comparison between 2 strings that are under the same weather conditions, but with and without the cooling system.

One particular aspect that must be discussed regarding the location of the panels is the existence of two surrounding buildings, in the north and west of the panels. This fact brings two main consequences:

1. The wind profile is significantly altered when it comes from the north when compared with available online meteorological data;

2. The panels are shadowed during the day, after 16:30-17:00h.

To avoid the effect of shadowing all experimental tests were done before these period, although the temperature of the panels is still high at this point and compensates for system operation.

A typical temperature profile can be seen in the Figure 5.4. As it can be seen, at 31-July-2016, the temperature of the panel presents a significant drop at 16:50h, after the panels are shadowed.

![Figure 5.4: Panel temperature for 31-July-2016.](image)

A series of experiments were made in order to determine the thermal behaviour of the panels. Probes were placed at different spots of the panel surface to measure the temperature profile of the panel. It was found that the panel surface temperature has a small variation across its dimensions. Thus, the panel can be considered to be in a uniform temperature. In the second experiment (3 days of measurements, 30-July-2016 till 1-August-2016, measurements taken every 20 seconds) the two sensors were placed in the front and back of the panel’s surface. The relative temperature difference was 0.55°C (1.9%), as shown in Figure 5.5. It can be seen that the temperature profiles have the same form and which vary not much.
A set of experiments were carried out during the months of August and September with a varied range of ON/OFF cycles. On 24-August-2016 experimental tests were performed with ON/OFF cycles of 30/30 mins, from 13:20h to 17h, as shown in Figure 5.6. When the cooling system is ON, the module temperature decreases from around 55°C to less than 35°C ($\Delta T = 20\, ^\circ C$), which will increase the PV efficiency. It was also verified that the panel cools off in 2 minutes and warms back to the initial temperature in 16 minutes. In Figure 5.7 it is verified that there is a clear increase of power at the time of the cooling (the "ups and downs" refers to the time when the system is ON and OFF respectively). Before the system is in operation, before 13h, there is a slight difference between the cooled and non-cooled string’s power. This was due to the cleaning effect that the cooling system has, which kept the panel cleaned from the previous day, as will be explained below.
Figure 5.7: Power output comparison between a cooled and non-cooled string (24 August).

On 1-September-2016, experimental tests were performed from 13h to 17h with the system always ON. In Figure 5.8 one can verify a 22-23°C decrease in the panel temperature, which translates into a 10% decrease in maximum power according to the panel’s datasheet. While the non-cooled panel temperature is between 55 and 60°C, the cooled panel is at 35°C or below. In Figure 5.9 is shown the data provided by the inverter regarding the cooled and non-cooled strings. There is an increase of power that can go up to 16% in the peak hour, with 27°C ambient temperature and around 800 W/m² of irradiance. Note again that the panel with the cooling system has an higher output power due to the cleaning effect from the previous day.

Figure 5.8: Temperature comparison between a cooled and non-cooled string (1 September).
For 9-August-2016, the temperature profiles for the strings with and without the cooling system are shown in Figure 5.10, with different ON/OFF cycles for different hours. The effect of the decrease of temperature on the cooled panel resulted in an increase of power. In Figure 5.11 it 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 irradiance are typically higher.
As already shown, 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 Figure 5.12, 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, a maximum increase of 17% was measured. In Figure 5.13 are presented the experimental results for the increase of efficiency for different ON/OFF cycles measured during the 3 months of experiments.
The experimental tests were all performed between 10h and 17h. The ambient temperature varied between 21-37°C and the irradiance between 500-1100 W/m². 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. Another 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. 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 liters/h for a range of wind speeds up to 6 m/s.

Even if the ambient temperature is low and the cooling system is not required, the system can be switched once a week to keep the panels cleaned and avoid power decrease due to dirt and dust.

5.1.1 Water flow

The system using sprinklers allows for lower mass flow rates, while still covering the whole PV panel’s surface. At this point it was necessary to realize the minimum flow rate to spend the minimum amount of water. There was an attempt to use different values of mass flow rates in order to verify the dependence of the final temperature of the panel (when cooled). The previous systems design [18] showed that a flow of 50 l/min would be necessary to spread the water uniformly along the panel’s surface.

For this particular case, in the park installed in RESUL, it was verified that the pump was correctly sized for this number of panels, so if the escape valve was opened a little more, the water coming out of the sprinklers had not enough pressure to cover the panels whole area. Each sprinkler had a overall mass flow of 17,86 ml/s which was the minimum flow and so the optimum value. Although the water was loosing pressure along the sprinkler tubing, the flow difference was not significant.
5.1.2 Pump startup

During the startup phase the pump has a current peak which results in a much higher power consumption, as can be consulted in the appendix A.7.

The manufacturer indicates the possible startups number per hour, that are usually around 15. As they would have to be many during the all day, the pump is always on and keeps its operation constant. This number of starts would also shorten the service life of the pump.

5.1.3 Water quality

Over time it was noticed that the water became dirty, with greenery and other debris and dust that usually stayed on top of the panels and flowed with the water. This dirt is not all filtered by the hydraulic pump and accumulates in the pipes over time, ending up clogging the sprinklers. Given this problem there was a need to think of filters in order to maintain quality and ensure the operation of the system. It is also necessary to take into account the properties of the water so that there is no contamination and check the effect of the water on the panels in the long term. After contacting a company specialized in the area, the following solution was offered:

- Anti-Corrosion Filter in order to reduce the harmful effects of limestone and iron (corrosion, incrustation, among others). "Anticale Filter" with recharge of anti-corrosion crystals (every year, 24 €) - to reduce the harmful effects of limestone - costs 60 €;
- Disinfection Filter, to keep water filtered and disinfected (no tastes, odours, suspended matter and no bacteria). Ultraviolet Filter "Aquatec UV Max 600" - eliminates bacteria - costs 340 €;
- Pre-filter at the water suction inlet of the pump to prevent dirt from entering the pipes. "F50 Filter" has an 10" polypropylene cartridge - to eliminate sediment and impurities - and costs 44 €. A replacement charge, which lasts from 6 to 12 months, costs 8 €.

Alternatively chlorine tablets may also be used inside the water tank. These tablets (sisinfectant, algacide, flocculant, stabilizer, bactericide, clarifier, pH controller, rinse aid, descaler and fungicide) cost 38 € for the use of 10 years and therefore are a more economical solution, compared with Anti-Corrosion and Disinfection filters.

5.2 Theoretical analysis

5.2.1 PV panel temperature

The 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 (Ross constant) [33] by irradiance $G$, as it is verified in the equation 5.1.

$$T_{PV} = T_{amb} + kG$$ (5.1)
It is possible to rearrange it into equation 5.2, where NOCT is given by the panel manufacturer in its datasheet. This value is relatively constant, generally ranging from 45 to 47°C.

\[ T_{PV} = T_{amb} + \frac{G(NOCT - 20)}{800} \] (5.2)

As it is possible to verify from Figure 5.14, this model is a good approximation of the actual panel temperature. This approach is relatively accurate in most cases. As can be seen in [34] the prediction of the temperature gives a Root Mean Square Error (RMSE) of 7.5 K for p-Si, 7.2 K for a-Si and 8.0 K for mo-Si panels for 15 minutes averages.

![Figure 5.14: Measured temperature (red) and theoretical temperature (blue).](image)

5.2.2 Cooled PV Panel Temperature

To simulate the ON/OFF water cycles, in order to obtain the optimal cycle of the prototype, the following solution was proposed: by the analysis of the experimental results of the cooled panel temperature, Figure 5.15, it was concluded that these could be approached by exponential transient curves.
These curves enable the calculus of the heating and cooling thermal time constants. The following equations, 5.3 and 5.4, were then deduced. The parameters have the following meaning:

- $T_{PV\,n\,cool}$ corresponds to the theoretical panel temperature.
- $T_{PV\,cool}$ corresponds to the sum of $T_{amb}$ with a $\Delta T$ value. $\Delta T$ varies between 2 and 4 (experimentally set).
- $t_{ON}$ corresponds to time, in minutes, that the panel is being cooled.
- $t_{OFF}$ corresponds to time, in minutes, that the panel is not being cooled.
- $\tau_{ON}$ corresponds to the cooling thermal time constant of the panel, equal to 0.6 minutes (experimentally set).
- $\tau_{OFF}$ corresponds to the heating thermal time constant of the panel, equal to 11 minutes (experimentally set).

\[
T_{cooling} = (T_{PV\,n\,cool} - T_{PV\,cool})e^{-\frac{t}{\tau_{ON}}} + T_{PV\,cool}
\]

(5.3)

\[
T_{heating} = (T_{PV\,n\,cool} - T_{PV\,cool})(1 - e^{-\frac{t}{\tau_{OFF}}}) + T_{PV\,cool}
\]

(5.4)

Equation 5.3 translates the cooling curve of the panel, $T_{cooling}$, while equation 5.4 translates its heating, $T_{heating}$. Through these equations the behaviour of the cooled panel temperature was simulated, Figure 5.16.
Figure 5.16: Validation of the theoretical model.

Through these parameters it is possible to adjust the curves to simulate the real case.

**Comparison of simulations with experimental tests**

To validate the analytical model, comparison between the experimental and estimated temperature was done. On 9-August-2016 tests were carried out for 4h with four different ON/OFF cycles every hour. The tests began at 11:20h and ran until 15:20h, precisely in the hours with the highest ambient temperature. In the theoretical model the same data was inserted and the results overlapped, as shown in Figure 5.17. The theoretical model is capable of predicting the behaviour of the PV temperature for different cycles of ON/OFF and for different ambient temperatures and solar radiations.

Figure 5.17: Comparison between experimental and theoretical data.

As it can be seen, the theoretical results approximate closely to the experimental ones. The fact that they are not perfect aligned at the end of the cooling part can be explained for one reason. In the theoretical model the final temperature is constant, it does not take into account the presence of the wind that influences the panel’s temperature.
It should be noted that this does not happen experimentally as there is always a layer of water on the surface of the panel for a few minutes, and it only begins to heat up when the water fully evaporates.

For this case, Figure 5.17, the mean value of theoretical module temperature is 36.64°C while the measured mean value is 37.87°C. Applying the Standard Deviation formula, the deviation result is 0.6°C. In Figure 5.18 it is possible to see the moving mean for both cases, with a moving mean in 20 in 20 minutes.

![Graph showing theoretical and experimental data comparison.](image)

Figure 5.18: Moving mean comparison between theoretical and experimental data, with moving mean in 20 in 20 minutes.

Table 5.3 shows the average value of the temperature measured during the tests and the simulation result.

Table 5.3: Average value of the panel temperature measured during the tests and its simulation result.

<table>
<thead>
<tr>
<th>Day</th>
<th>09/08/16</th>
<th>11/08/16</th>
<th>24/08/16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental temperature mean (°C)</td>
<td>37.9</td>
<td>38.4</td>
<td>39.9</td>
</tr>
<tr>
<td>Theoretical temperature mean (°C)</td>
<td>36.6</td>
<td>37.1</td>
<td>40.1</td>
</tr>
</tbody>
</table>

As can be seen, the variation is not significant and the maximum value is 1.3°C. Since the average cooling temperature is the desired one, this model is considered to be suitable.
**Influence of the system configuration in energy production**

Once the theoretical model has been confirmed, there is a need to check which cycle will bring greater profitability. Here it is necessary to mention that water is a very important element in terms of costs, so it should be used as little time as possible. Experimental tests showed that it takes at least 2 minutes with the system switched on for the panel to be completely cooled.

In order to perform the tests, it was used meteorological data with a periodicity of 1h, of the ambient temperature and irradiance, from July to September, 2009 to 2013. The data come from the Meteorological Station of Lisbon - Gago Coutinho and therefore is considered to be appropriated for the case study.

Since it is desired to cool the maximum possible number of strings using the same pump, several ON/OFF cycles have been chosen to synchronize their operation. For example, the fact that it is 2 minutes ON and 4 minutes OFF allows the same pump to be used in 3 different strings, as shown in Figure 5.19. With other configuration, for example, of 2 minutes ON and 3 minutes OFF, it would be impossible to synchronize with one single pump.

![Figure 5.19: Example of cooling 3 strings, with 2/4 ON/OFF cycle.](image)

Using the meteorological data it was possible to calculate the average cooling temperature, the energy produced by the panels when they are cooled and the energy produced when they are not cooled, in order to calculate their energy efficiency. For this case it was considered only 1 string, 25 panels, where the system would be running from 10h to 18h (8h daily). The calculations performed can be analysed in Table 5.4.

The PV temperatures are an average of 8 hours during the cooling time. The ON/OFF times were chosen so that the pump can be always operating without interruptions. Third row shows the number of strings that could be cooled with the respective ON/OFF cycle. Comparing the cooling of 1 string with 5 strings, it shows there is a difference of 6° C in the average temperature of the cooled panel which translates into a loss of 0.4 MWh in that period of time. It is also verified that the panel should be cooled as short as possible, which corroborates with the experimental results.

Table 5.5 shows the energy gain for a 5 string park. From the last row it is possible to conclude that the system compensates to be used in the greater number of strings. For this particular case, the system would be optimized if it is used on 5 strings, with a 2/8 minute ON/OFF cycle, and there is a gain of 6.79% of energy. System optimization will be done in the next chapter.
Table 5.4: Calculations for 5 year data.

<table>
<thead>
<tr>
<th>ON (min)</th>
<th>OFF (min)</th>
<th>N° of strings</th>
<th>$T_{PV\text{cooled}}$ (°C)</th>
<th>$T_{PV}$ (°C)</th>
<th>$E_{\text{cooled}}$ (MWh)</th>
<th>$E_{\text{n cooled}}$ (MWh)</th>
<th>Gain (per string)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>1</td>
<td>28,76°C</td>
<td>46,37°C</td>
<td>14,26</td>
<td>13,06</td>
<td>9,19 %</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>29,93°C</td>
<td>46,37°C</td>
<td>14,18</td>
<td>13,06</td>
<td>8,58 %</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>30,27°C</td>
<td>46,37°C</td>
<td>14,16</td>
<td>13,06</td>
<td>8,40 %</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2</td>
<td>30,58°C</td>
<td>46,37°C</td>
<td>14,14</td>
<td>13,06</td>
<td>8,24 %</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2</td>
<td>30,87°C</td>
<td>46,37°C</td>
<td>14,12</td>
<td>13,06</td>
<td>8,09 %</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3</td>
<td>31,17°C</td>
<td>46,37°C</td>
<td>14,10</td>
<td>13,06</td>
<td>7,93 %</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>3</td>
<td>31,94°C</td>
<td>46,37°C</td>
<td>14,05</td>
<td>13,06</td>
<td>7,53 %</td>
</tr>
<tr>
<td>3.33</td>
<td>6.66</td>
<td>3</td>
<td>32,17°C</td>
<td>46,37°C</td>
<td>14,03</td>
<td>13,06</td>
<td>7,41 %</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>4</td>
<td>32,61°C</td>
<td>46,37°C</td>
<td>14,00</td>
<td>13,06</td>
<td>7,18 %</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>4</td>
<td>32,32°C</td>
<td>46,37°C</td>
<td>14,02</td>
<td>13,06</td>
<td>7,33 %</td>
</tr>
<tr>
<td>2.5</td>
<td>7.5</td>
<td>4</td>
<td>32,90°C</td>
<td>46,37°C</td>
<td>13,98</td>
<td>13,06</td>
<td>7,03 %</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>4</td>
<td>33,43°C</td>
<td>46,37°C</td>
<td>13,94</td>
<td>13,06</td>
<td>6,75 %</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>5</td>
<td>33,36°C</td>
<td>46,37°C</td>
<td>13,95</td>
<td>13,06</td>
<td>6,79 %</td>
</tr>
<tr>
<td>2.5</td>
<td>10</td>
<td>5</td>
<td>34,09°C</td>
<td>46,37°C</td>
<td>13,90</td>
<td>13,06</td>
<td>6,41 %</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>5</td>
<td>34,73°C</td>
<td>46,37°C</td>
<td>13,86</td>
<td>13,06</td>
<td>6,07 %</td>
</tr>
</tbody>
</table>

Table 5.5: Energy gain for a 5 string park.

<table>
<thead>
<tr>
<th>ON (min)</th>
<th>OFF (min)</th>
<th>N° of Strings</th>
<th>Total Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>1</td>
<td>1,84 %</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3,41 %</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3,63 %</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3,30 %</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2</td>
<td>3,24 %</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4,76 %</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>3</td>
<td>4,52 %</td>
</tr>
<tr>
<td>3.33</td>
<td>6.66</td>
<td>3</td>
<td>4,45 %</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>3</td>
<td>4,31 %</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>4</td>
<td>5,86 %</td>
</tr>
<tr>
<td>2.5</td>
<td>7.5</td>
<td>4</td>
<td>5,52 %</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>5</td>
<td>5,40 %</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>5</td>
<td>6,79 %</td>
</tr>
<tr>
<td>2.5</td>
<td>10</td>
<td>5</td>
<td>6,41 %</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>5</td>
<td>6,07 %</td>
</tr>
</tbody>
</table>
Chapter 6

Economic analysis

Recalling that the time spent cooling the panel should be the minimum possible, i.e., ON/OFF cycles should be as short as possible and considering the revenue and costs, it is possible to make an economic analysis of the system. For simplification reasons, these calculations do not consider discount rate or depreciation over the years. Two case studies were analysed for a PV power plant with 5 strings, each one with 25 panels, located in: a) Lisbon, Portugal and b) Barreiras, Brazil. These locations were chosen to analyse the cooling system feasibility in different world locations. The number of strings was chosen due to being an optimum value as will be explained below in this chapter.

6.1 Fixed costs

The fixed costs of the water cooling system were considered the same for two 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. Two cases were considered: the use of a conventional pump (case 1), as it was used in the experimental tests, and the use of a solar pump (case 2), in case the photovoltaic park does not have access to the grid (this type of pump is directly attached to a panel).

Table 6.1 has initial fixed costs for the system assembly. Note that these costs remain the same for different cooled string numbers.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>50€</td>
</tr>
<tr>
<td>Tank</td>
<td>200€</td>
</tr>
<tr>
<td>Initial water</td>
<td>2,80€</td>
</tr>
<tr>
<td>Filters</td>
<td>80€</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As an alternative to the panels purchase, one can use panels that were already in the park. However, since installation contracts limit the amount of power injected into the grid, it is preferable to buy new
panels (off grid).

The material cost depends on the number of strings to be cooled. This value decreases by string, as a greater number of strings is considered, as it can be seen in the Table 6.2. For the filter problems there are several solutions.

For a park of this size, the solution is pre-filtering (eliminating small debris) and placing tablets in the tank to eliminate infections (tablets properties: disinfectant, algicide, flocculant, stabilizer, bactericide, clarifier, pH controller, rinse aid, fungicide).

For larger systems other care, such as UV filter, may be required. This filter has a cost of 340 € plus lump (70 €) and coal cartridge (18 €) - replacement every year.

Table 6.2: Material costs.

<table>
<thead>
<tr>
<th></th>
<th>1 String</th>
<th>2 Strings</th>
<th>3 Strings</th>
<th>4 Strings</th>
<th>5 Strings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller kit</td>
<td>50€</td>
<td>50€</td>
<td>50€</td>
<td>50€</td>
<td>50€</td>
</tr>
<tr>
<td>Controlled serco valves</td>
<td>25€</td>
<td>50€</td>
<td>75€</td>
<td>100€</td>
<td>125€</td>
</tr>
<tr>
<td>Pipe system</td>
<td>145€</td>
<td>253€</td>
<td>360€</td>
<td>466€</td>
<td>576€</td>
</tr>
<tr>
<td>Gutters</td>
<td>20€</td>
<td>40€</td>
<td>60€</td>
<td>80€</td>
<td>100€</td>
</tr>
<tr>
<td>Sprinklers</td>
<td>40€</td>
<td>80€</td>
<td>113€</td>
<td>150€</td>
<td>185€</td>
</tr>
<tr>
<td>Cost per string</td>
<td>280€</td>
<td>240€</td>
<td>220€</td>
<td>210€</td>
<td>205€</td>
</tr>
</tbody>
</table>

Taking into account the cost of the material, one can then calculate the total value of the fixed cost for each of the studied cases. The values are shown in the Table 6.3.

Table 6.3: Total costs for each case.

<table>
<thead>
<tr>
<th></th>
<th>1 String</th>
<th>2 Strings</th>
<th>3 Strings</th>
<th>4 Strings</th>
<th>5 Strings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>610€</td>
<td>800€</td>
<td>990€</td>
<td>1181€</td>
<td>1371€</td>
</tr>
<tr>
<td>Case 2</td>
<td>2000€</td>
<td>2290€</td>
<td>2410€</td>
<td>2570€</td>
<td>2810€</td>
</tr>
<tr>
<td>Cost per String (1)</td>
<td>610€</td>
<td>400€</td>
<td>330€</td>
<td>300€</td>
<td>275€</td>
</tr>
<tr>
<td>Cost per String (2)</td>
<td>2000€</td>
<td>1150€</td>
<td>800€</td>
<td>645€</td>
<td>560€</td>
</tr>
</tbody>
</table>

It is possible to conclude that the higher the number of strings, the lower the cost per string. The main difference between the two cases is that the solar pump operates with lower voltage and higher rated power and therefore has a much higher cost compared to a conventional pump.
6.1.1 Case study: Lisbon, Portugal - 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.

Variable costs

For the variable costs the following considerations were made.

- The water in the tank is at ambient temperature.
- The system operates whenever the panel temperature exceeds 30° C;
- Water losses are 15 liters per hour (based on experimental data);

The tariff of the energy sold to the grid, produced by the panels, in this case, is 0,25 €/kWh; the price of energy purchased from the grid to supply the pump is 0,1634 €/kWh; and the water price is 1,438 €/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.

The water cost, $C_{\text{water}}$, equation 6.1, due to the water losses, annually, is:

$$C_{\text{water}} = 0.001438 \text{€/m}^3 \times 15\text{liters} \times 1912\text{h} = 41.2\text{€}$$ (6.1)

The electrical pump energy cost, $C_{\text{pump}}$, equation 6.2, spent by the pump, annually, is:

$$C_{\text{pump}} = 0.1634 \text{€/kWh} \times 0.250\text{kW} \times 1912\text{h} = 78.1\text{€}$$ (6.2)

These costs are independent of the number of strings cooled. The second cost is only considered in the case of the conventional pump.

Annual Revenue

The annual revenue is calculated considering two situations as reference: a fully periodically cleaned panel and a typical non-cleaned panel.

This value depends on which case is chosen. In case 2, with the solar pump, it is not necessary to subtract the cost of the pump because it is fed directly from the panels. Equations 6.3 and 6.4 show the calculations for annual revenues for cases 1 and 2, respectively, where $R_1$ and $R_2$ are the annual revenues for each case, respectively, and $E_{\text{sold}}$ is the energy sold to the grid (in €).

$$R_1 = E_{\text{sold}} - C_{\text{pump}} - C_{\text{water}}$$ (6.3)

$$R_2 = E_{\text{sold}} - C_{\text{water}}$$ (6.4)
In this case, with the tank installed at ambient temperature, the comparison is made between cooled PV panels and cleaned PV panels. The numerical values are shown in Table 6.4.

<table>
<thead>
<tr>
<th>Nº de strings</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>388€</td>
<td>467€</td>
</tr>
<tr>
<td>4</td>
<td>320€</td>
<td>398€</td>
</tr>
<tr>
<td>3</td>
<td>237€</td>
<td>315€</td>
</tr>
<tr>
<td>2</td>
<td>138€</td>
<td>216€</td>
</tr>
<tr>
<td>1</td>
<td>18€</td>
<td>96€</td>
</tr>
</tbody>
</table>

Through this table it was possible to reach the results shown in the Figures 6.1 to 6.4. There are only figures of 4 and 5 strings as they are the cases of interest for this study. It can be concluded that the profit will be approximately 6500 € in 5 strings case and there is a four-year payback period (case 1).

All calculations are based on a clean panel. However in practice this does not happen, as dust and other dirt accumulate on top of the panel over time. From experimental results, after cleaning the panel, in 3-4 days it is already dirty. It has been verified, through the experimental tests, that there is an increase of 5% only counting the cleaning of the panel using water. With this information a comparison was made closer to a more real scenario. The new revenue values, considering a non-cleaned panel as reference, are shown in Table 6.5.

![Figure 6.1: Financial return for 4 strings (case 1) after 20 years for case study of Lisbon, 2015.](image1)

![Figure 6.2: Financial return for 4 strings (case 2) after 20 years for case study of Lisbon, 2015.](image2)
The reason for considering 20 years is due to the fact that the lifetime of PV panels is 25 years. Since the cooling system is to be assembled in parks already working, the chosen value seems appropriate.

Table 6.5: Annual revenue for both cases, with a dirty panel as reference, Lisbon 2015.

<table>
<thead>
<tr>
<th>Nº de strings</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>862€</td>
<td>939€</td>
</tr>
<tr>
<td>4</td>
<td>698€</td>
<td>776€</td>
</tr>
<tr>
<td>3</td>
<td>521€</td>
<td>599€</td>
</tr>
<tr>
<td>2</td>
<td>327€</td>
<td>405€</td>
</tr>
<tr>
<td>1</td>
<td>113€</td>
<td>191€</td>
</tr>
</tbody>
</table>

Through this table it was possible to reach the results shown in the Figures 6.5 to 6.8, corresponding to a more realistic situation. In this case there is a return increase, so the system pays out faster.
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. Since the water does not heat up, the temperature of the cooled panel is lower and therefore produces more energy. In this particular case, in the Lisbon region, it was verified that the increase of energy is not significant (less than 5 %), however this is not verified for regions with a higher temperature.

**Optimal number of strings**

To maximize profit, it is necessary to calculate the optimal number of strings that should be cooled by one water pump. Figure 6.9 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 or one pump cooling 1 string and the other 4 strings). In this case of Lisbon, a second pump should be bought if the PV park has more than 5 strings.

![Graph showing optimal number of strings for one pump (a conventional pump) with a dirty panel as reference (case study of Lisbon, 2015).](image)

6.1.2 Case study: Barreiras, Brazil - 2016

Taking into account other case studies, the Barreiras region of the state of Bahia, Brazil was chosen. This decision derives from the fact that the region has a high irradiance index and an higher environment temperature. These conditions are similar to other African countries, as for example Angola, which are a target market for several Portuguese companies.

**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 for the whole year.

The water cost, $C_{water}$, equation 6.5, annually, is:

$$C_{water} = 0.001438€/m^3 \times 15\text{liters} \times 3628h = 78.3€ \quad (6.5)$$

The electrical pump energy cost, $C_{pump}$, equation 6.6, spent by the pump, annually, is:

$$C_{pump} = 0.1634€/kWh \times 0.250kW \times 3628h = 148.2€ \quad (6.6)$$

**Annual revenue**

Following the same reasoning, one calculates the revenue results for water cooling system installed in Barreiras, Brazil shown on Table 6.6. The calculations were done considering the tank installed at
ambient temperature, and the comparison is between a cooled and a cleaned panel. It is verified that the financial return will be higher, which was already expected. The high temperatures reduce the efficiency of the panel, which makes this cooling system more profitable.

Table 6.6: Annual revenue for both cases, Brazil 2016.

<table>
<thead>
<tr>
<th>N° of strings</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>579€</td>
<td>727€</td>
</tr>
<tr>
<td>4</td>
<td>469€</td>
<td>617€</td>
</tr>
<tr>
<td>3</td>
<td>338€</td>
<td>486€</td>
</tr>
<tr>
<td>2</td>
<td>180€</td>
<td>329€</td>
</tr>
<tr>
<td>1</td>
<td>-9€</td>
<td>140€</td>
</tr>
</tbody>
</table>

Figures 6.10 to 6.13 show the financial return (case 1) after this period. In this case, for 5 string and the conventional pump, and using a cleaned panel as reference, the financial return would be higher (around 10000 €) with a financial return after 3 years of the investment.

Figure 6.10: Financial return for 4 strings (case 1) after 20 years for case study of Brazil, 2016. Figure 6.11: Financial return for 4 strings (case 2) after 20 years for case study of Brazil, 2016.
As in the previous case, it was also compared to a dirty panel in order to have a case closer to reality. Table 6.7 contains the new numeric values.

Table 6.7: Annual revenue for both cases, with a dirty panel as reference, Brazil 2016.

<table>
<thead>
<tr>
<th>Nº of strings</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1084€</td>
<td>1232€</td>
</tr>
<tr>
<td>4</td>
<td>873€</td>
<td>1022€</td>
</tr>
<tr>
<td>3</td>
<td>641€</td>
<td>789€</td>
</tr>
<tr>
<td>2</td>
<td>383€</td>
<td>531€</td>
</tr>
<tr>
<td>1</td>
<td>93€</td>
<td>241€</td>
</tr>
</tbody>
</table>

Through this table one can calculate the annual revenue shown from Figure 6.14 to Figure 6.17. In this case, a financial return is obtained after 2 years of the investment for the use of a conventional pump. At the end of the total time considered there is a profit of approximately 20000 € and 22000 € for conventional pump and solar pump cases, respectively.
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 6.8 and therefore in Figures 6.18 to 6.21.

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 31000 €, with 5 strings. This case, mainly due to the temperature, is similar to places like Angola, where RESUL has the possibility to invest.
Table 6.8: Annual revenue for both cases, with a dirty panel as reference, Brazil, 2016. With a tank buried underground.

<table>
<thead>
<tr>
<th>Nº of strings</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1580€</td>
<td>1728€</td>
</tr>
<tr>
<td>4</td>
<td>1302€</td>
<td>1450€</td>
</tr>
<tr>
<td>3</td>
<td>989€</td>
<td>1137€</td>
</tr>
<tr>
<td>2</td>
<td>633€</td>
<td>782€</td>
</tr>
<tr>
<td>1</td>
<td>227€</td>
<td>375€</td>
</tr>
</tbody>
</table>

Figure 6.18: Financial return for 4 strings (case 1) after 20 years, with water temperature at 20°C, for case study of Brazil, 2016.

Figure 6.19: Financial return for 4 strings (case 2) after 20 years, with water temperature at 20°C, for case study of Brazil, 2016.

Figure 6.20: Financial return for 5 strings (case 1) after 20 years, with water temperature at 20°C, for case study of Brazil, 2016.

Figure 6.21: Financial return for 5 strings (case 2) after 20 years, with water temperature at 20°C, for case study of Brazil, 2016.
Optimal number of strings

Figure 6.22 shows from which number of strings it compensates to use a second pump. For this case, one pump refrigerating 4 strings still has a higher revenue than two pumps cooling 4 strings. In this case of Barreiras, Brazil, a second pump should be bought if the PV park has more than 4 strings to cool.

Figure 6.22: Optimal number of strings for one pump (a conventional pump) with a dirty panel as reference, with water temperature at 20° C (case study of Brazil, 2016).
6.1.3 Case study: 5 year-summer data

Although the meteorological data received were only 3 months each year, the results were extrapolated to the whole year. The data, from the Meteorological Station of Lisbon - Gago Coutinho, has a periodicity of 1h, of ambient temperature and irradiance, from July to September 2009 to 2013.

Variable costs

The following considerations were made for the calculation of variable costs:

- The system only works for 3 months (July, August, September) - Summer.
- The system is switched on 8h daily, from 10h to 18h.
- The water losses would be 15 liters per hour.
- A string consists of 25 panels, which is equivalent to a surface of 32 m$^2$.

The tariff of the energy sold to the grid, produced by the panels, is 0.25 €/kWh; the price of energy purchased from the grid to supply the pump is 0.1634 €/kWh; and the water price is 1.438 €/m$^3$.

Equation 6.7 shows the annually water cost:

$$C_{water} = 0.001438€/m^3 \times 15\text{liters} \times 8h \times 120\text{days} = 20.7€$$ (6.7)

Equation 6.8 shows the annually energy cost spent by the pump.

$$C_{pump} = 0.1634€/kWh \times 0.250kW \times 8h \times 120\text{days} = 39.2€$$ (6.8)

Since only one string is cooled at a time, the costs are independent from the number of strings in the solar park.

Annual Revenue

Following the same reasoning, one calculates the revenue results for water cooling system installed in Lisbon shown on Table 6.9. The calculations were done considering the tank installed at ambient temperature, and the comparison is between a cooled and a cleaned panel.

<table>
<thead>
<tr>
<th>N° de strings</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>605€</td>
<td>644€</td>
</tr>
<tr>
<td>4</td>
<td>491€</td>
<td>530€</td>
</tr>
<tr>
<td>3</td>
<td>369€</td>
<td>408€</td>
</tr>
<tr>
<td>2</td>
<td>237€</td>
<td>273€</td>
</tr>
<tr>
<td>1</td>
<td>94€</td>
<td>133€</td>
</tr>
</tbody>
</table>
Figure 6.23: Financial return for 1 string (case 1) after 20 years for study case of 5 year data.

Figure 6.24: Financial return for 1 string (case 2) after 20 years for study case of 5 year data.

Figure 6.25: Financial return for 4 strings (case 1) after 20 years for study case of 5 year data.

Figure 6.26: Financial return for 4 strings (case 2) after 20 years for study case of 5 year data.

Figure 6.27: Financial return for 5 strings (case 1) after 20 years for study case of 5 year data.

Figure 6.28: Financial return for 5 strings (case 2) after 20 years for study case of 5 year data.
Using the equations 6.7 and 6.8 the following results were obtained, as shown in the Figures 6.23 to 6.28.

Through the figures 6.27 and 6.28 it is also possible to conclude that the conventional pump has a slightly larger return. However, this fact depends directly on the cost associated with the pump operation, i.e., depends on the local tariff, and this may vary.
Chapter 7

Conclusions

7.1 Achievements

In the present work, a closed loop water cooling system for photovoltaic panels is fully designed and implemented with the purpose of increasing their efficiency, by lowering the modules temperatures. The built system was installed in 5 kW of a 20 kW solar power plant 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 analyse 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 analysed: 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 16000 €, for the case of Lisbon, and it is paid in 1 year and with a 20-years revenue of around 32000 €. Therefore, it was concluded that the system is economically viable even for different world locations.

The determining factor is the effect of wind on the system. At times when the velocity of wind is high, water leaves the system circuit and is lost, leaving the system no longer viable.

7.2 Future Work

Although experimental and theoretical tests have already been done, there are still some areas that have not been investigated and need to be studied to ensure the success of this system, such as:

1. The degradation of the panels in humid environments.

2. The water losses in meteorological conditions different from those seen in Lisbon.
3. The treatment of the water to be used, in order to avoid problems like fungi or bacteriological
problems.

4. Test the use of small holes instead of sprinklers because these clog easily.

Given the results obtained, it is suggested that experimental tests be performed in real conditions in
warmer environments, such as Alentejo or Angola, where the economic return would be faster.


new-world-record-for-solar-cell-efficiency-at-46-percent-1599/.


solarpowerworldonline.com/2016/05/advantages-disadvantages-solar-tracker-system/.


worlds-biggest-floating-solar-farm-power-up-outside-london.

Europees-largest-floating-solar-farm-powers-up.html.


Appendix A

Technical Datasheets
A.1 STP190S - 24/Ad+ Datasheet

STP190S - 24/Ad+

190 Watt
MONOCRystALLine SOLAR MODULE

Features

- High module conversion efficiency (up to 14.9%), through superior cell technology and leading manufacturing capability
- Positive tolerance
  Guaranteed positive tolerance from 0~5% ensures power output reliability
- Suntech’s TruPower™
  Suntech’s TruPower™ process neutralizes the initial LID effect
- Excellent weak light performance
  Excellent performance under low light environments (mornings, evenings, and cloudy days)
- Withstand high wind and snow loads
  Entire module certified to withstand high wind loads (2400 Pascal) and snow loads (5400 Pascal) *
- Suntech current sorting process
  All Suntech modules sorted and packaged by amperage, maximizing system output by reducing mismatch losses by up to 2%

Trust Suntech to Deliver Reliable Performance Over Time
- World’s No.1 manufacturer of crystalline silicon photovoltaic modules
- Unrivaled manufacturing capacity and world-class technology
- Rigorous quality control meeting the highest international standards: ISO 9001: 2008 and ISO 14001: 2004

Industry-leading warranty
- Warrants 6.7% more power than the market standard over 25 years
- 25-year transferrable power output warranty: 5 years/95%, 12 years/90%, 18 years/85%, 25 years/80% **
- Based on nominal power
- 5 years material and workmanship warranty

Certifications and standards:
IEC 61215, IEC 61730, conformity to CE

Specially designed drainage holes and rigid construction prevent frame from deforming or breaking due to freezing weather and other forces.

Latest IP67 rated junction box improves module performance stability. High performance connectors provide low resistance interconnection to ensure the full utilization of module power output.

* Please refer to Suntech Standard Module Installation Manual for details.
** Please refer to Suntech Product Warranty for details.

Figure A.1: Technical information regarding type STP190S - 24/Ad+ photovoltaic panel.
Current-Voltage & Power-Voltage Curve (190S-24)

Excellent performance under weak light conditions: at an irradiation intensity of 200 W/m² (AM 1.5, 25 °C), 95.5% or higher of the STC efficiency (1000 W/m²) is achieved.

Temperature Characteristics

| Nominal Operating Cell Temperature (NOCT) | 45±2 °C |
| Temperature Coefficient of Pmax | -0.45 %/°C |
| Temperature Coefficient of Voc | -0.34 %/°C |
| Temperature Coefficient of Isc | 0.050 %/°C |

Mechanical Characteristics

| Solar Cell | Monocrystalline 125 × 125 mm (5 inches) |
| No. of Cells | 72 (6 x 12) |
| Dimensions | 1580 x 808 x 35mm (62.2 x 31.8 x 1.4 inches) |
| Weight | 15.5 kgs (34.1 lbs.) |
| Front Glass | 3.2 mm (0.13 inches) tempered glass |
| Frame | Anodized aluminium alloy |
| Junction Box | IP67 rated |
| Output Cables | TUV (2Pfg1169:2007), UL 4703, UL 44 |
| Connectors | RADOX® SOLAR integrated twist locking connectors |

Packing Configuration

| Container | 20' GP | 40' GP |
| Pieces per pallet | 26 | 26 |
| Pallets per container | 12 | 28 |
| Pieces per container | 312 | 728 |

Specifications are subject to change without further notification.
High module conversion efficiency (up to 13.6%), through superior cell technology and leading manufacturing capability.

Positive tolerance
Guaranteed positive tolerance from 0~5% ensures power output reliability.

Suntech’s TruPower™
Suntech’s TruPower™ process neutralizes the initial LID effect.

Excellent weak light performance
Excellent performance under low light environments (mornings, evenings, and cloudy days).

Withstand high wind and snow loads
Entire module certified to withstand high wind loads (2400 Pascal) and snow loads (5400 Pascal) *

Suntech current sorting process
All Suntech modules sorted and packaged by amperage, maximizing system output by reducing mismatch losses by up to 2%

Contact Suntech for more information.

Certifications and standards:
IEC 61215, IEC 61730, conformity to CE

* Please refer to Suntech Standard Module Installation Manual for details.

** Please refer to Suntech Product Warranty for details.

Figure A.3: Technical information regarding type STP225 - 20/Wd photovoltaic panel.
Current-Voltage & Power-Voltage Curve (225-20)

Excellent performance under weak light conditions: at an irradiation intensity of 200 W/m² (AM 1.5, 25 °C), 95.5% or higher of the STC efficiency (1000 W/m²) is achieved.

Temperature Characteristics

| Nominal Operating Cell Temperature (NOCT) | 45±2°C |
| Temperature Coefficient of Pmax | -0.44 %/°C |
| Temperature Coefficient of Voc | -0.33 %/°C |
| Temperature Coefficient of Isc | 0.055 %/°C |

Electrical Characteristics

<table>
<thead>
<tr>
<th>STC</th>
<th>STP225-20/Wd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum Operating Voltage (Vmp)</td>
<td>29.6 V</td>
</tr>
<tr>
<td>Optimum Operating Current (Imp)</td>
<td>7.61 A</td>
</tr>
<tr>
<td>Open - Circuit Voltage (Voc)</td>
<td>36.7 V</td>
</tr>
<tr>
<td>Short - Circuit Current (Isc)</td>
<td>8.15 A</td>
</tr>
<tr>
<td>Maximum Power at STC (Pmax)</td>
<td>225 W</td>
</tr>
<tr>
<td>Module Efficiency</td>
<td>13.6%</td>
</tr>
<tr>
<td>Operating Module Temperature</td>
<td>-40 °C to +85 °C</td>
</tr>
<tr>
<td>Maximum System Voltage</td>
<td>1000 V DC (IEC) / 600 V DC (UL)</td>
</tr>
<tr>
<td>Maximum Series Fuse Rating</td>
<td>20 A</td>
</tr>
<tr>
<td>Power Tolerance</td>
<td>0/+5 %</td>
</tr>
</tbody>
</table>

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5; Power measurement tolerance ± 3%

NOCT: Irradiance 800 W/m², ambient temperature 20 °C, wind speed 1 m/s; Power measurement tolerance ± 3%

Mechanical Characteristics

| Solar Cell | Polycrystalline 156 × 156 mm (6 inches) |
| No. of Cells | 60 (6 x 10) |
| Dimensions | 1665 × 991 × 50mm (65.6 × 39.0 × 2.0 inches) |
| Weight | 19.8 kgs (43.7 lbs.) |
| Front Glass | 3.2 mm (0.13 inches) tempered glass |
| Frame | Anodized aluminium alloy |
| Junction Box | IP67 rated |
| Output Cables | TUV (2Pfg1169:2007), UL 4703, UL 44 |
| Connectors | RADOX® SOLAR integrated twist locking connectors |

Packing Configuration

| Container | 20’ GP | 40’ HC |
| Pieces per pallet | 21 | 21 |
| Pallets per container | 6 | 28 |
| Pieces per container | 126 | 588 |

Specifications are subject to change without further notification.

Figure A.4: Technical information regarding type STP225 - 20/Wd photovoltaic panel.
Tinytag Talk 2s are compact, lightweight, economical loggers housed in a 35mm film canister.

These loggers are used in a wide range of applications including building condition monitoring (especially for pipe work temperatures and air conditioning validation), fridge monitoring and academia.

The TK-4023 is supplied with an external probe allowing fast changing temperatures in difficult to access areas to be accurately tracked.

**Popular Applications**
- Building condition monitoring
  - Pipe work temperatures
  - Air conditioning validation
- Pharmaceutical storage
- Dry food storage
- Museum display and repository

**Features**
- Temperature recorder
- 16,000 reading capacity
- High Accuracy
- High Reading Resolution
- Fast Data Offload
- 2 user-programmable alarms
- Low battery monitor
- User-replaceable battery
Features

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Reading Capacity</td>
<td>16,000 readings</td>
</tr>
<tr>
<td>Memory type</td>
<td>Non Volatile</td>
</tr>
<tr>
<td>Delayed Start</td>
<td>Relative / Absolute (up to 45 days)</td>
</tr>
<tr>
<td>Stop Options</td>
<td>When full</td>
</tr>
<tr>
<td>After n Readings</td>
<td>After n Readings</td>
</tr>
<tr>
<td>Never (overwrite oldest data)</td>
<td>Never (overwrite oldest data)</td>
</tr>
<tr>
<td>Reading Types</td>
<td>Actual, Min, Max</td>
</tr>
<tr>
<td>Logging Interval</td>
<td>1 sec to 10 days</td>
</tr>
<tr>
<td>Offload</td>
<td>While stopped or when logging in minutes mode</td>
</tr>
<tr>
<td>Alarms</td>
<td>2 fully programmable; latchable</td>
</tr>
</tbody>
</table>

Reading Specification

The information below refers to the performance of the data logger when used with the supplied PB-5005-0M6 probe.

- **Reading Range**: -40°C to +125°C (−40°F to +257°F)
- **Sensor Type**: 10K NTC Thermistor (external probe)
- **Reading Resolution**: ±0.01°C change from 25°C
- **Temperature Stability**: ±0.01°C/°C change from 25°C
- **Response Time**: 10 seconds (to 90% FSD) in water

Accuracy

![Temperature Calibration Graph](image)

Notes

- **Battery Type**: SAFT LST14250 or LST14250; Tekcell SBA402P
- **Replacement Interval**: Annually
- **Before replacing the battery**: the data logger must be stopped.
- **After removing an old battery from a logger**: wait five minutes before inserting the new one.
- **Data stored on the logger**: will be retained after a battery is replaced.
- **If used at low temperatures**: the data logger should be allowed to warm to room temperature before it is opened to avoid condensation forming inside the unit.

Physical Specification

**Logger**

- **IP Rating**: IP30 (not water-proof)
- **Operational Range**: -40°C to +85°C (-40°F to +185°F)
- **Logger Dimensions**: Diameter 34mm / 1.34”, Height 54mm / 2.13”, Weight 30g / 1.06oz

- **The Operational Range of the logger indicates the physical limits to which it can be exposed.**

**Probe**

- **IP Rating**: IP68
- **Operational Range**: -40°C to +125°C (-40°F to +257°F)
- **Dimensions**
  - **Weight**: 5g / 0.18oz

Calibration

This unit is configured to meet Gemini’s quoted specification during its manufacture.

We recommend that the calibration of this unit should be checked annually against a calibrated reference meter.

A certificate of calibration, traceable to a national standard, can be supplied for an additional charge either at the point of purchase, or if the unit is returned for a service calibration.

Approvals

Gemini Data Loggers (UK) Ltd. operates a Business Management System which conforms to ISO 9001 and ISO 14001.

Required and Related Products

- **To use this data logger**: you will also require:
  - A PB-5005-0M6: Talk Thermistor Probe (supplied)
  - The following software:
    - SWCD-0040: Tinytag Explorer software
    - CAB-0005-USB: Tinytag Transit/Talk USB Download Cable
- **Further Related Products**
  - SER-9500: Tinytag Data Logger Service Kit

**Figure A.6: Temperature Logger Datasheet.**
A.4 Pump model DOC 7 technical information

**Figure A.7: Pump model DOC 7 technical information.**
A.5 Timer 411RTOAM technical information

Figure A.8: Timer used to regulate the operation of the controlled valve.
A.6 Cooling system specifications

Figure A.9: Cooling system specifications.

Design specifics:

1. Elements 1,2,3,4,5, 8 and 9 are flexible pipes.
2. Elements 6,7,10 and 11 are non-flexible pipes.
3. Pipes 1,2,3, 8 and 9 have 0.0254m (1 inch) diameter.
4. Pipes 4,5,6,7 have 0.0127m (1/2 inch) diameter.
5. The combined length of the pipes 1,2 and 3 are 14 meters.
6. Pipes 4 and 5 are 3 meters long.
7. Pipes 6 and 7 are 13 meters long.
8. Pipes 8 and 9 are 7 meters total.
9. Pipes 10 and 11 are cut in half in the axial direction and have 0.16m diameter.
10. Connection 1 and 2 are hose connections.
11. The pump is the LOWARA DOC 7 model.
12. The electro valve is the ASCO N.F. 1” 230V model.

13. The controller is the 411RTOAM62301 for 230 V AC.
A.7 Pump startup current

Figure A.10: Current peak during the startup phase.