Proyecto Fin de Grado
Grado en Ingeniería de la Energía

Improvement of a PV Cell efficiency by using cooling techniques. A techno-economic study.

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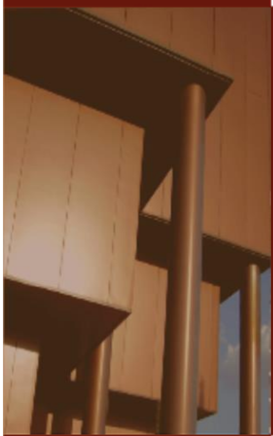

Dpto. Ingeniería Eléctrica
Escuela Técnica Superior de Ingeniería
Universidad de Sevilla

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1. Introduction

During the normal performance of a solar photovoltaic panel it needs sun radiation in order to produce energy (as a power output) but due to the continuous exposure to the sun radiation, the temperature of the panel increases affecting its normal performance. There's a relation between the efficiency and the temperature; the higher the temperature, the lower is the efficiency.

This work is about wondering if there's a plausible solution of boosting the panel efficiency (to the normal values) by using different cooling systems, and the main question here is about the power consumption of the cooling system with two possible scenarios:

The power surplus production (compared to the base case with no cooling) is higher than the power consumption of the cooling system. This scenario is interesting because the net production (power surplus production minus power consumption) is positive and it will be suitable of a posterior economic analysis.

The power surplus production (compared to the base case with no cooling) is less than the power consumption of the cooling system. This scenario is discarded because the net production (power surplus production minus power consumption) is negative and it's even worse than the base case.

The evaluated cooling fluids will be water and air. In this work aren't considered other kind of cooling fluids like conventional HVAC refrigerants or organic mixtures.

2. Objective

The main objective of this work is to know if using a cooling fluid that reduces the temperature of the solar cell, we could obtain a boost in the power and energy output of the system (i.e., improving its efficiency) and know if the solution is suitable in an economic way for the implementation. So, the two concepts (technical and economic) will be tightly connected for the optimal solution.

In instance, the work will be split in several areas for the correct global analysis:

1) Explain the behaviour of a solar cell as a semiconductor dispositive and describe the electronic model that fits its performance when exposed to solar radiation.
2) Obtain the temperature of the system by doing an energy balance (in a simplified model) we will obtain different temperatures when the fluid used in the convective balance is different.
3) Once we have the sets of temperatures in three scenarios considered in this work:

- No cooling fluid is used.

- Cooling by air driven by a fan.
- Cooling by sprayed water driven by a pump.

We will use those temperature as the main input for the electronic model and obtain the desired outputs (i.e., intensity current and voltage, therefore the power), then we could evaluate the power output and select the optimal cooling system.

4) Finally, having the power output of the solar cell we need to consider the electrical consumption of the subsystems that allow the cooling to be possible (i.e. fan and pump) and compare the economic value f the plus of power output (compared to the base case with no cooling) versus the power consumption of the subsystem. First, we will evaluate the value by means of the power gained, and secondly, we will see if also it is economically optimal by adding the costs of the electrical energy.

3. Fundamentals

The content of this section is mainly based on explaining the electronic model of the photovoltaic (PV) cell and describing the system temperature (by doing a proper energy balance).

3.1. Photoelectrical effect

The photoelectrical effect is produced when the solar radiation falls upon the upper layers of the PV cell (a semiconductor made of silica) and the electrons of the material are released.

The electrons are released because the energy that bind them to the atom nucleus is severed by the energy carried by the photons (energized particles located in the solar radiation) and subsequently they can freely flow through the material.

The motion of the electrons on the material due to internal electrical fields generate the electrical current (I) that flows through the solar cell, so, the expression:

$$I = \frac{dQ}{dt} \sim \frac{nq_e}{T}$$

Where, $\frac{dQ}{dt}$ describes the electrons flowing per unit of time that could be approximate by $\frac{nq_e}{T}$ (n is the number of electrons released, q_e is the electron charge and T is the time measured)

The equation of the current I will be explained on the next section, taking into account the non-linear electronic model of the PV cell.

3.2. Electronic model (PV cell)

In order to understand how the solar cell works, we first need to understand its composition and physical behavior (in a microscopic way) to infer the equations in a macroscopic way. Those equations will be the ones used on the work.

The basic electronics of the solar cell is based on the junction of two kind of silica layers, one dopped with phosphorus which gives more electrons, and other dopped with boron with less electrons, thus, is conformed the electron-hole pair which is responsible of the widely known p-n junction, schematically shown in Figure 1 [18]:

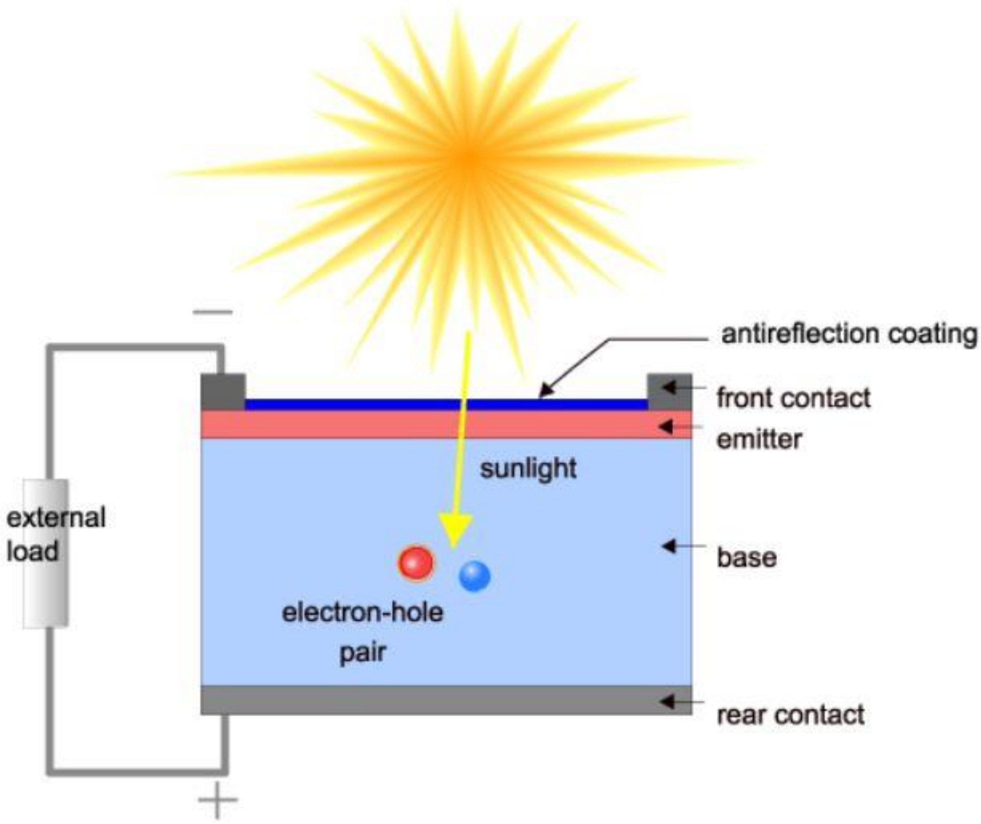

Figure 1. Photoelectric Effect (Semiconductor)

Then, we can describe a circuit model for the photovoltaic cell based on:

1) The electron generation based on the photoelectrical effect (explained before) will be modeling as a current source dependent of temperature and solar radiation, I_{pv}.

2) The p-n junction of the solar cell will be described as a simple diode on the model (I_d is the current through the diode)

3) The no ideality of the model will be modeled with a shunt (R_{sh}) and series (R_s) resistance, as shown in Figure 2 [19]:

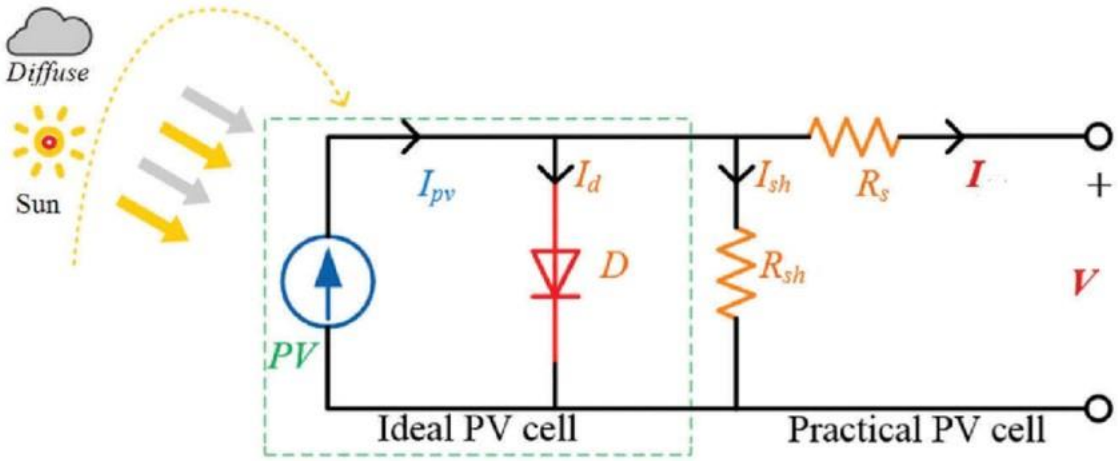

Figure 2. Equivalent Electronic Circuit (PV Cell)

In Figure 2 (the electric circuit model of the PV cell) several currents and voltages can be identified:

I_{pv} is the photonic intensity, due to the electrons produced by sun radiation

I_d is the current through the diode (the p-n junction is modeled as a diode)

I_{sh} is the current through the shunt resistor.

I is the current output in the terminals of the PV cell.

V is the voltage on the terminals of the PV cell.

And, by applying Kirchoff law in the node connecting the series and shunt resistances:

$$I = I_{pv} - I_d - I_{sh} \quad \textbf{(1)}$$

The photonic current I_{ph} (the total production of electrons) is diminished by losses due to the internal p-n junction (I_d) and the non-ideality of the model (I_{sh}) modelled as the shunt resistance.

Next, the particular expression of each current will be described.

The photonic current expression [1]:

$$I_{pv} = [I_{sc} + k_i \cdot (T - T_n)] \cdot G \quad \textbf{(2)}$$

Where:

I_{sc} is the value of the short-circuit current (Independent of G and T values)

k_i is the value of the short-circuit current (at $T = T_n = 298\ K$ and $G = 1000\ \frac{W}{m^2}$)

T is the temperature of the cell (ºC)

G is the value of sun irradiation (W/m^2)

The current through the diode, due to the p-n junction is [1]:

$$I_d = I_{rs} \cdot \left(\frac{T}{T_n}\right)^3 e^{\left[q \cdot E_{g0} \left(\frac{1}{T} - \frac{1}{T_n}\right) \frac{1}{n \cdot k}\right]} \quad \textbf{(3)}$$

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q \cdot V_{OC}}{n \cdot N_S \cdot k \cdot T}\right)} - 1} \quad \textbf{(4)}$$

Where:

q is the electron charge

E_{g0} is the energy band gap of the semiconductor

n is the ideality factor of the diode

k is the Boltzmann constant

I_{rs} is the reverse saturation current

V_{oc} is the open-circuit voltage

N_s the number of cells connected in series to conform an array.

The expression of I_{sh} by simply applying the Kirchoff law is:

$$I_{sh} = \frac{V + I \cdot R_S}{R_{sh}} \quad \textbf{(5)}$$

Where respectively R_S and R_{sh} are the series and parallel (shunt) resistances.

The numerical values of the parameters are shown in Table 1 [1] and [2]:

Table 1. Semiconductor Properties

k_i (A) Standarized SCC	q (C) Electron Charge	k $\left(\frac{J}{K}\right)$ Boltzmann Constant	n Diode Ideality Factor	E_{g0} (eV) Energy Band Gap	R_s (Ω) Series Resistance
$0{,}0032$	$1{,}6 \cdot 10^{-19}$	$1{,}3 \cdot 10^{-23}$	$1{,}3$	$1{,}12$	$0{,}221$
R_p (Ω) Shunt Resistance	T_n (K) Room Temperature	V_{oc} (V) Open Circuit Voltage	I_{sc} (A) Short Circuit Current	N_s Number of unitary PV cells	
$415{,}4$	298	$30{,}6$	$8{,}13$	-	

4. System Analysis

In this section, all the calculations to obtain the current of the PV cell (I) will be explained. Once the current is obtained, given a fixed voltage V (calculated and explained on Section 4.4), the power output (P) of the PV cell can be derived from those two variables.

4.1. Temperature analysis.

We need to know the evolution of the temperature T of the solar cell when it's exposed to energetic inputs (the sun irradiation) and outputs (heat dissipation by convection and radiation to the environment) because is a fundamental parameter to obtain the value of the PV cell, I.

4.2. Previous observation. (Convective coefficient h)

The main topic of this work is about knowing the power output P of a PV cell when exposed to different working spaces (cooling techniques) ;

- Without any kind of refrigeration/cooling method, this is equal to using a free air convective coefficient, which will be called from now on h_1.
- Using a forced air convective coefficient by fan to boost the ambient air towards the panel surface. The corresponding convective coefficient will be h_2.
- Spraying the panel surface with water (by using a pump and hydraulic system), this will be from now the convective coefficient h_3.

So, recalling:

- h_1 is free convective air coefficient (no cooling technique applied)
- h_2 is forced convective air coefficient (air boosted by a fan)
- h_3 is free convective water coefficient (water sprayed by hydraulic and pump system)

From this point, as a result of the energy balance, we will see the temperature T is a direct function of the convection coefficient, h , so, as a consequence of having three different types of h , three different sets of temperature will be obtained, in consequence three different sets of currents, I, and three different sets of powers, P:

- $T(h_1) = T_1 \rightarrow I_1 \rightarrow P_1$
- $T(h_2) = T_2 \rightarrow I_2 \rightarrow P_2$
- $T(h_3) = T_3 \rightarrow I_3 \rightarrow P_3$

For briefing, we will refer to the set of all convective coefficients, temperatures, current intensities, and power outputs as: h_i, T_i, I_i, P_i with $i = \{1, 2, 3\}$.

4.3. Energy balance

For the thermal energy balance, we will consider the PV cell exposed to a main energetic input, (the sun irradiation,) and two different kinds of energy dissipation; (convection and radiation) .

Conduction and accumulations effects will be neglected because the thickness, e , of the PV cell is insignificant compared to the major dimensions (large, L, and width, W), taken as an example of these values will be the ones shown [3] commented on Section 4.4. and they are defined as $e = 35\ mm$, $L = 1332\ mm$, $W = 992\ mm$.

We can define the volume, V, of the PV cell as:

$V = e \cdot W \cdot L$

And the area A as:

$A = W \cdot L$

Since the thickness is negligible compared to the other dimensions (large or width of the PV cell), its area is much greater than its volume ($W, L \gg e \rightarrow A \gg V$) as is seen in the previous expressions, the volume V is diminished because of e value.

So, the volume, V is not significant compared to the surface A, this will have a direct consequence on the thermal model as will be commented later.

The equation for modeling the system is:

$$\rho C_p V \frac{\partial T}{\partial t} = \alpha G A - hA(T - T_a) - \varepsilon \sigma F A(T^4 - T_a^4) \qquad \textbf{(6)}$$

The parameters of the equation are:

ρ is the density of the solar array (we can assume it to be the density of silica)

C_p is the specific heat of the silica

V is the volume of the solar array

α is the absorptivity of the silica

A is the area of the solar array

h is the convection coefficient

T_a is the room temperature

σ is the Stephan-Boltzmann constant

ε is the emissivity of the silica

F is the shape factor between the solar cell, the sky and the environment

This equation represents the variation of energy of a given volume V when is affected by energetic inputs (increase the volume energy) and outputs (decrease the volume energy), the term that takes in into account is $\rho C_p V \frac{\partial T}{\partial t}$ which is a simplification of $\frac{\partial}{\partial t}(\rho C_p V T)$ (the parameters $\rho C_p V$ can be extracted from the time derivation because they don't depend on time itself) in this case, recalling the fundamental equation of heat $Q = mC_pT = \rho V C_p T$ (being m the mass expressed later in terms of density ρ and volume V), the previous term $\frac{\partial}{\partial t}(\rho C_p V T)$ can be quickly identified as $\frac{\partial Q}{\partial t}$ (the energy variation as commented before). This variation is due to various energy inputs and outputs as commented before. An energy input due to the sun irradiation expressed on αGA, where GA represents the incident irradiation on the PV cell surface, this radiation is absorbed partially (the rest is reflected or transmitted through the material), for taking this effect into account the parameter α (absorptivity) is added. The term $hA(T - T_a)$ expresses the dissipation (energy reduction) due to the temperature difference $(T - T_a)$ between the hot surface T and the ambient T_a, this rate of dissipation is proportional to h (the convective coefficient, a fluid property), another term of dissipation is $\varepsilon\sigma FA(T^4 - T_a^4)$ which expresses the dissipation of energy through the radiation phenomena modelled by the Stephan-Boltzmann Law $\sim \sigma(T^4 - T_a^4)$ which conceals the radiation exchange between two bodies (in this case the PV cell and the environment) and because the PV cell isn't a black body (perfect radiation emissor), the radiation effect must be diminished by adding the emissivity factor ε, finally for taking into account the geometric effect (how the radiation is exchanged) between the radiation emissor and receptor the shape factor F is added.

In the next figure [21], those effects can be seen graphically.

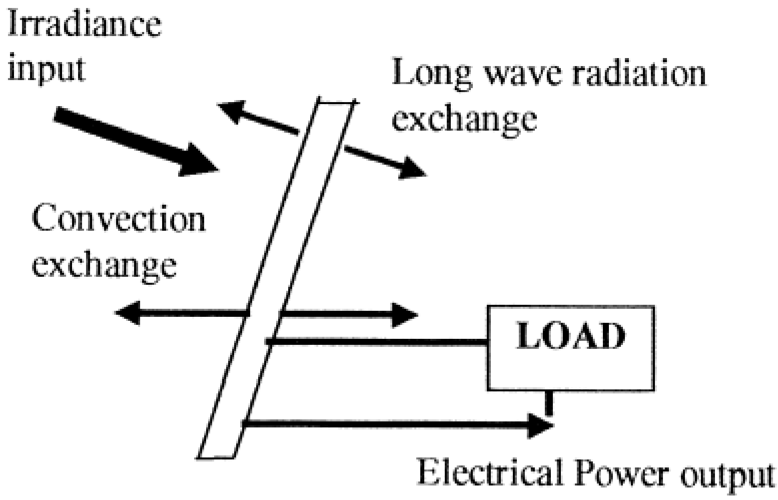

Figure 3. Energy Balance (PV panel)

The term $\rho C_p V \frac{\partial T}{\partial t}$ as commented before (the energy variation) also measures the accumulation effect (i.e the capacity of energy storage) of the system when exposed to the energetic inputs and outputs. Recalling, in our system, he have assumed the hypothesis of the area being so much larger than the volume, so when comparing $A \gg V$, $V \sim 0$ (due to the value of the thickness e) and it leads to $\rho C_p V \frac{\partial T}{\partial t} = 0$, this deduction, can be also conducted by assuming the system is in permanent state (no transient effects considered of accumulation due to the minimal volume V) so $\frac{\partial T}{\partial t} \sim 0$ it also leads to $\rho C_p V \frac{\partial T}{\partial t} = 0$ and will be the case of this study.

In any case, the equation **(6)** will be transformed into:

$$0 = \alpha G A - hA(T_o - T_a) - \varepsilon \sigma F A(T_o^4 - T_a^4) \qquad \textbf{(7)}$$

From the previous equation, the sub-zero in T_o is refered to the temperature term but now in permanent state, for simplify the notation from this point will be simplified considered as T, for the whole study is considered in permanent state. So, **(7)** will be expressed as:

$$0 = \alpha G A - hA(T - T_a) - \varepsilon \sigma F A(T^4 - T_a^4) \qquad \textbf{(8)}$$

The equation **(8)** will be the model to evaluate for obtaining the temperature of the system.

The value of the parameters involved on the calculus of **(8)** will be shown on Table 2. [3], [4]:

Table 2. Radiation Calculus Parameters

ε Emissivity	α Absorptivity	$A\ (m^2)$ Surface Area	$\sigma\left(\frac{W}{m^2 \cdot K^4}\right)$ Stephan-Bolztmann Constant	F Shape Factor Surface-Sky
0,68	0,8	1,4	$5{,}67 \cdot 10^{-8}$	1

The values of h considered will be also show on Table 3 [5]:

Table 3. Convection Coefficient Typical Values

$h_1\ (\frac{W}{m^2K})$ Air free flow convective coefficient.	$h_2\ (\frac{W}{m^2K})$ Air forced flow convective coefficient.	$h_3\ (\frac{W}{m^2K})$ Water free flow convective coefficient.
20	100	500

Recalling the notation, the index 1 is referred to static air (ambience), 2 is referred to air in motion (by fan) and the index 3 is referred to the value of the coefficient for water light motion (sprayed water by a pump) .

On the other hand, the values of T_a (room temperature) and G (sun irradiation) will be considered variable on the study, because they depend on time (hourly, daily, monthly or yearly basis) . On this work, have been considered the hourly values of a whole day on the middle day of each month (15^{th}) expanded to the twelve months of a year.

The values of G and T_a have been obtained from the weather database PVGIS [6] for the 15^{th} day of each month of the year 2015. The values will be shown on the plots of Figure 4 and Figure 5, here as an example, the values corresponding to January, and the geographical location is Almeria (located on Andalucía, south of Spain), the values corresponding to the other months are added to the Annex I and II.

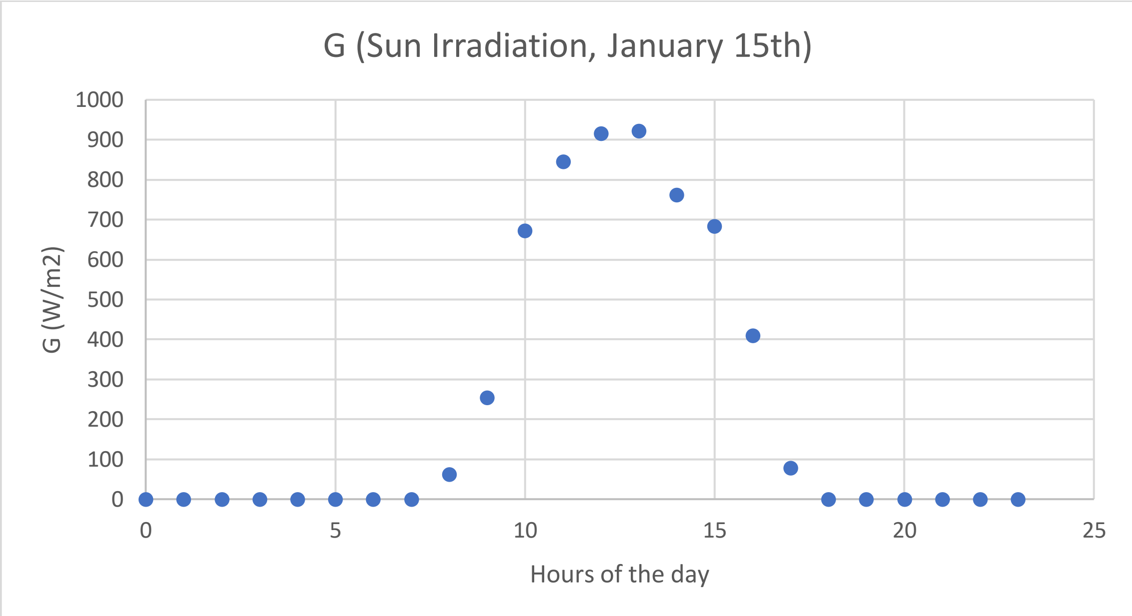

Figure 4. Horizontal Sun Irradiation (January)

In this plot (Figure 4) the values of the sun irradiation G can be seen on a hourly basis from the 00:00 to 23:00 hours of the day, as expected there's no radiation on the night hours, on dawn the value rises reaching its maximum peak at mid-day, and then, the value decreases corresponding to dusk, and zero again in the night hours.

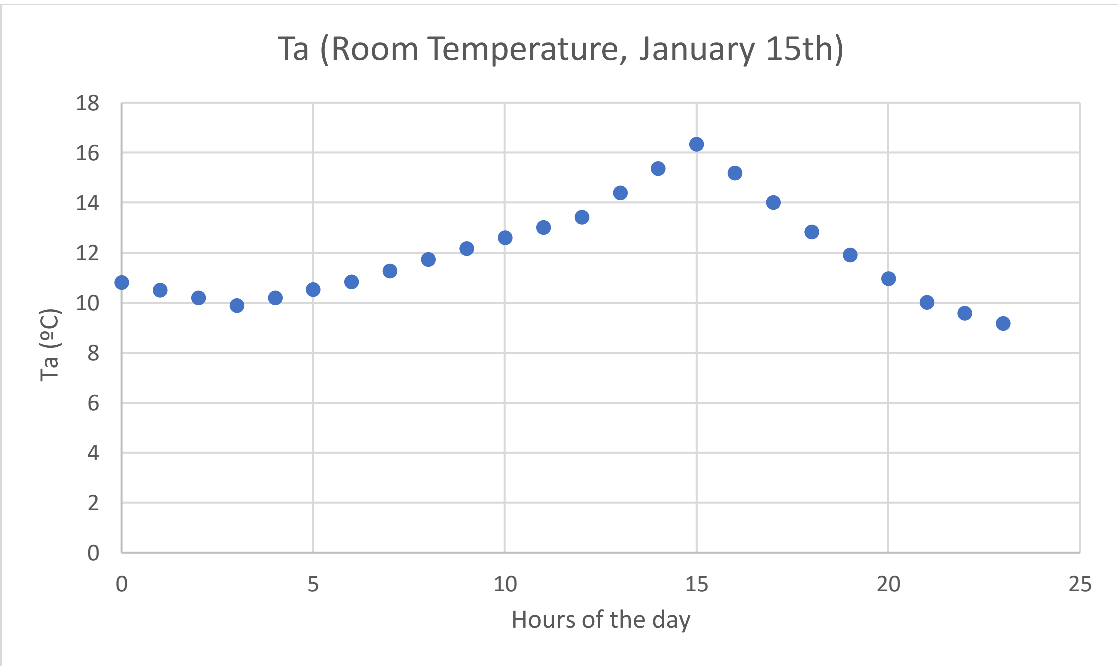

Figure 5. Room Temperature (January)

The plot of Figure 5i shows the values of the room temperature T_a on a day basis range (January 15th) as expected the lower temperatures are corresponding to the night hours, and the higher temperatures on the mid-day when the sun is on the top of the sky.

Once we have the parameters settled to the numerical values, we solve the equation **(8)** and obtain the values of T for each hour of the day (according to G and T_a) , also we will vary the value of h by considering the different h_i, so, we will obtain a set of hourly values of T_i for the 15th day of each month.

The method for solving the equation **(8)** is based on the GRG Non Linear method (Excel). Once the equation is solved, the values of T_i will be shown on Figure 6, for example for the month of January.

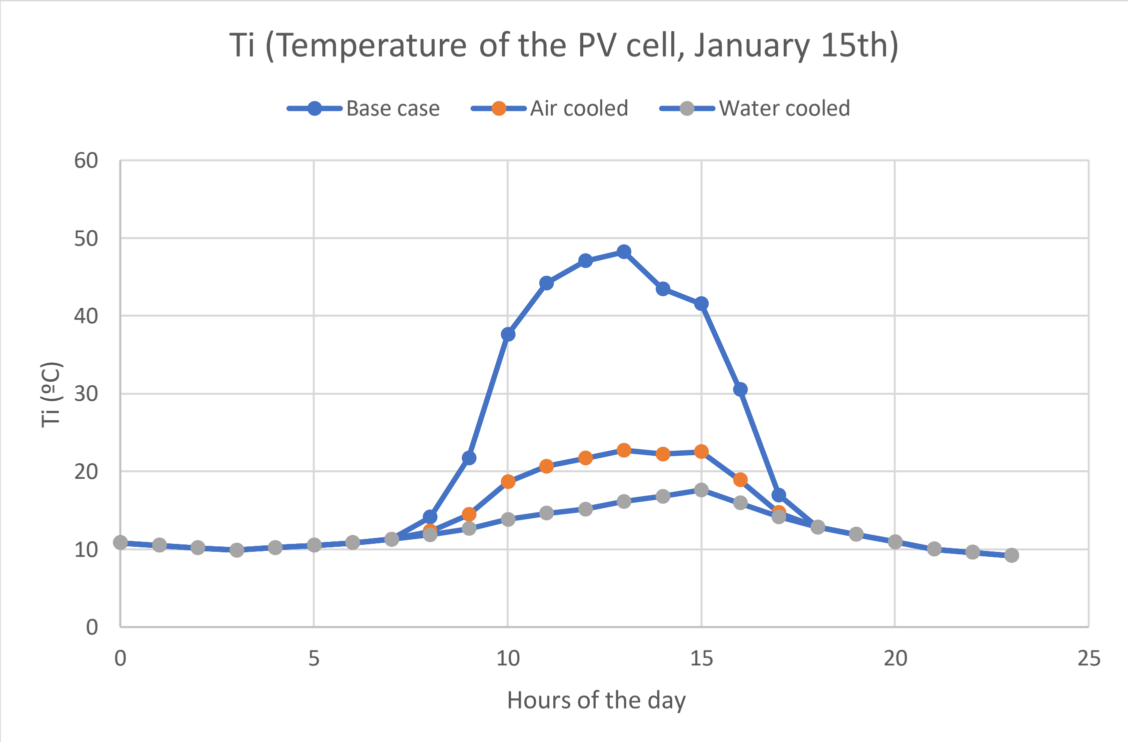

Figure 6. Cell Surface Temperature (January)

Figure 6 shows the values of the PV cell temperature (T_i) on the three series corresponding to the temperatures of the system if it is cooled by air or water, or the base case (no cooling applied) . There is a evident variation of the system temperature reached by each series, with the higher values of T corresponding to the base case (no cooling) and lower values of T with the two cooled series (as naturally expected), Figure 6 also shows the water cooled series is getting a lower temperature than the air cooled series. This is also a expected behavior due to the upper value of the convective coefficient h for water. The shape of the series tendencies is similar to the shape of the series showed in Figure 4 (plot for sun irradiation G) because the factor that contributes to the PV cell heating (increase of T due to an energy input) is only G (sun irradiation).

The hourly temperatures corresponding to the twelve months can be seen in the Annex III.

When seeing the hourly distribution for temperature (for the twelve months) on the central day of each month (15th), there may be some peaks and irregular shapes, this is caused because from the data exported from the weather station, we can't assure the day is clear, the appearance of clouds while the sensor is taking the values of sun irradiation can lead to a shutdown of the value, and so does the temperature.

4.4. Current and power analysis

Once the hourly temperature dataset for the central day of the twelve months of the year are obtained, we can evaluate the hourly values of current, *I*, and power, *P*, and obtain new datasets of each one, here will be shown the tendencies for a month and the rest will be added to the Annex.

First, by seeing the equations **(1)** to **(5)** we need to express the current I in a implicit way, so:

$$I - I_{ph} - I_D - I_{Rp} = 0 = f(T, V) \quad \textbf{(9)}$$

Expressing the equation in the original terms:

$$I - [I_{sc} + k_i \cdot (T - T_n)] \cdot G - \frac{I_{sc}}{e^{\left(\frac{q \cdot V_{OC}}{n \cdot N_S \cdot k \cdot T}\right)} - 1} \cdot \left(\frac{T}{T_n}\right)^3 e^{\left[q \cdot E_{go}\left(\frac{1}{T} - \frac{1}{T_n}\right)\frac{1}{n \cdot k}\right]} - \frac{V + I \cdot R_s}{R_p} = 0 \quad \textbf{(10)}$$

Here, for solving the equation, we will try to adequate the parameter N_s to a real case/approximation. Recalling N_s is the number of solar cells connected in series on the whole system, we will consider $N_S = 50\ cell$ for it's the mean and standard of solar cells (the number may differ from 40 to 140) taking as reference [7].

For $N_s = 50\ cell$, we also in the previous study know the voltage fixed for each PV cell is approximately to $V_{PVCell} = 0.5 \frac{V}{cell}$ and by doing the extrapolation to the total number of cells:

$$V_{PVArray} = V_{PVCell} \cdot N_s = 0.5 \frac{V}{cell} \cdot 50\ cell = 25\ V$$

From now on, it will be simply called V instead of $V_{PVArray}$

We will also fix the power rating for the PV Panel (Peak Capacity) as a value of $P_{PVArray} = 200\ Wp$, from now on just noted as P. We take as an reference, the model from [3] .

On that situation, all the values of equation **(10)** are known and the values I_i will be calculated for the central day of each month by each set of T_i obtained. Once we have calculated the I_i set, we can obtain the set of power outputs by simply multiplying the I_i by the fixed V value:

$$P_i = I_i \cdot V \quad \textbf{(11)}$$

Now, in Figure 7, the P_i series has been plotted for the central day of January. The twelve months of the year are available in the Annex V.

Additionally, on posterior sections, will be discussed the accuracy of the results on the discussion section, when comparing the I_i dataset with the I theoretical value obtained from [3].

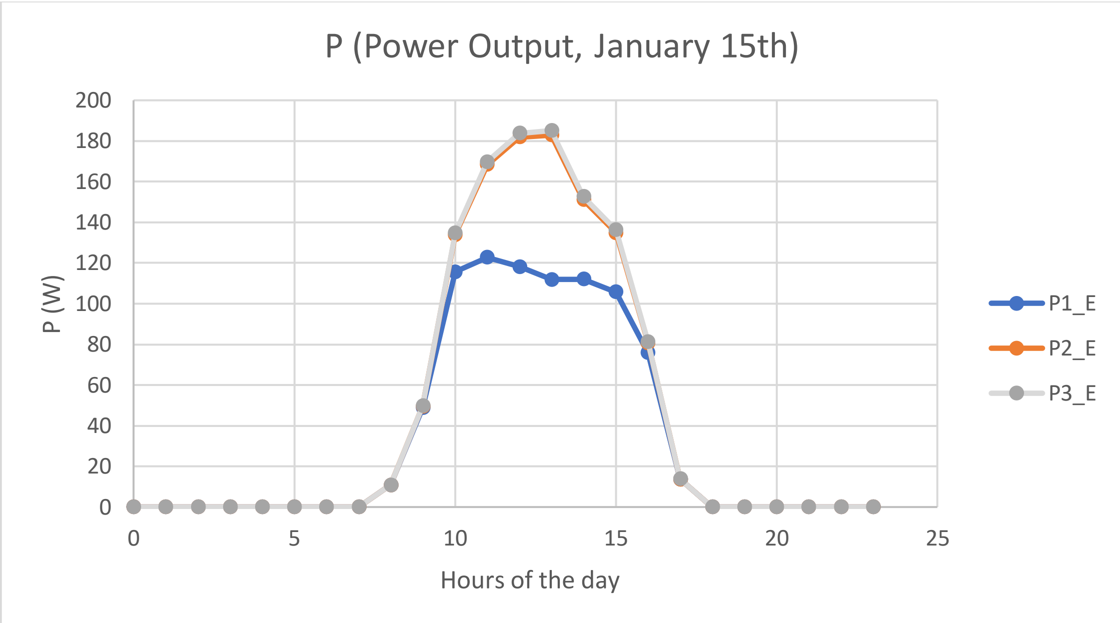

Figure 7. Power Output from PV Panel (January)

From this series, we can see there's a surplus of power output coming from P_2 and P_3 (air-cooled and water-cooled) compared to P_1 (base case), so the benefits from cooling in a first instance are shown. We can also see that there's not much difference between the P_2 and the P_3 series in terms of power output. Although the P_3 series (water-cooled) is coming from using water as a cooling fluid which got a lower temperature on the system than using the air-cooled solution, that difference of temperatures isn't not translated into an improvement of power output due to the nature of the current (I expression). As can be seen in **(10)** the temperature T mostly appear into the exponential term ($\sim e^{\left(\frac{1}{T}\right)}$) and a lineal variation in T (got in water-cooled against air-cooled) isn't translated onto the same variation on $e^{\left(\frac{1}{T}\right)}$ which is dominant on the I expression.

For knowing whether using air or water (the most suitable option), two major questions must be considered:

- Is the reservoir of the natural resource feasible to be accessed?
- What is the complexity and costs of the system for using and distribute the water or air?

In terms of the natural resource, the air is more accessible than water because is everywhere in the planet, meanwhile the water access isn't not on all places to be reached. So, the air is the better option considering this first question.

Talking about the system that must provide the water or air on the scope of this work, the air will be provided by a fan that will take the ambient air and boost it onto the surface of the solar array, the motioned air will have the convection coefficient h_2. The water, on the other hand, must be taken from the located natural resource (a well, a pond, a lake, the sea…) and extracted from it with the help of a pump and a hydraulic system (based on pipes) and finally will be sprayed to the surface of the solar array, acting with the convection coefficient value h_3. Between these two options, the more complex one is the water system, due to the complexity of the hydraulic system (pressure drops must be calculated) and the pump performance is more difficult than the fan, plus, in terms of economic cost, the water system for sure will be more expensive than the air.

By asking those questions (technical and economic) the air system seems to be a better option than the water system. On the next sections this matter will be justified with data.

5. Calculations of energy output

Once we have calculated the P_i sets of hourly power output, we could extrapolate this from the central day of the month (15th) to the whole month by simply multiplicate the power production of the day by the total days of the month (assumed on average to be 30), so, as follows:

$$E_{MONTH} \left[\frac{Wh}{month}\right] = P_i\,[W] \cdot \frac{24h}{1\,day} \cdot 30\,\frac{day}{month} \qquad \textbf{(12)}$$

If we want to obtain this result on the annual base, being different the power out value each month:

$$E_{ANNUAL} \left[\frac{Wh}{year}\right] = \sum_{k=1}^{12} P_k\,[W] \cdot \frac{24h}{1\,day} \cdot 30\,\frac{day}{month}$$

5.1. Gross energy output

We will procedure this way for the three power series P_i with $i = \{1,2,3\}$, we obtain the results summarized in Table 4.

Table 4. Gross Monthly (Annual) Energy Output (Base/Air/Water)

	E (kWh)											
	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Base	25.05	29.84	18.32	14.45	20.88	21.20	6.71	10.52	16.34	21.27	22.61	21.43
Air	33.23	39.61	19.58	15.84	38.45	29.10	36.55	26.15	38.74	36.76	33.52	24.29
Water	33.53	39.92	22.25	16.00	39.62	29.74	40.86	28.18	40.17	37.63	34.07	24.42
	Annual											
Base	228.64											
Air	371.82											
Water	386.40											

Figure 8 shows the evolution of the monthly gross energy output:

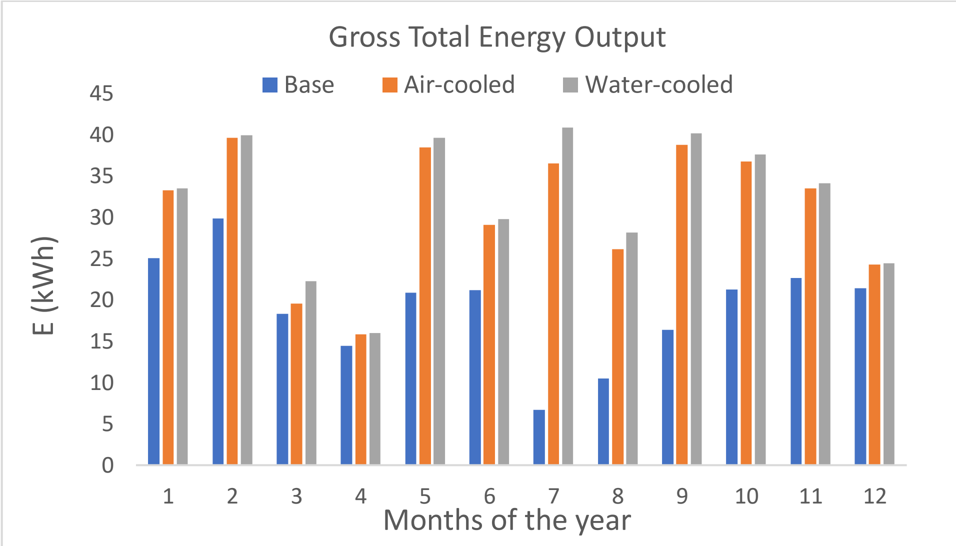

Figure 8. Gross Monthly Energy Output (Base/Air/Water)

Figure 9 shows the annually accumulate series of gross energy output:

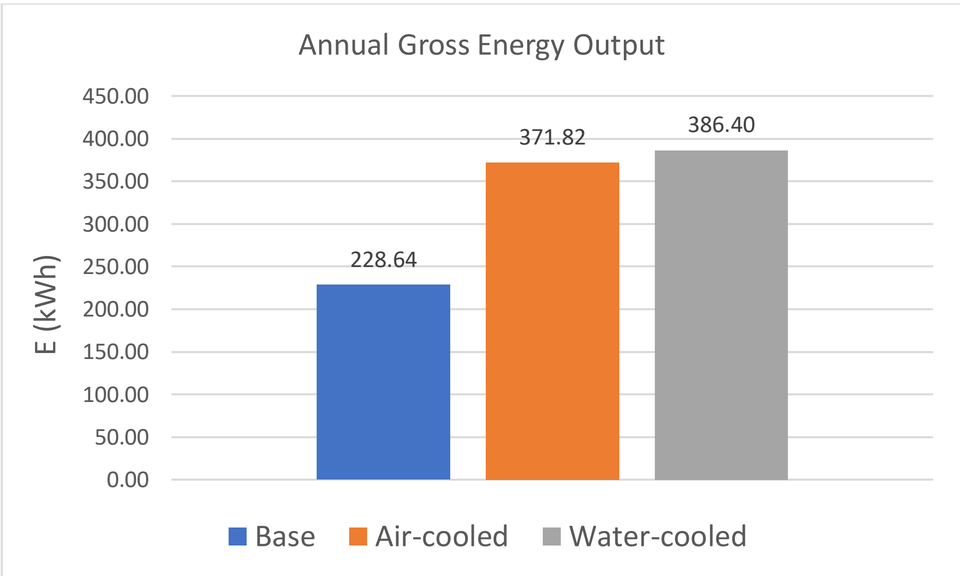

Figure 9. Gross Annually Energy Output (Base/Air/Water)

An improvement on the energy output it's seen on the cooled series (both air and water) versus the base case, so, in a first approximation, using the cooling systems is beneficial in terms of energy output.

Now, comes the question of considering the Gross Total Energy Output against the Net Total Energy Output, the main differentiation is the considering (or not) the consumption of the subsystems involved on the cooling process. On the previous results we have included the effect of cooling (resulting on the energy output surplus compared to the base case) but we haven't considered the energy consumption of the subsystems, when considered, we would have a penalization of the energy output, so for a net energy output result we must subtract to the gross total energy output the subsystem consumption in order to have the net total energy output, which is an approximation to the real case for having in account the whole system.

If the net total energy output is higher than the case base, then, we obtain a legit surplus and the cooling system can be considered for the use, on the contrary, if the net total energy output is lesser than the case base, this situation is discarded because the cooling system consumption is higher than the energy output surplus and makes no sense to implement it.

5.2. Cooling Systems (Operation)

For evaluating the cooling subsystem consumption, the energy of both the fan and the pump (and hydraulic system) will be considered on the next section.

The first thing to be evaluated is the surface S in m^2 that needs to be cooled, in this work, having in account the commercial model of solar array in the first section, the surface is $S = (1332 \cdot 992)\ mm^2 = (1{,}332 \cdot 0{,}992)\ m^2 = 1{,}32\ m^2$ and eventually this surface will be hot and in need of cooling, the energy of both the fan and the pump must be choosen to give a proper cooling service.

The chosen fan for the study, from [8] which is an axial fan of covering surface of $S = (220 \cdot 220)\ mm^2$ and since the airflow is tangential to the surface and sufficient airflow $(Q = 790 \frac{m^3}{h})$ it will fully cover it. The consumption of this fan is $W_{FAN} = 35\ W$. Secondly, The chosen water pump from [9] which has a consumption of $W_{PUMP} = 80\ W$ providing a water flow of approximately $(Q = 1 \frac{l}{s})$ which is enough for spraying all over the surface, plus, if we take in account the pressure drop energy consumption of the pipe system with an 10 % of the total energy consumption, we can estimate the total power consumption in $W_{PUMP} = 90\ W$.

5.3. Net Energy Output

Now, that we have chosen the cooling systems, we must evaluate its performance during the operation of the solar array.

First, the cooling purpose will be needed when the solar panel surface is hot enough for lowering its efficiency. From [10] (widely, among others) it's known that the optimal performance conditions of the panel are $T = 25\ ºC$ for the temperature and $G = 1000 \frac{W}{m^2}$ for the sun irradiation. So, a binary control will be implemented for taking in account the discontinuous operation of the cooling system.

$T > 25\ ;\ P = (P_2\ , P_3)$

$T \leq 25\ ;\ P = P_1$

When the temperature is superior to 25 ºC, the refrigeration is activated because we surpass the optimum limit temperature and we get the power cooling output. When the temperature is lower of 25 ºC isn't activated (base power output).

Table 5 shows the evolution of the net monthly energy output:

Table 5. Net Monthly (Annual) Energy Output (Base/Air/Water)

	E (kWh)											
	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Base	25.05	25.05	18.32	14.45	20.88	21.20	6.71	10.52	16.34	21.27	22.61	21.43
Air	25.85	24.82	14.93	8.41	26.88	16.49	17.64	7.24	27.17	26.26	25.09	17.95
Water	14.62	16.40	8.07	-2.92	9.91	-2.66	-7.75	-20.42	10.47	10.63	12.47	8.21
	Annual											
Base	223.85											
Air	238.74											
Water	57.03											

Evaluating the % of annual energy efficiency (η) (respect to the gross case) for each net system (air and water), considering the power output in the gross case to be the 100% (maximum power output available) :

$$\eta_{AIR}\ (\%) = \frac{238,74}{371,82} \cdot 100 \equiv 64,20\ \%$$

$$\eta_{WATER}\ (\%) = \frac{57,03}{386,40} \cdot 100 \equiv 14,75\%$$

Here it's seen the air system is closer (in power output terms) to the gross result (once diminished the value of the auxiliar subsystems) and the value is much higher than the water. This fact, could be also seen by the power losses (which is the complementary to the efficiency):

$$\Delta L_{AIR}\ (\%) = (100 - 64,20)\ \% = 35,2\ \%$$

$$\Delta L_{WATER}\ (\%) = (100 - 14,75)\ \% = 85,25\ \%$$

The water case has dramatic losses (85,25 %) respectively to the air case (35,2 %) once considered the whole system. This is logically reflected in the net final annual energy value as seen in Table 5:

$$E_{AIR} = 238.74\ kWh$$

$$E_{WATER} = 57.03\ kWh$$

The values of Table 5 are monthly plotted on Figure 10:

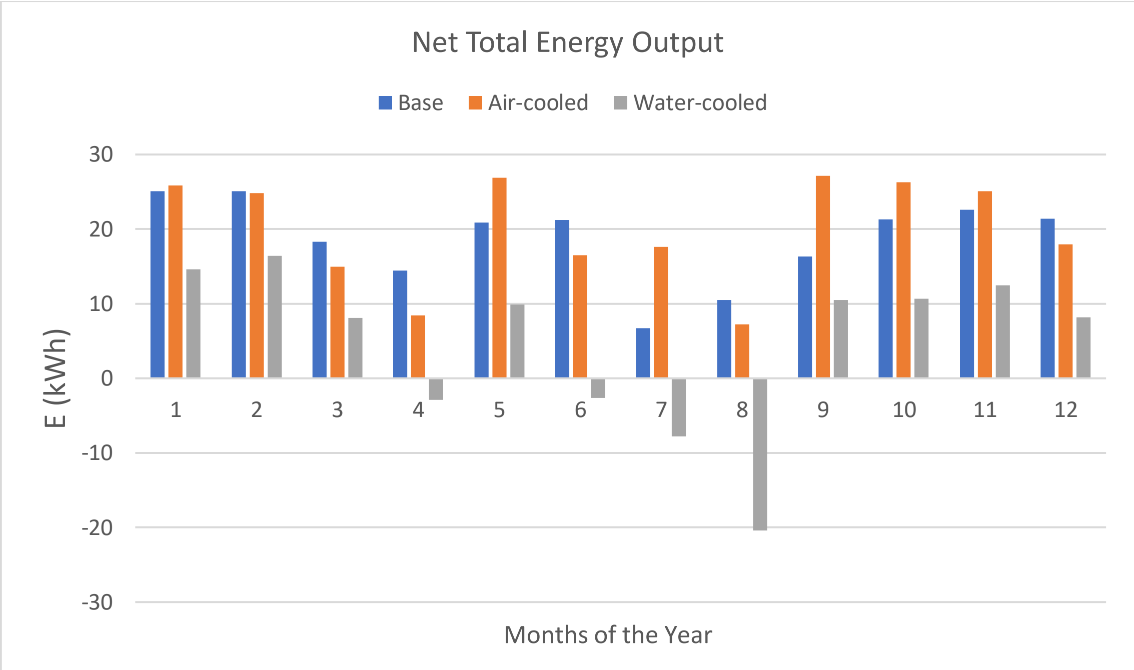

Figure 10. Net Monthly Energy Output

It is seen in Figure 11 that there are even months with negative values of power output (which is in fact, a power consumption).

Annual accumulation (Figure 11) can be seen the previous commented energy values.

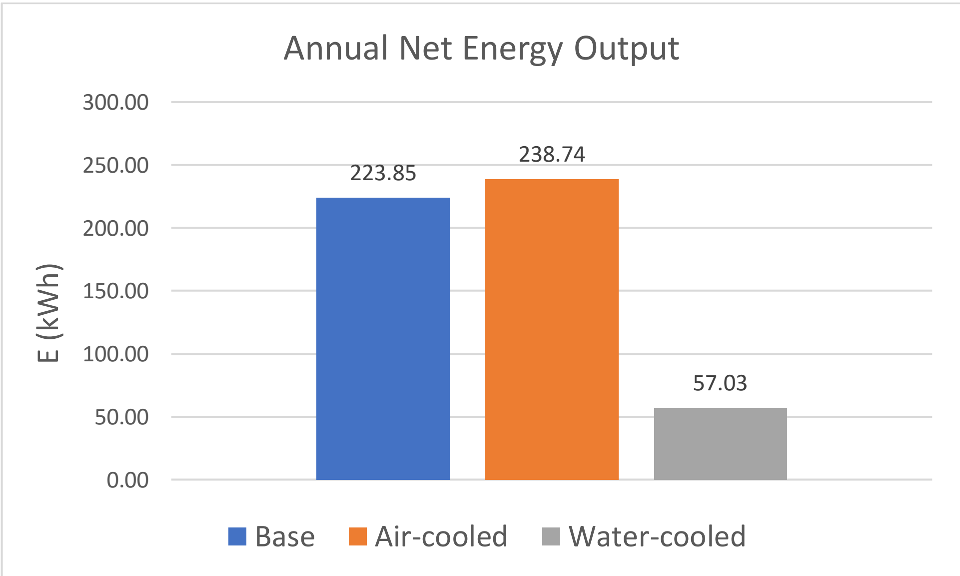

Figure 11. Net Annually Energy Output

Also, as a global result, the water series is being really diminished against the air series (due to a minor consumption) and the most suitable option in terms of power output is the air series. We can conclude, for the next economic evaluation that the two options considered will be the base case and the air-cooled series.

6. Economic Evaluation

On this section, the economic aspects of the two chosen options (base and air-cooled) will be evaluated in two scenarios (residential and industrial) for both of them, the economic expression of the NPV (Net Present Value) will be used:

$$NPV = -C_O + \sum_{i=0}^{N} C_i \cdot \frac{(1 + \Delta p_E)^i}{(1 + k)^i}$$

On this expression, we identify the following terms:

C_O is the investment cost (initial cost) of the evaluated system.

C_i is the economic gain derived from the photovoltaic production.

Δp_E is the variation of the electric energy prices.

k is the discount rate, assumed in this case as an 3% annual variation [20].

N are the evaluated years for the expression, considered to be 25 (the expected live of the system).

For simplifying the previous expression, a equivalent discount rate k_{eq} can be defined taking into account the effect of Δp_E :

$$\frac{1 + \Delta p_E}{1 + k} = \frac{1}{1 + k_{eq}}$$

So, the expression of NPV:

$$NPV = -C_O + \sum_{i=0}^{N} C_i \cdot (\frac{1}{1 + k_{eq}})^i$$

On the simplified model, the annual economic revenue C_i will be considered constant (C_E) through the years of evaluation, so:

$$NPV = -C_O + C_E \cdot \sum_{i=0}^{N} (\frac{1}{1 + k_{eq}})^i$$

For the sum series, it can be also considered the next simplification, knowing the mathematical expression of the geometric series:

$$S_n = \sum_{i=0}^{N} r^i = \frac{1 - r^{N+1}}{1 - r}$$

So, identifying r as $\frac{1}{1+k_{eq}}$:

$$NPV = -C_O + C_E \cdot \left(\frac{1 - \left(\frac{1}{1 + k_{eq}}\right)^{N+1}}{1 - \frac{1}{1 + k_{eq}}} \right)$$

Previous to the numeric evaluation of NPV, the value of Δp_E will be obtained.

For knowing the value of Δp_E we will consider the inter-annual variation of the energy prices [11] taking as reference the mean price values (€/MWh) across the years (2019 to 2022) shown in Figure 13.

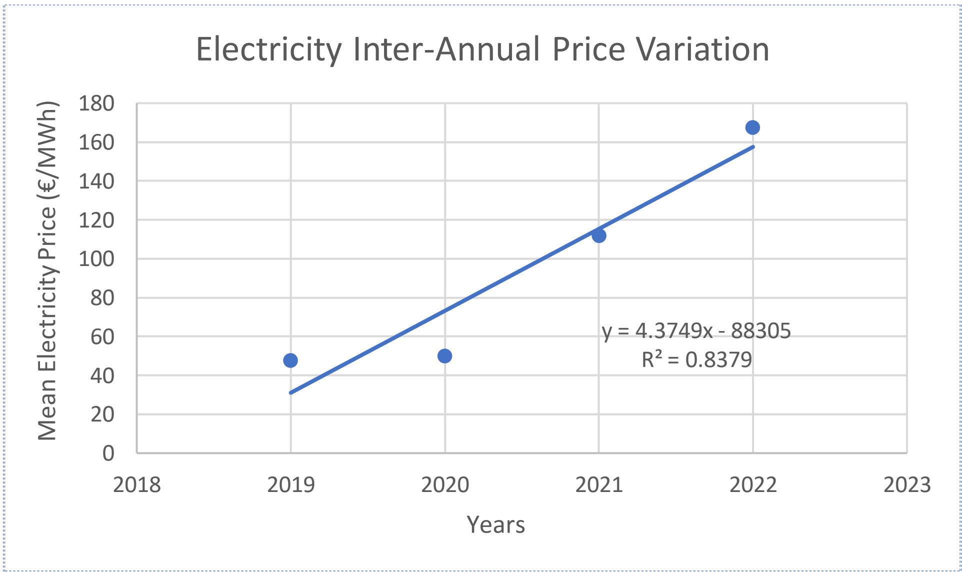

Figure 12. Electricity Inter-Annual Price Variation

In this case, once plotted the two series, for obtaining the value of Δp_E the value of the equation slope $m = 4{,}375 \; \frac{\frac{EUR}{MWh}}{year}$ and it's normalized by the maximum value of all periods $p_M = 167{,}52 \; \frac{\frac{EUR}{MWh}}{year}$, then:

$$\Delta p_E = \frac{m}{p_M} = \frac{4{,}375 \; \frac{\frac{EUR}{MWh}}{year}}{167{,}52 \; \frac{\frac{EUR}{MWh}}{year}} \equiv 0{,}02$$

This approximation will be considered for the NPV evaluation.

The exact value of the NPV can be calculated by knowing that:

$\Delta p_E = 0{,}02$

$k = 0{,}03$

$N = 25$

$$\frac{1 + \Delta p_E}{1 + k} = \frac{1}{1 + k_{eq}} = \frac{1 + 0{,}02}{1 + 0{,}03} = 0{,}99$$

$$\left(\frac{1 - \left(\frac{1}{1 + k_{eq}} \right)^{N+1}}{1 - \frac{1}{1 + k_{eq}}} \right) \rightarrow \left(\frac{1 - (0{,}99)^{26}}{1 - 0{,}99} \right) = \frac{1 - 0{,}77}{1 - 0{,}99} \equiv 23$$

So, approximately:

$NPV = -C_O + 23 \cdot C_E$

Is the expression that will be used on the next sections.

The signs of the expression (plus or minus) are arbitrary if it's referred as a NPV only for expenses or the general expression. On this case, we are using the general expression because C_O has a negative sign (because it's a cost) and the sum term is positive (because the photovoltaic production is evaluated at the market price and considered as a profit), thus the addition of the two terms expressed above will result on a positive, zero or negative NPV value, the desirable case is the positive one because it means that the economic profit from operation is higher than the initial investment (cost) .

An approximation to the simple payback can be expressed through the simple return time of the inversion or simple payback (t_R) when $NPV = 0$.

$NPV = 0 = -C_O + t_R \cdot C_E$

So:

$$t_R = \frac{C_O}{C_E}$$

This parameter will be evaluated on all the cases for the estimation of the inversion return.

Additionally, a certain discount rate k could nullify the value of NPV, this k is called IRR (internal rate of return) and its expression:

$$0 = -C_O + \sum_{i=0}^{N} C_i \cdot \frac{(1+\Delta p_E)^i}{(1+IRR)^i}$$

The analytic (or numerical) solution of the previous equation deliver the value of IRR.

A more simpler expression can be used for the IRR calculation on a simple approximation by knowing the value of t_R (simple payback):

$$IRR \approx \frac{1}{t_R}$$

Subsequently, IRR will be calculated by approximation instead of using the analytical expression.

6.1. Domestic Home Case

For the domestic home case, the two options will be evaluated (base case and air-cooled). Prior to the evaluation it's mandatory to know about the sizing of photovoltaic arrays to be considered on the energy production (and posterior economic evaluation). For this, the solar power capacity will be seized on function of the electricity consumption of the building. The typical consumption values will be searched on the data based on [12].

From [12], it's known that the typical annual consumption of a single family home is approximately $C_{ANUAL} \equiv 4000 \frac{kWh}{year}$ not taking into account the differences between climatical zones (hot ones vs cold ones) and the differences between extreme consumption habits (the reference is a mean value)

For sizing the PV capacity, it's taken in account the hours of annual performance hours of the solar arrays [13]:

$$t_P = 6\,\frac{hour}{day} \cdot 30\,\frac{days}{month} \cdot 12\,\frac{month}{year} = 2160\,\frac{hour}{year}$$

Now, the peak system capacity can be obtained:

$$P_{SYSTEM} = \frac{C_{ANUAL}}{t_P} = \frac{4000\,\frac{kWh}{year}}{2160\frac{h}{year}} = 1{,}85\,kWp \equiv 2\,kWp$$

The type of PV array was chosen with a capacity of $P_{PANEL} = 200\frac{Wp}{panel}$ so, the number of panels to be seized:

$$N_{PANEL} = \frac{P_{SYSTEM}}{P_{PANEL}} = \frac{2000\,Wp}{200\frac{Wp}{panel}} \equiv 10\,panel$$

Now, knowing the energy production per panel (calculated previously on both cases) and the electricity cost (unitary prices obtained from OMIE), it can be monthly (on the central day of the month) obtained the economic revenue for the two scenarios. The economic revenue, in that situation, is calculated as follows:

$$C_i\ [€] = \sum_{t=0}^{23} C_t\ [€] = \sum_{t=0}^{23} c_t \left[\frac{€}{kWh}\right] \cdot E_t\ [kWh] = \sum_{t=0}^{23} c_t \left[\frac{€}{kWh}\right] \cdot P_t\ [kW] \cdot T[h]$$

Where the variable t represent a generic hour of the central day of each month considered, the summatory is extended from the 0 hours (considered to be 00:00) until the value 23 (23:00) and its scope is extended to the whole day. c_t is the unitary price of energy at the hour t considered and E_t is the energy output at the hour T (in this case, is specified as an constant hour gap) (obtained by multiplying the power output P_t by one hour T) and by multiplying these two factors C_t is obtained which is the economic revenue in each hour t and extending the summatory to all the hours, the total economic revenue of the central day C_i is obtained. By plotting those values monthly and through the year the tendencies shown in Figure 13 are obtained.

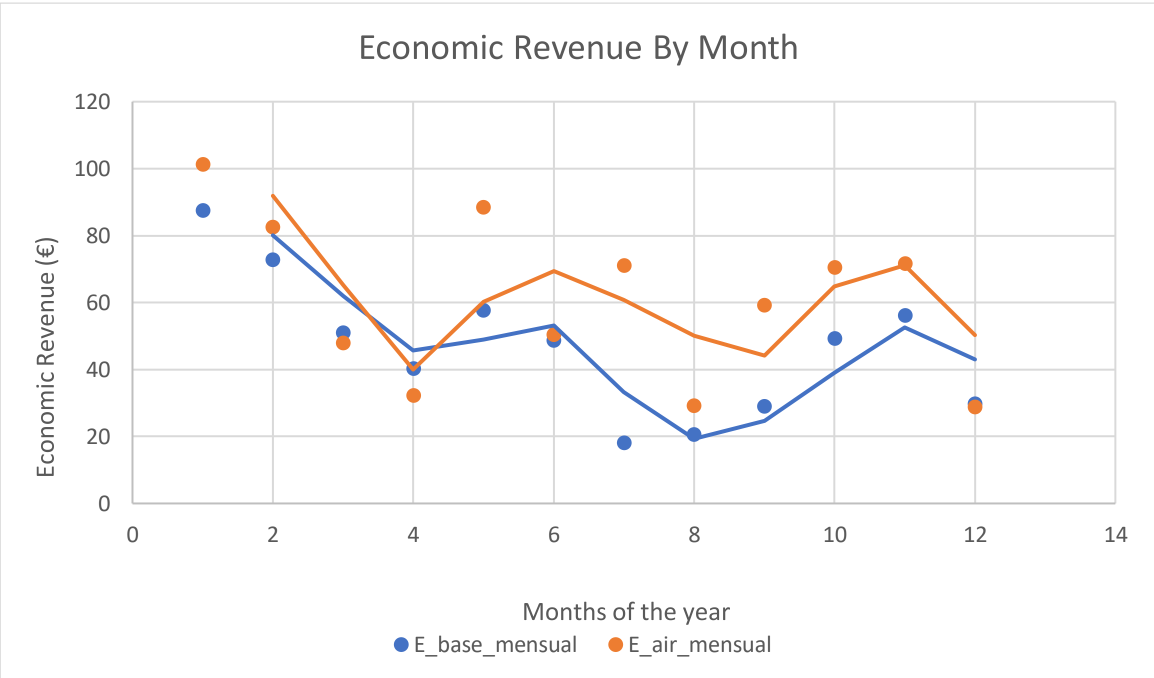

Figure 13. Monthly Economic Revenue

The two tendencies through the year are, base case (blue) and air-cooled (orange), it's clearly seen than the air case obtain a higher revenue (on most of the months) due to the higher power output, if we sum all the gain month (C_i) by month we obtain the annual total revenue C_A for each tendency:

$$C_A\,[€] = \sum_{i=1}^{12} C_i\,[€]$$

Where the index i goes through January $(i = 1)$ to December $(i = 12)$, this result is obviously normalized by year evaluated and corresponding to the energy delivered for unitary solar array, so, for the two series:

$$C_{A-BASE} = 560{,}38\,\frac{€}{year \cdot panel}$$

$$C_{A-AIR} = 732{,}95\,\frac{€}{year \cdot panel}$$

If it's extrapolated taking in account, the whole domestic system (considering all the solar arrays), the annual value (C_T) is obtained:

$$C_{T-BASE} = 560{,}38\,\frac{€}{year \cdot panel} \cdot 10\,panel = 5603{,}8\,\frac{€}{year}$$

$$C_{T-AIR} = 732{,}95\,\frac{€}{year \cdot panel} \cdot 10\,panel = 7329{,}5\,\frac{€}{year}$$

Now, we evaluate the initial cost C_O of the system considering the proposed model on the previous sections. C_O will comply with the cost of the solar arrays [3], the inverter technology [14] and the installation/reposition cost [14]:

$$C_{O-BASE} = \left(300\frac{€}{panel} \cdot 10\,panel + 1000\,€\right) \cdot 1{,}1 = 4400\,€$$

Additionally, on the air-cooled case, it's also included the fan cost [8]:

$$C_{O-AIR} = \left(300\frac{€}{panel} \cdot 10\,panel + 200\,\frac{€}{fan} \cdot 10\,fan + \;1000\,€\right) \cdot 1{,}1 = 6600\,€$$

In that situation, the NPV for both cases is:

$$NPV_{BASE} = \;-4400 + 23 \cdot 5603{,}8 = 124487\,€ = 0{,}12\,M€$$

$$NPV_{AIR} = \;-6600 + 23 \cdot 7329{,}5 = 161987\,€ = 0{,}16\,M€$$

So, we can conclude that being positive is a profit situation and since $NPV_{AIR} > NPV_{BASE}$, the cooled-air option is more profitable than the base case even if is the initial cost is superior.

Additionally, the simple payback:

$$t_{R-BASE} = \frac{C_{O-BASE}}{C_{T-BASE}} = \frac{4400\,€}{5603{,}8\,\frac{€}{year}} = 0{,}78\,year\; \equiv 1\,year$$

$$t_{R-AIR} = \frac{C_{O-AIR}}{C_{T-AIR}} = \frac{6600\ €}{7329{,}5\ \frac{€}{year}} = 0{,}90\ year\ \equiv 1\ year$$

Both situations (base and air-cooled) are retributed in a period inferior a one year.

The value of IRR by approximation:

$$IRR_{BASE} \approx \frac{1}{t_{R-BASE}} = \frac{1}{0{,}78\ year} = 1{,}28\ \frac{1}{year}$$

$$IRR_{AIR} \approx \frac{1}{t_{R-AIR}} = \frac{1}{0{,}90\ year} = 1{,}1\ \frac{1}{year}$$

6.2. Industrial Case

Proceeding equivalently with the industrial case, the two options will be evaluated (base case and air-cooled), and prior to the evaluation it's estimated the industry consumption. From [12] (IDEA) it's considered a manufacturing industry with an mean annual consumption $C_{ANUAL} \equiv 150 \frac{MWh}{year}$.

For sizing the PV capacity, it's taken in account the hours of annual performance hours of the solar arrays [13]:

$$t_P = 2160\ \frac{hour}{year}$$

Now, the peak system capacity can be obtained:

$$P_{SYSTEM} = \frac{C_{ANUAL}}{t_P} = \frac{150\ \frac{MWh}{year}}{2160\ \frac{h}{year}} = 69{,}4\ kWp\ \equiv\ 70\ kWp$$

The type of PV array was chosen with a capacity of $P_{PANEL} = 200 \frac{Wp}{panel}$ so, the number of panels to be seized:

$$N_{PANEL} = \frac{P_{SYSTEM}}{P_{PANEL}} = \frac{70000\ Wp}{200\ \frac{Wp}{panel}} = 350\ panel$$

The tarifary cost [15] and evaluated through the year with the production (two systems) follows the same procedure that the previous section (Section 6.1) and the results the same tendency that Figure 14, so it can be assumed the same energy production tendency from the individual panel.

If it's extrapolated taking in account, the whole system:

$$C_{T-BASE} = 560{,}38 \ \frac{EUR}{year \cdot panel} \cdot 350\, panel = 196133 \ \frac{EUR}{year}$$

$$C_{T-AIR} = 732{,}95 \ \frac{EUR}{year \cdot panel} \cdot 350\, panel = 256532{,}5 \ \frac{EUR}{year}$$

Now, we evaluate the initial cost C_O of the system considering the proposed model on the previous sections. C_O will comply with the cost of the solar arrays [3], the inverter technology [14] and the installation/reposition cost [14]:

$$C_{O-BASE} = \left(300 \frac{EUR}{panel} \cdot 350\, panel + 1500 \frac{EUR}{inverter} \cdot 1 \frac{inverter}{string} \cdot 14\, string\right) \cdot 1{,}1 = 138600\, EUR$$

And the air-cooled case [8]:

$$C_{O-BASE} = \left(300 \frac{EUR}{panel} \cdot 350\, panel + 200 \frac{EUR}{fan} \cdot \ 350\, fan + 1500 \frac{EUR}{inverter} \cdot 1 \frac{inverter}{string} \cdot 14\, string\right) \cdot 1{,}1 = 215600\, EUR$$

In that situation, the NPV for both cases is:

$$NPV_{BASE} = \ -138600 + 23 \cdot 196133 = 4372459\, EUR \equiv 4{,}4\, MEUR$$

$$NPV_{AIR} = \ -215600 + 23 \cdot 256532{,}5 = 5684636 \equiv 5{,}7\, MEUR$$

The air-cooled case in this case is also superior to the base case $NPV_{AIR} > NPV_{BASE}$ so, in conclusion it’s chosen the air-cooled case against the base case configuration.

For this case, the recuperation of the inversion:

$$t_{R-BASE} = \frac{C_{O-BASE}}{C_{i-BASE}} = \frac{138600\, EUR}{196133 \ \frac{EUR}{year}} = 0{,}71\, year \ \equiv 1\, year$$

$$t_{R-AIR} = \frac{C_{O-AIR}}{C_{i-AIR}} = \frac{215600\, EUR}{256532{,}5 \ \frac{EUR}{year}} = 0{,}84\, year \ \equiv 1\, year$$

Both situations (base and air-cooled) are retributed in a period inferior a one year.

The value of IRR by approximation:

$$IRR_{BASE} \approx \frac{1}{t_{R-BASE}} = \frac{1}{0{,}71\, year} = 1{,}4 \ \frac{1}{year}$$

$$IRR_{AIR} \approx \frac{1}{t_{R-AIR}} = \frac{1}{0{,}84\, year} = 1{,}19 \ \frac{1}{year}$$

6.3. Economic Evaluation Summary

On the next table, the summary of the previous situations will be shown:

Table 6. Economic Evaluation Summary

	Home			Industrial		
	NPV (MEUR)	tR (years)	IRR (1/years)	NPV (MEUR)	tR (years)	IRR (1/years)
Base	0,13	0,78	1,28	4,4	0,71	1,4
Air-cooled	0,16	0,90	1,1	5,7	0,84	1,19

As concluded, the VAN value of the air-cooled systems in both cases (home and industrial) is higher than the base system, so it's more suitable for this configuration to be chosen over the base system. In both cases, the recuperation is short (less than a year) for the two configurations.

The variation (and improvement) respect to the base case is, for both home and industrial:

$$\Delta NPV_{HOME}(\%) = \frac{0{,}16 - 0{,}13}{0{,}13} \cdot 100 = 23{,}07\ \%$$

$$\Delta NPV_{INDUSTRIAL}(\%) = \frac{5{,}7 - 4{,}4}{4{,}4} \cdot 100 = 29{,}54\ \%$$

So, the air-cooled option is more profitable than the base case.

6.4. Economic Sensitivity Analysis

In this section, two situations will be studied and evaluated respect to the base case. One scenario, supposed the solar arrays increased the original price on a 20% [16] (real possible scenario due to the semiconductor volatility) and other scenario where the price energy is increased in a mean of 40% [17] (as seen in the year 2022 due to geopolitical matters) .

For the domestic case, those two scenarios will be evaluated.

For considering the increase of solar arrays price, it directly affects the value of C_O, so:

$$C_{O-BASE} = \left(300\frac{€}{panel} \cdot 10\ panel \cdot 1{,}2 + 1000\ €\right) \cdot 1{,}1 = 5060\ €$$

Additionally, on the air-cooled case, it's also included the fan cost [8]:

$$C_{O-AIR} = \left(300\frac{€}{panel} \cdot 10\ panel\ \cdot 1{,}2\ + 200\ \frac{€}{fan} \cdot 10\ fan + \ 1000\ €\right) \cdot 1{,}1 = 7260\ €$$

The NPV is evaluated, remaining constant the operational term:

$$NPV_{BASE} = \ -5060 + 23 \cdot 5603{,}8 = 123827\ € \equiv 0{,}123\ M€$$

$$NPV_{AIR} = \ -7260 + 23 \cdot 7329{,}5 = 161318\ € = 0{,}16\ M€$$

And comparing to the original situation:

$$\Delta NPV_{PV-BASE}(\%) = \frac{0{,}123 - 0{,}13}{0{,}13} \cdot 100 = -5{,}38\ \%$$

$$\Delta NPV_{PV-AIR}(\%) = \frac{0{,}1613 - 0{,}1619}{0{,}1619} \cdot 100 = -0{,}37\ \%$$

In both situations, there is a negative variation due to the higher initial cost, but due to the better performance of air system, the initial cost C_O has a lesser negative impact.

Now, the variation of electric price is evaluated. For this, in a simplified way of calculation, we consider the operational values and get them increased on a 40 %.

$$C_{T-BASE} = 5603{,}8\ \frac{€}{year} \cdot 1{,}4 = 7845{,}32\ \frac{€}{year}$$

$$C_{T-AIR} = 7329{,}5\ \frac{€}{year} \cdot 1{,}4 = 10261{,}3\ \frac{€}{year}$$

Again, the NPV value is evaluated, varying the operational value under those circumstances:

$$NPV_{BASE} = -4400 + 23 \cdot 7845{,}32 = 176042{,}36\ € = 0{,}176\ M€$$

$$NPV_{AIR} = -6600 + 23 \cdot 10261{,}3 = 229409{,}9\ € = 0{,}229\ M€$$

The variation respect the original is:

$$\Delta NPV_{PV-BASE}(\%) = \frac{0{,}176 - 0{,}13}{0{,}13} \cdot 100 = 35{,}38\ \%$$

$$\Delta NPV_{PV-AIR}(\%) = \frac{0{,}229 - 0{,}161}{0{,}161} \cdot 100 = 42{,}23\ \%$$

On both cases, the variation of prices gets a higher NPV than the original on the same range.

7. Discussions and Conclusions

On that section, first, several aspects of this work will be discussed for a different approach to other related circumstances. Secondly, conclusions about this work will be addressed.

7.1. Current Calculation Accuracy

The first aspect of the discussion is the accuracy on the current I calculated by using the numerical method (GRG Non Linear) for the different cases and datasets (I_i) how nearly is to the theoretical value derived from the datasheet considered values.

The final value of the I_i will differ with an error from the operational ones (may measured with sensors in system O&M mode) because the GRG Non Linear Method is limited for solving the equation **(10)** due to its complexity (Non linear terms and exponential functions) so the accuracy of the output results may not be the ideal for a more serious study (the optimal solution and more accurate is computed by using neuronal networks, among other methods, and is out of scope of this preliminary work).

A reference current I_R is calculated using the parameters of the sun array [3] and the considerations of Section 4.4, considering the nominal power of the sun array P_N and the calculated voltage V based on each PV cell individual voltage.

The calculation of I_R:

$$I_R = \frac{P_N}{V} = \frac{200\ Wp}{25\ V} \equiv 8\ A$$

This value, is the maximum value of the current I at standardized conditions, this value will be compared with the maximum value of each current set I_i (I_{i-MAX}) for each central day of the month and each month through the year.

This maximum current value is defined as:

$$I_{i-MAX} = \max\{I_i\}$$

And will be plotted on series with the constant value of I_R through the months on a annual basis as is shown on Figure 14.

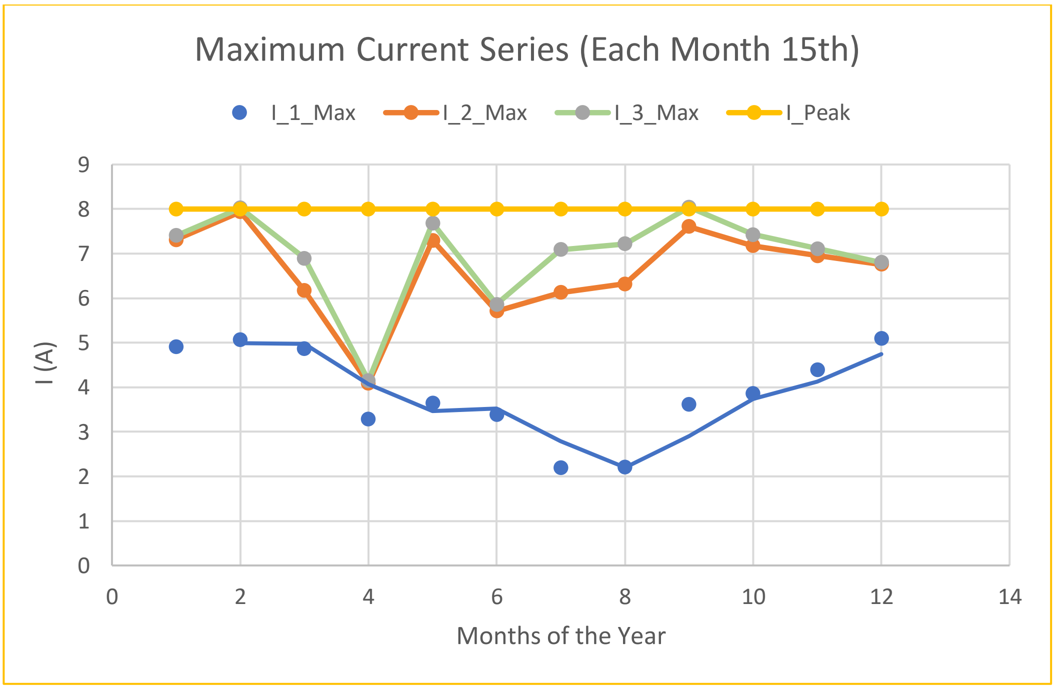

Figure 14. Maximum Current Series Comparation

From this picture, we can see the maximum current production on each month from the I_i compared to the theoretical result I_R . We could conclude that the output of results from the GRG Non Linear method (I_i) is underestimating the value of I_R due to the convergence difficult of the solution and the not perfect accuracy of the parameters values.

7.2. Other Considerations

On this section, other considerations are briefly noted:

- The value of V is fixed by considering a constant voltage drop ΔV on each solar cell as explained on Section 4.4 until the superior limit N_s. This value of V may vary depending on the type of the PV cell considered (different ΔV due to the microscopical properties of the semiconductor) and the number of PV cells (N_s) on the solar array considered.
- In the energy production E_i isn't considered the degradation of the power output (solar array) over the years [3] and is considered invariable all over the period for the electronic model to be easily modelled and calculated. Solar arrays show a degradation of the power output through its lifecycle due to the degradation of the electronic/electrical properties of the material, in a real case the power output P is diminished due to this effect. On this work, this effect is compensated because the current is diminished as explained on Section 7.1 but the power output is maximized as explained before (not temporary degradation considered).
- The values of C_i (cash flow) are calculated for a base year and supposed constant to all $N = 25\ years$ period of evaluation, it allows to simplify the NPV expression but it's not accurate because each year has a different P_i and c_i depending on the life stage of the solar array and weather conditions, the same applies for c_i (unitary price of energy) because is a geopolitical matter. The same conclusion for the expression and value of t_R and IRR.
- The calculations values have been considered from various sources including commercial products, meteorological stations and material properties as commented through the work and stated in References.
- This work is mainly focused on thermal, electrical and economic aspects of the cooling subsystems, but also must be considered the structural and mechanical aspect (inclusion and develop of the cooling subsystem) and comfort aspects (the noise produced by the operation of the fan must be bearable specially for the domestic user) .
- Convective coefficient h is the special key of this work, and the values have obtained from literature [5] but it may be tested on operation mode (experimental) to confirm those asseverations. It also applies for the performance of the cooling subsystems.
- A positive aspect of this work is about the crashing or failing of the cooling subsystems, if they fail, the solar array continues its performance (not shutting down, only be diminished its power output due to the lack of refrigeration) and just the cooling subsystem must be replaced.

7.3. Conclusions

Through this work, two cooling options (air and water) have been evaluated for improving the performance of a photovoltaic array with the following conclusions (in a first instance technical, in a second; economics)

1) Adding a cooling factor to the performance of a photovoltaic array shows an improvement on the power output performance (the temperature of the surface stays cold and there's no degradation of the power output compared to the base case)

2) When evaluated both air and water, water shows a better cooling potential than air (gets the surface in a $\Delta T = 10ºC$ cooler than air), however the lineal variation ΔT doesn't mean a significant improvement of the I (current production) because the expression of the current I has the term of temperature T on a exponential form $\sim e^{\frac{1}{T}}$, so when the power output is calculated $P_i = V \cdot I_i$ there's no signification between the air-cooled and water-cooled configuration.
3) The net power output is evaluated taking into account the auxiliar consumption of the cooling system of both air-cooled and water-cooled, by doing the analysis, the auxiliar water subsystem is more consuming than the air auxiliar system, so, the net power output of water isn't favorable and is discarded on this point. From now on, base and air-cooled cases are considered.
4) The economic evaluation of the base and air-cooled is based on the NPV value, two scenarios are considered (home and industrial case) with individual configurations, energy prices and photovoltaic sizing. So, four cases are evaluated, in all the cases the NPV value is positive (meaning a profitable investing) and the return of the inversion is short (less than a year)

So, concluding, the cooling scenarios are suitable and profitable to implement for a performance improvement of the photovoltaic array.

8. Annex

8.1. Annex I (Monthly Sun Irradiation, Central Day)

Table 7. Monthly Central Day G Values

G (W/m2)												
Hours	January	February	March	April	May	June	July	August	September	October	November	December
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	61,15	11,55	45,32	55,1	44,43	22,22	0	0	0	0
7	0	0	114,4	78,4	219,23	211,2	185,12	161,24	160,12	108,59	0	0
8	62,45	215,38	432,57	254,16	451,84	423,04	401,17	382,39	409,53	373,13	279,63	178,95
9	253,33	496,92	808,16	263,74	675,93	595,98	613,46	588,1	650,23	592,05	514,81	477,65
10	671,94	731,13	858,79	296,37	860,93	743,35	793,86	722,68	838,02	773,56	711,26	696,99
11	845,45	896,64	213,4	207,78	494,97	738,28	921,83	817,5	957,76	900,57	840,55	846,27
12	914,85	997,79	137,59	395,03	685,49	564,72	978,6	984,88	1026,49	937,6	892,69	684,27
13	922,17	917,68	602,65	527,05	980,28	367,05	990,97	465,23	758,3	853,68	854,37	380,79
14	762,4	860,69	333,67	341,35	820,45	311,99	899,1	328,85	831,76	756,24	752,1	510,7
15	682,73	764,23	128,54	138,52	674,26	237,76	747,23	280,54	705,24	583,85	562,8	251,75
16	409,65	524,97	75,59	123,55	507,35	444	565,95	214,96	382,24	364,56	309,22	61,43
17	77,65	239,01	8,23	113,33	265,67	321,67	341,6	198,57	135,52	125,9	0	0
18	0	0	0	41,63	95,49	108,45	125,51	97,56	27,61	0	0	0
19	0	0	0	0	10,66	31,99	30,22	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

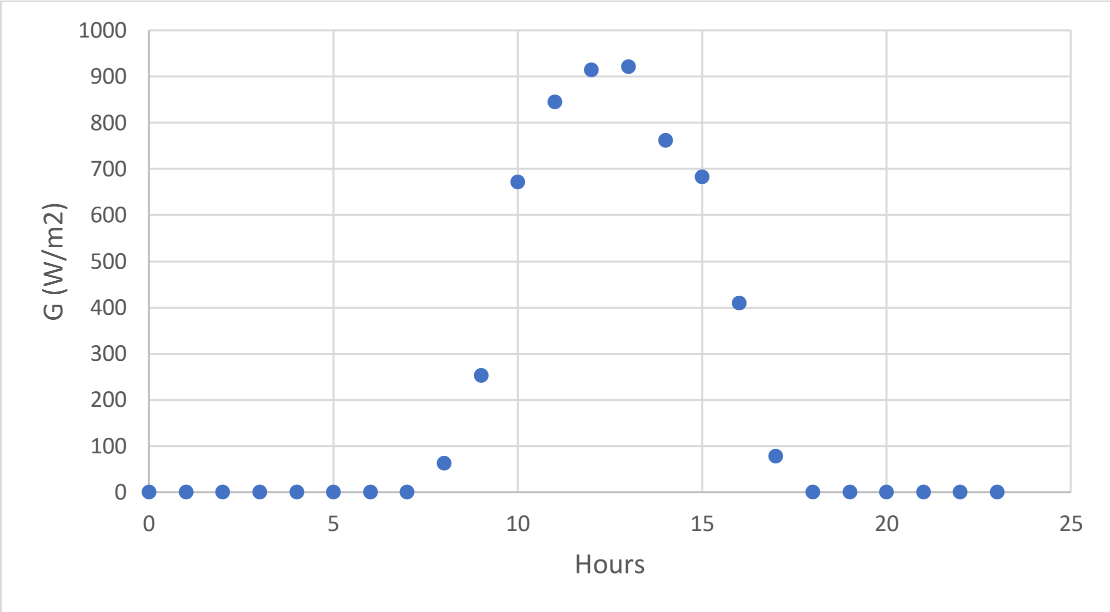

Figure 15. Annex I. Monthly Sun Irradiation (January)

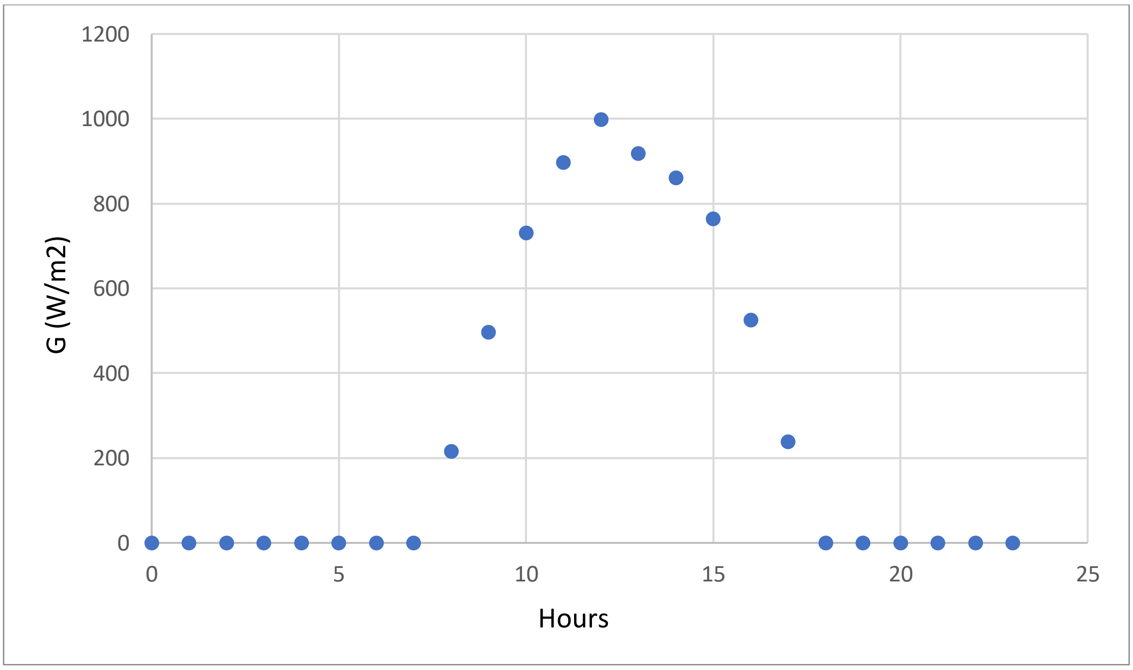

Figure 16. Annex I. Monthly Sun Irradiation (February)

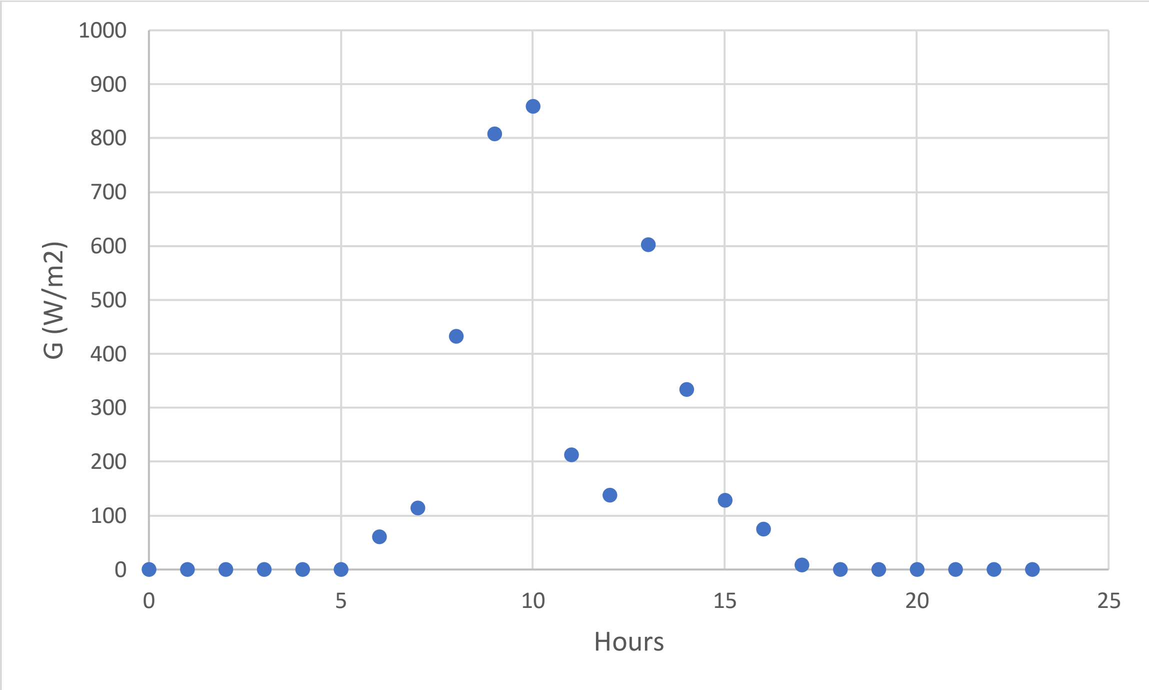

Figure 17. Annex I. Monthly Sun Irradiation (March)

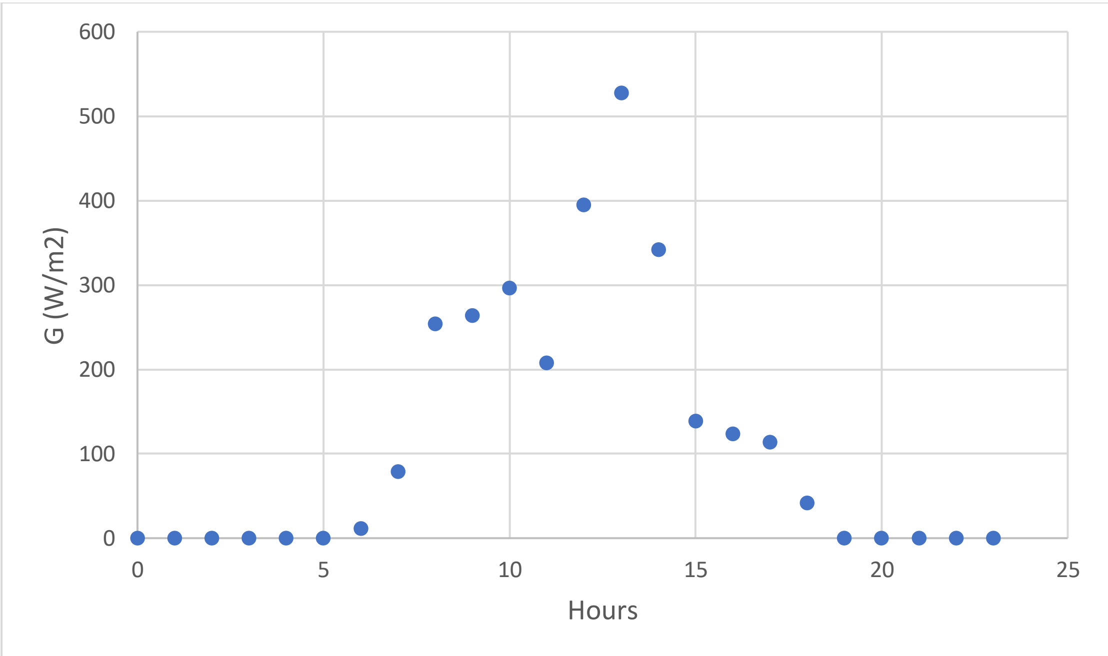

Figure 18. Annex I. Monthly Sun Irradiation (April)

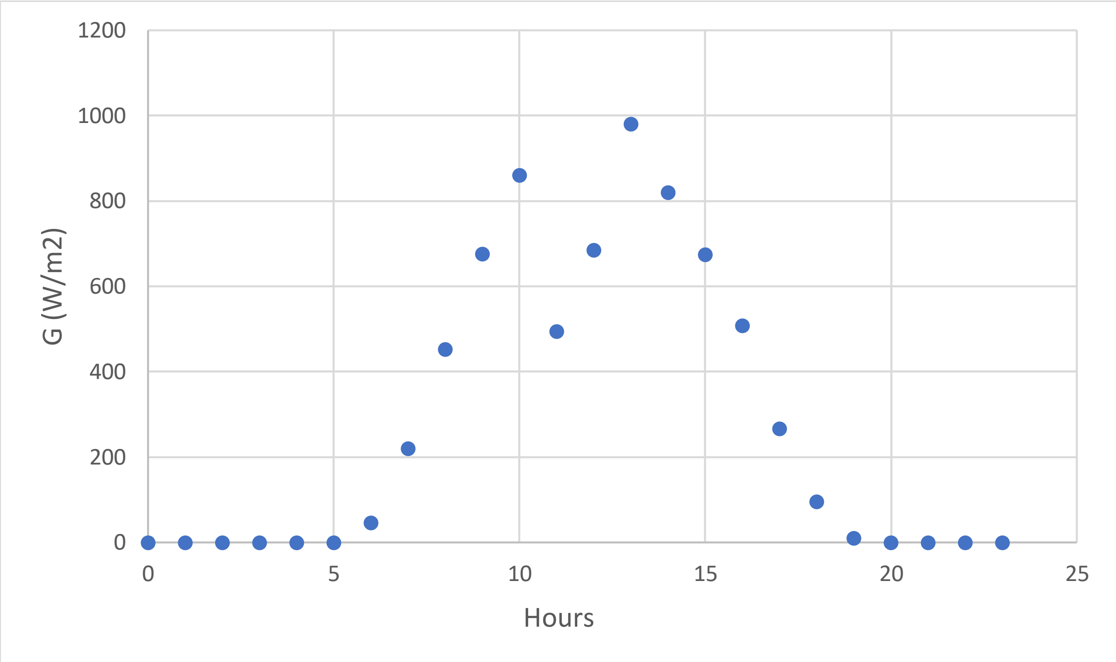

Figure 19. Annex I. Monthly Sun Irradiation (May)

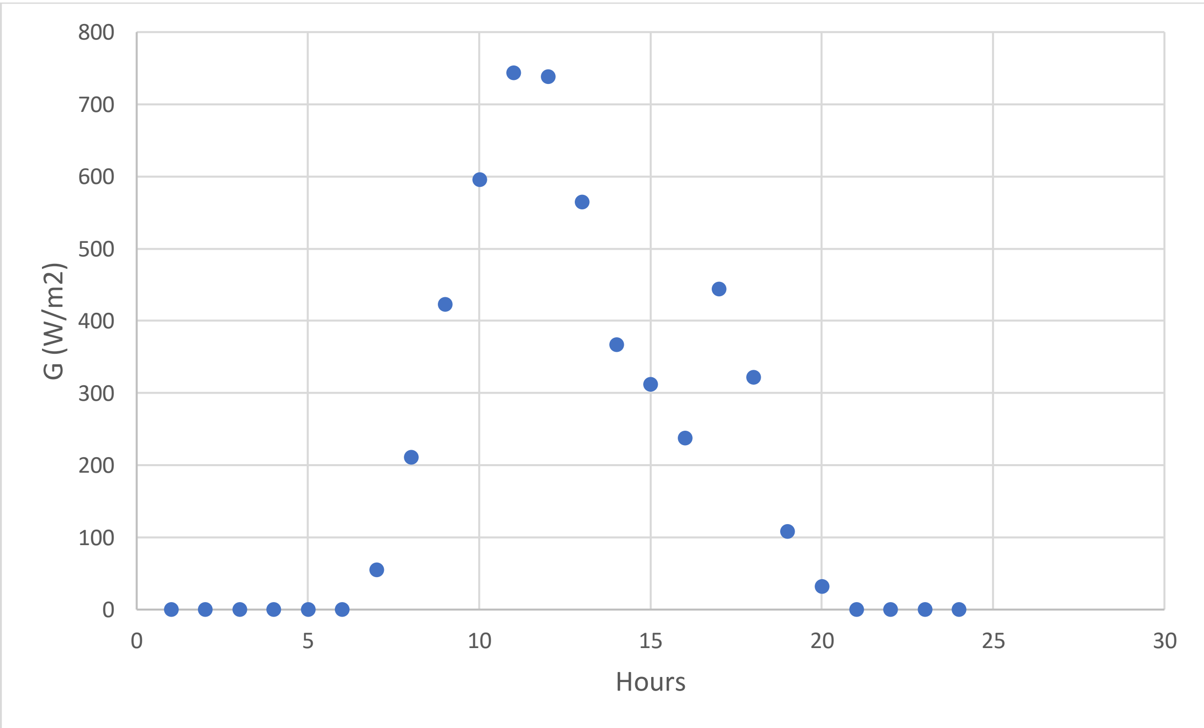

Figure 20. Annex I. Monthly Sun Irradiation (June)

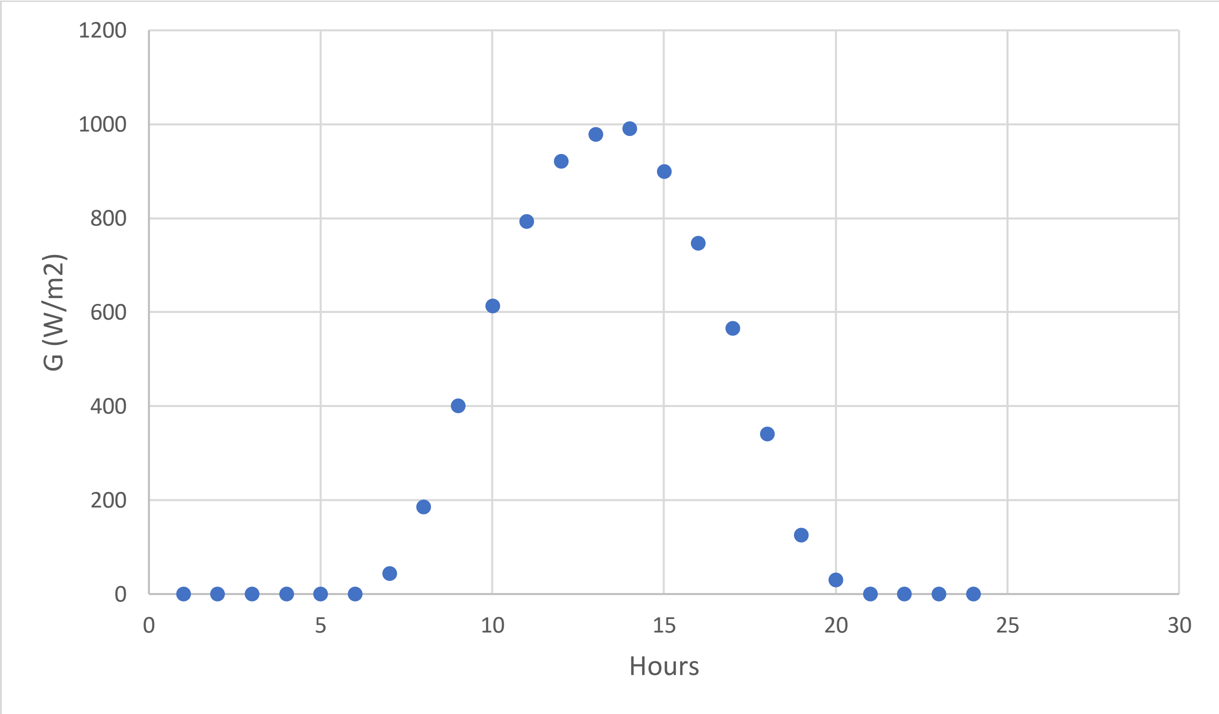

Figure 21. Annex I. Monthly Sun Irradiation (July)

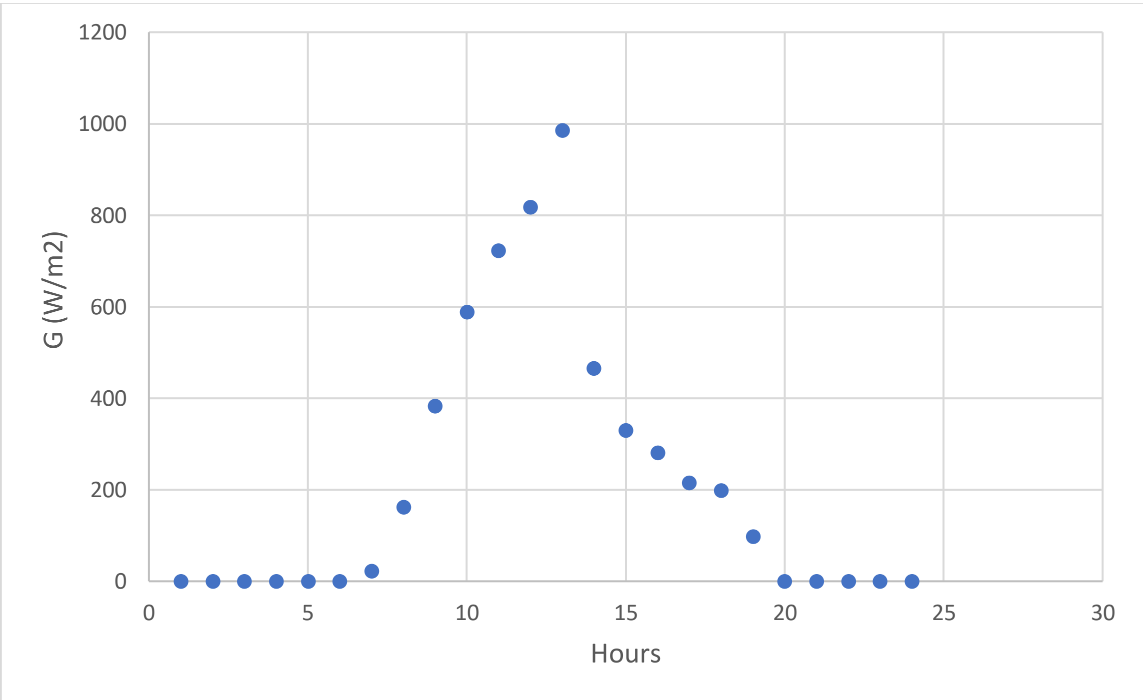

Figure 22. Annex I. Monthly Sun Irradiation (August)

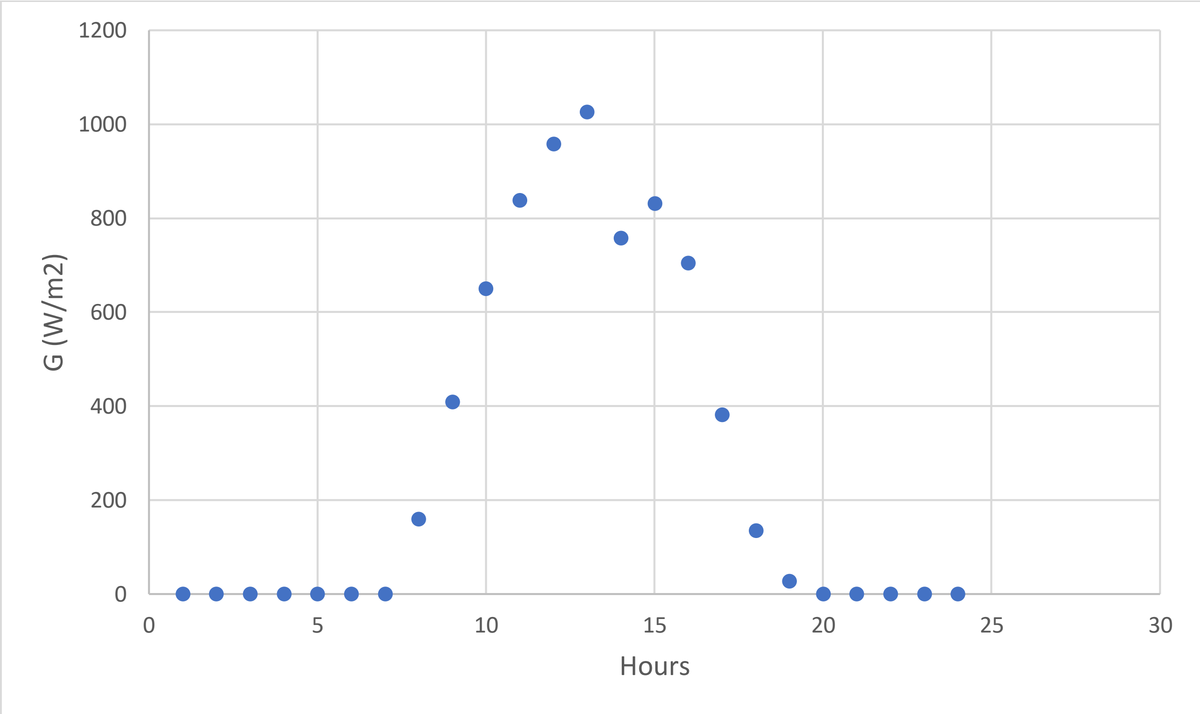

Figure 23. Annex I. Monthly Sun Irradiation (September)

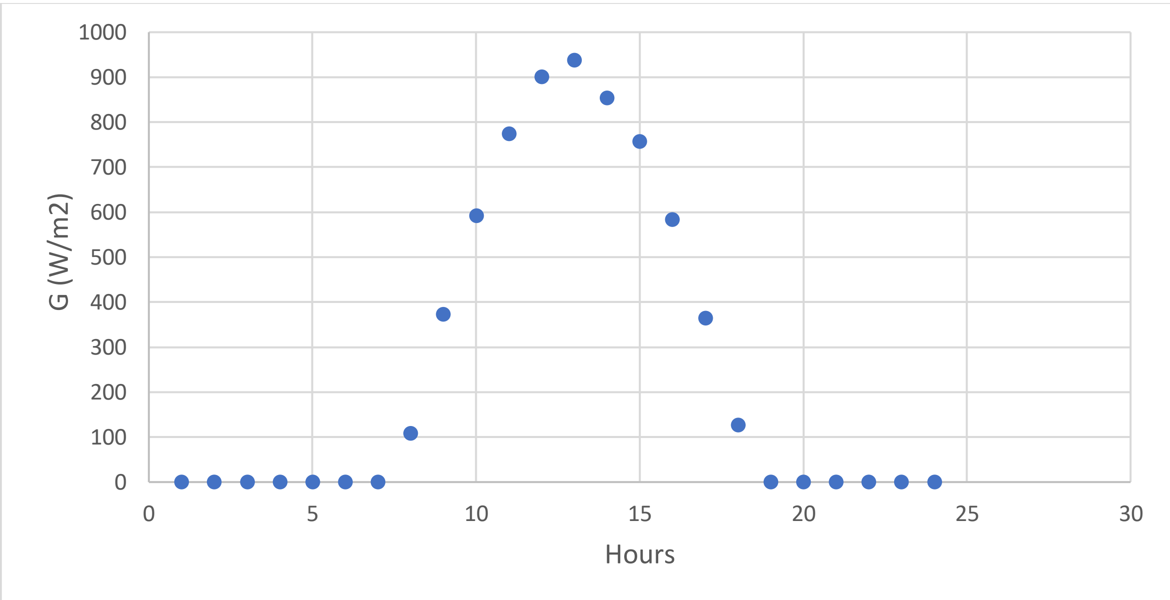

Figure 24. Annex I. Monthly Sun Irradiation (October)

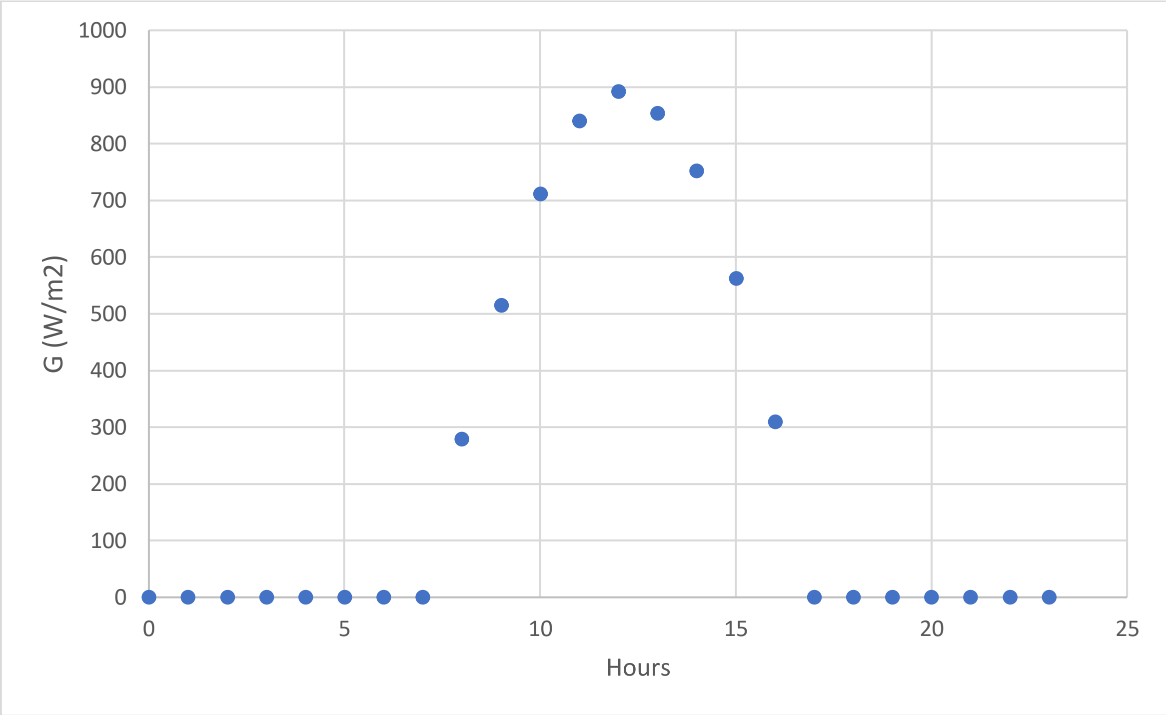

Figure 25. Annex I. Monthly Sun Irradiation (November)

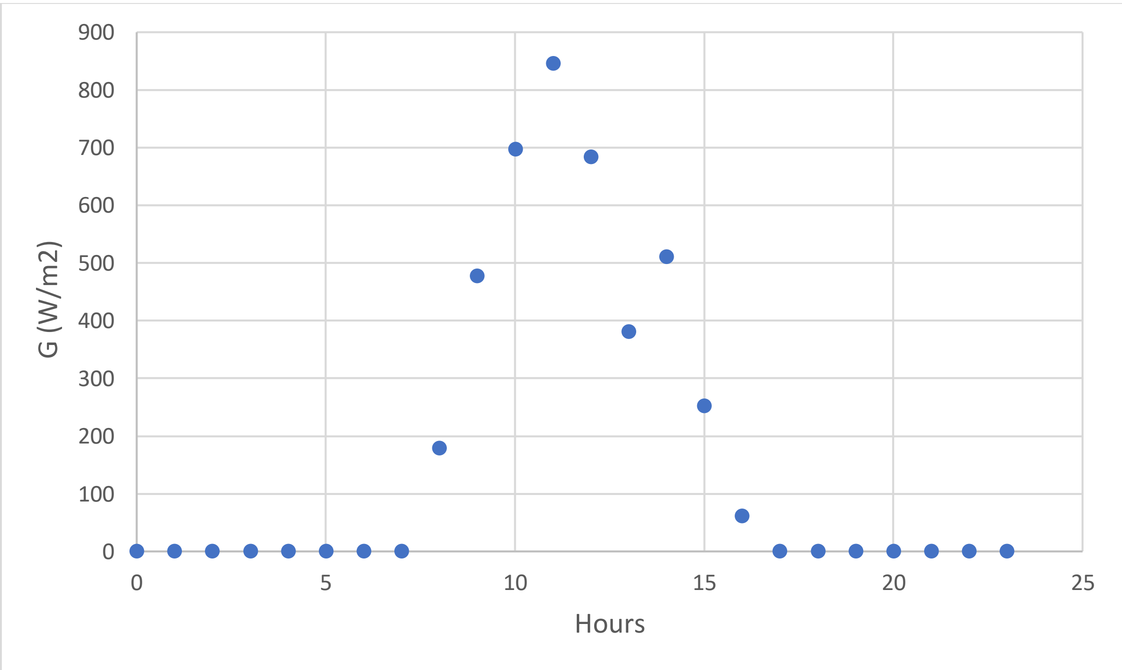

Figure 26. Annex I. Monthly Sun Irradiation (December)

8.2. Annex II (Monthly Room Temperature, Central Day)

Table 8. Monthly Central Day T Values

	T (ºC)											
Hours	January	February	March	April	May	June	July	August	September	October	November	December
0	10,81	7,91	9,06	13,46	13,31	22,72	25,43	25,3	17,91	16,31	12,14	9,12
1	10,49	7,93	8,7	12,97	12,76	22,12	24,49	24,51	17,15	15,88	12,01	8,83
2	10,18	7,96	8,35	12,47	12,21	21,51	23,56	23,73	16,4	15,45	11,87	8,54
3	9,87	7,98	7,95	11,98	11,66	20,91	22,63	22,94	15,64	15,02	11,73	8,24
4	10,19	8,11	7,55	11,54	11,78	20,58	22,69	22,78	15,4	13,85	11,36	8,02
5	10,51	8,24	7,16	11,1	11,9	20,25	22,76	22,63	15,16	12,68	11	7,8
6	10,83	8,37	8,81	10,66	12,03	19,92	22,82	22,48	14,92	11,5	10,63	7,58
7	11,27	8,95	10,46	12,84	14,69	20,35	24,8	24,24	16,68	13,45	11,7	8,23
8	11,72	9,53	12,11	15,01	17,36	20,79	26,79	26,01	18,43	15,41	12,76	8,88
9	12,16	10,11	13,2	17,19	20,02	21,22	28,77	27,77	20,18	17,36	13,83	9,52
10	12,58	11,03	14,29	18,36	21,23	22,11	30,34	29,37	21,56	18,72	15,6	10,72
11	13	11,96	15,38	19,53	22,44	23	31,9	30,97	22,95	20,09	17,36	11,91
12	13,42	12,88	16,39	20,7	23,64	23,89	33,47	32,56	24,33	21,46	19,13	13,11
13	14,39	13,43	17,4	20,68	24,25	24,31	34,27	33,17	24,91	22,1	19,63	13,75
14	15,36	13,98	18,4	20,65	24,85	24,73	35,07	33,78	25,49	22,73	20,13	14,38
15	16,34	14,53	17,62	20,63	25,45	25,14	35,87	34,39	26,07	23,37	20,63	15,02
16	15,17	13,79	16,83	19,88	24,97	24,55	35,03	33,67	25,4	22,5	19,13	13,84
17	14	13,05	16,04	19,13	24,49	23,95	34,19	32,94	24,73	21,64	17,63	12,66
18	12,83	12,31	14,9	18,38	24	23,36	33,35	32,22	24,06	20,78	16,13	11,48
19	11,89	11,45	13,76	17,27	21,74	22,42	31,52	30,46	22,5	19,91	14,92	10,98
20	10,95	10,6	12,62	16,17	19,48	21,48	29,69	28,7	20,94	19,03	13,72	10,47
21	10,01	9,74	12,55	15,06	17,22	20,54	27,86	26,93	19,37	18,16	12,51	9,96
22	9,58	9,15	12,49	14,84	16,62	20,07	27,12	26,06	18,88	17,06	12,02	10,46
23	9,16	8,56	12,49	14,61	16,02	19,6	26,38	25,19	18,39	15,96	11,53	10,96

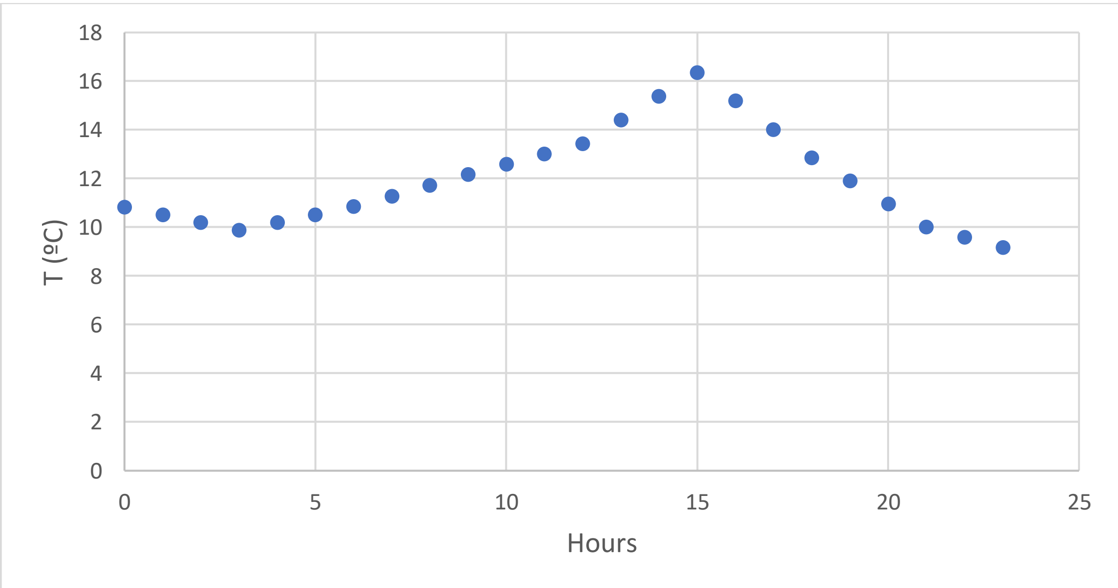

Figure 27. Annex II. Monthly Room Temperature (January)

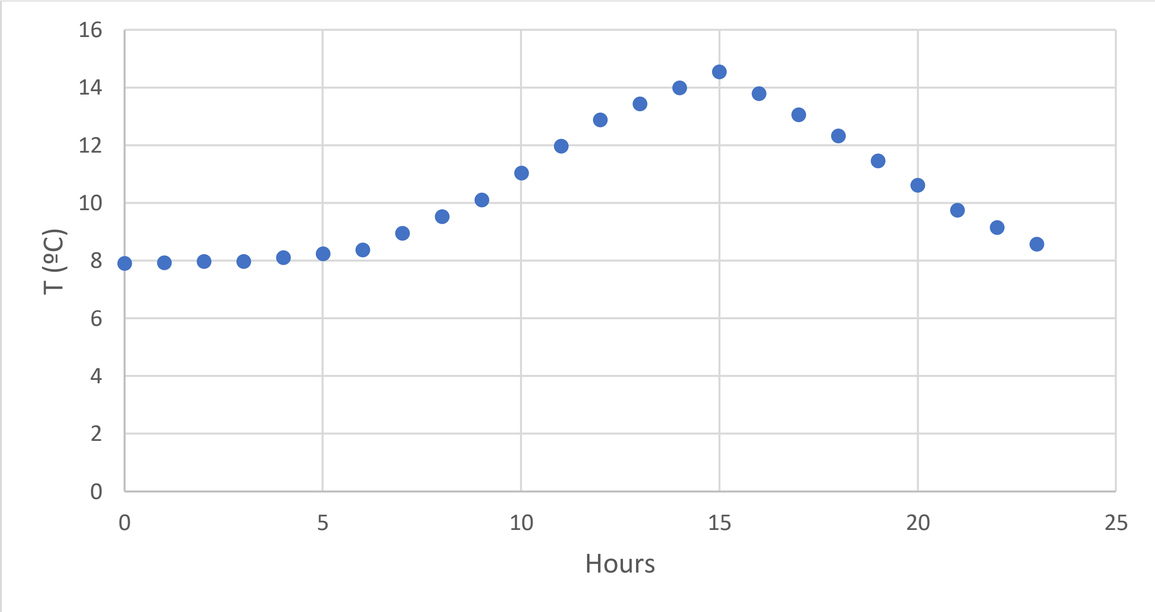

Figure 28. Annex II. Monthly Room Temperature (February)

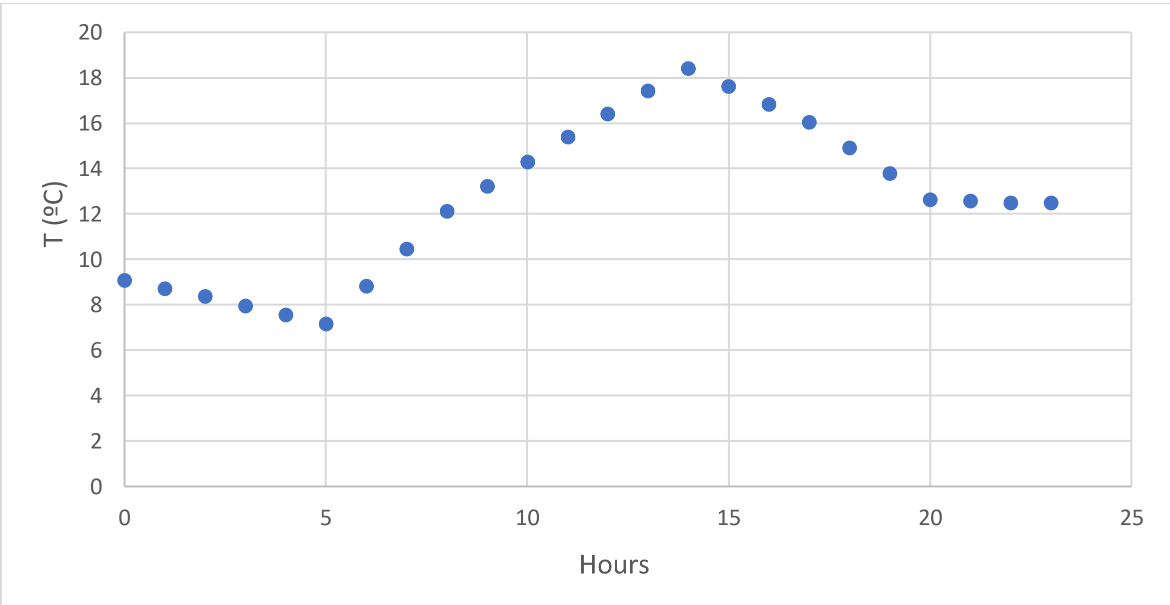

Figure 29. Annex II. Monthly Room Temperature (March)

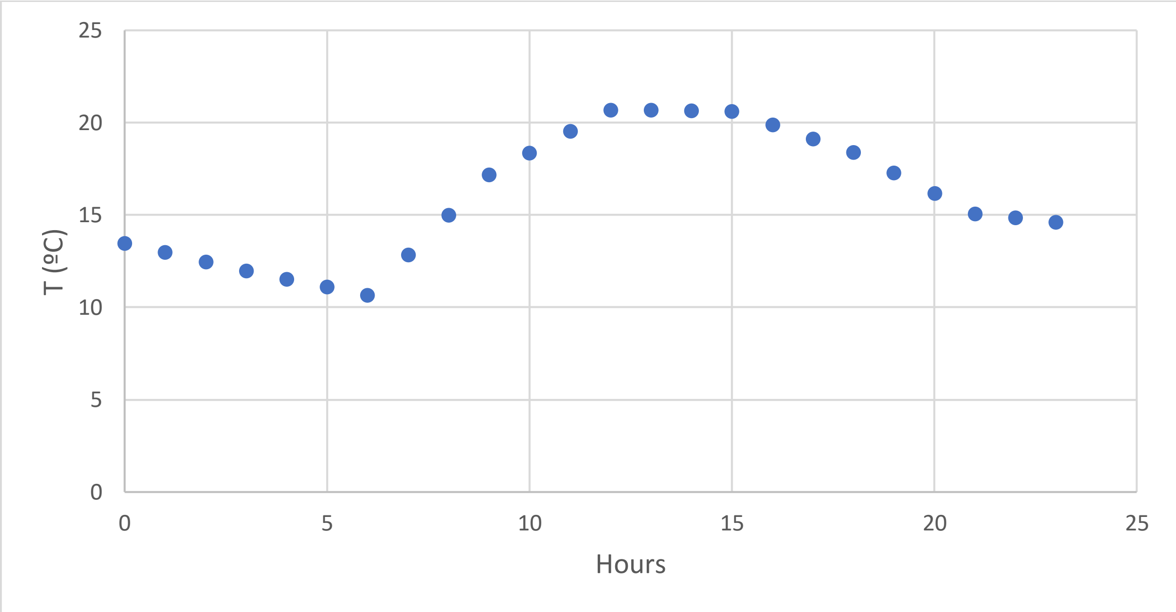

Figure 30. Annex II. Monthly Room Temperature (April)

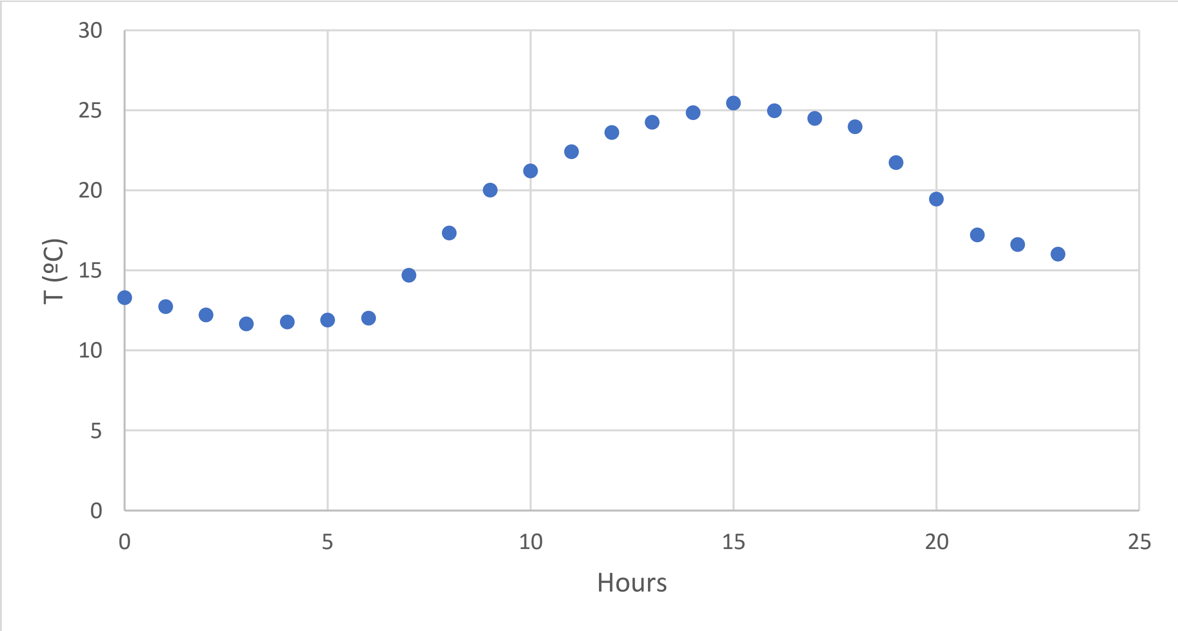

Figure 31. Annex II. Monthly Room Temperature (May)

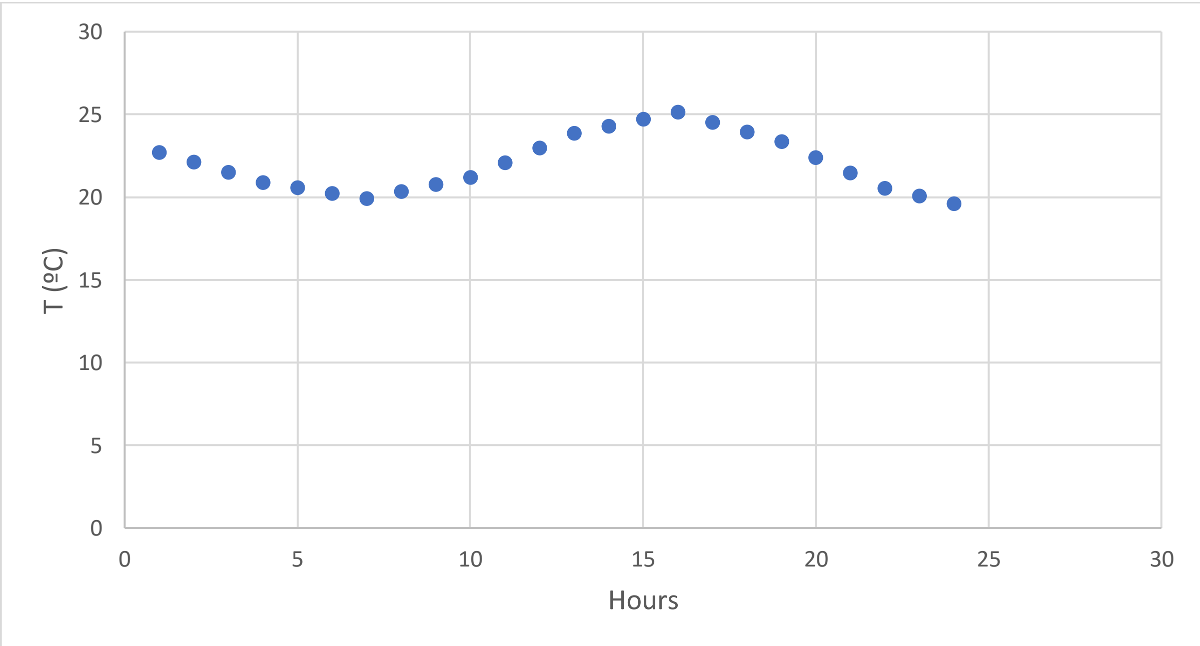

Figure 32. Annex II. Monthly Room Temperature (June)

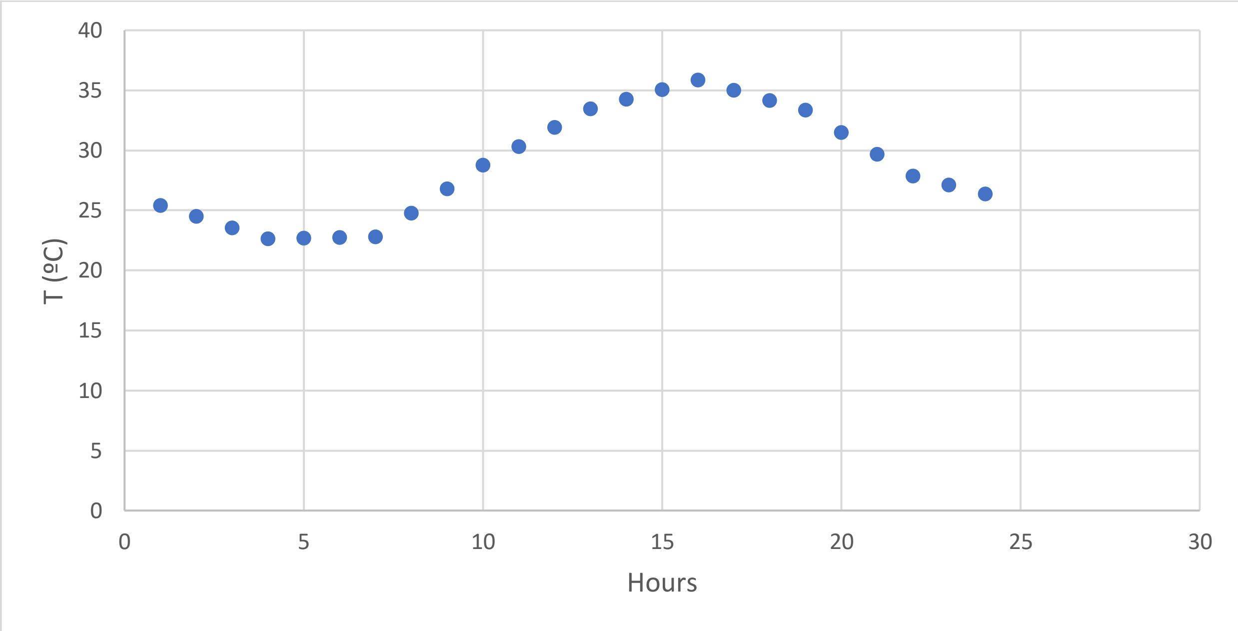

Figure 33. Annex II. Monthly Room Temperature (July)

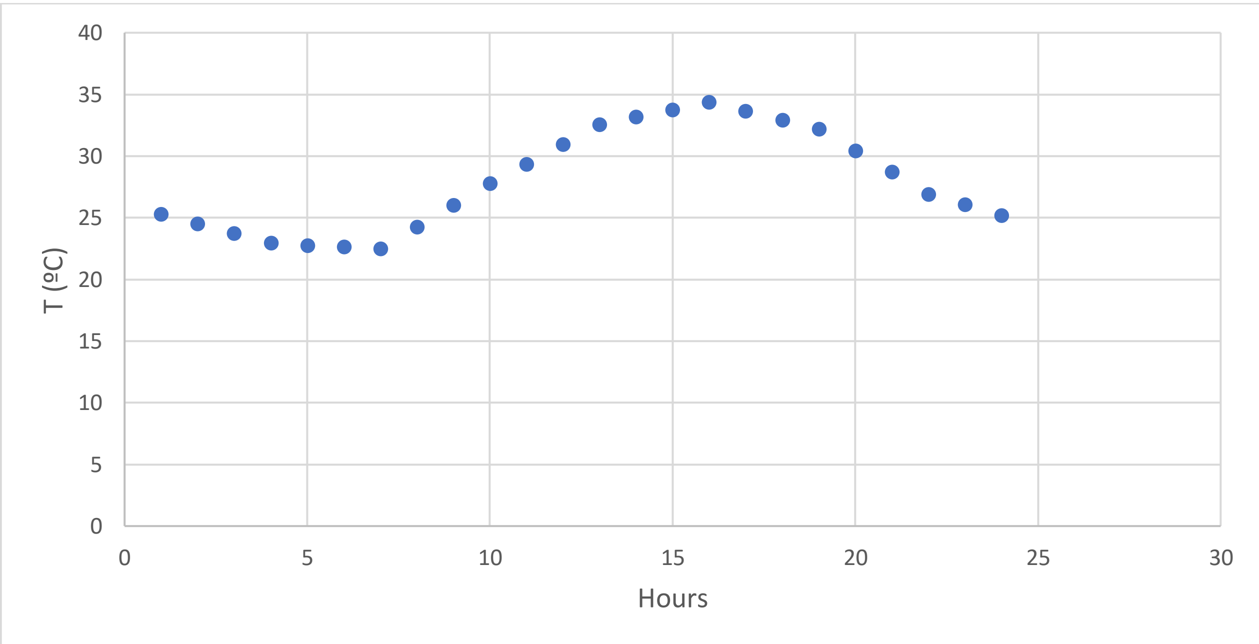

Figure 34. Annex II. Monthly Room Temperature (August)

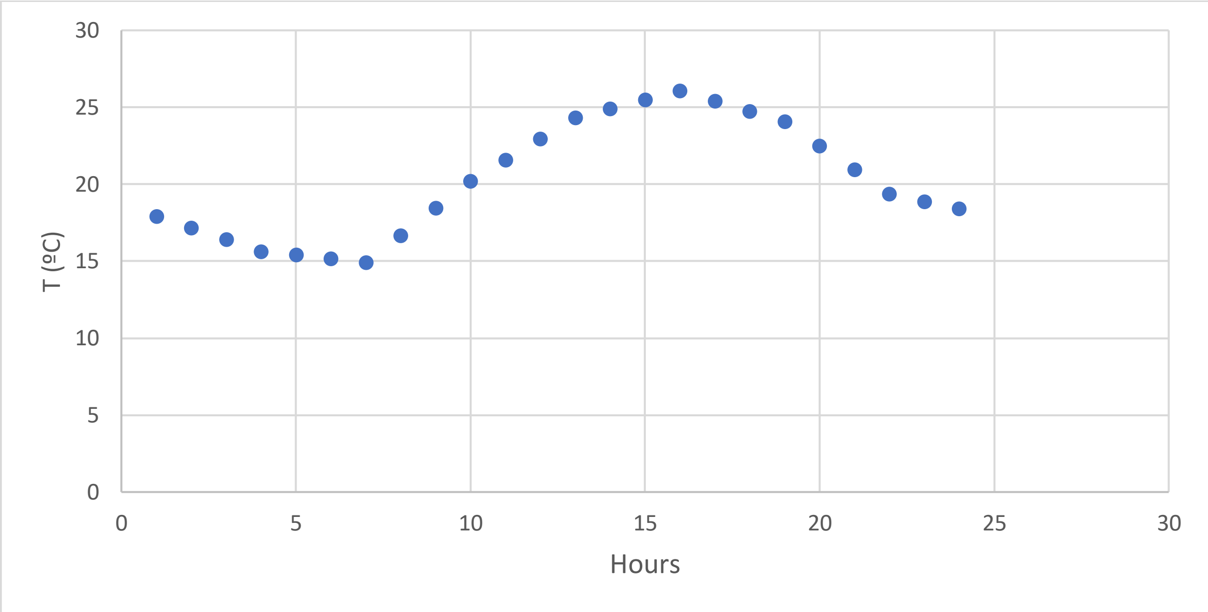

Figure 35. Annex II. Monthly Room Temperature (September)

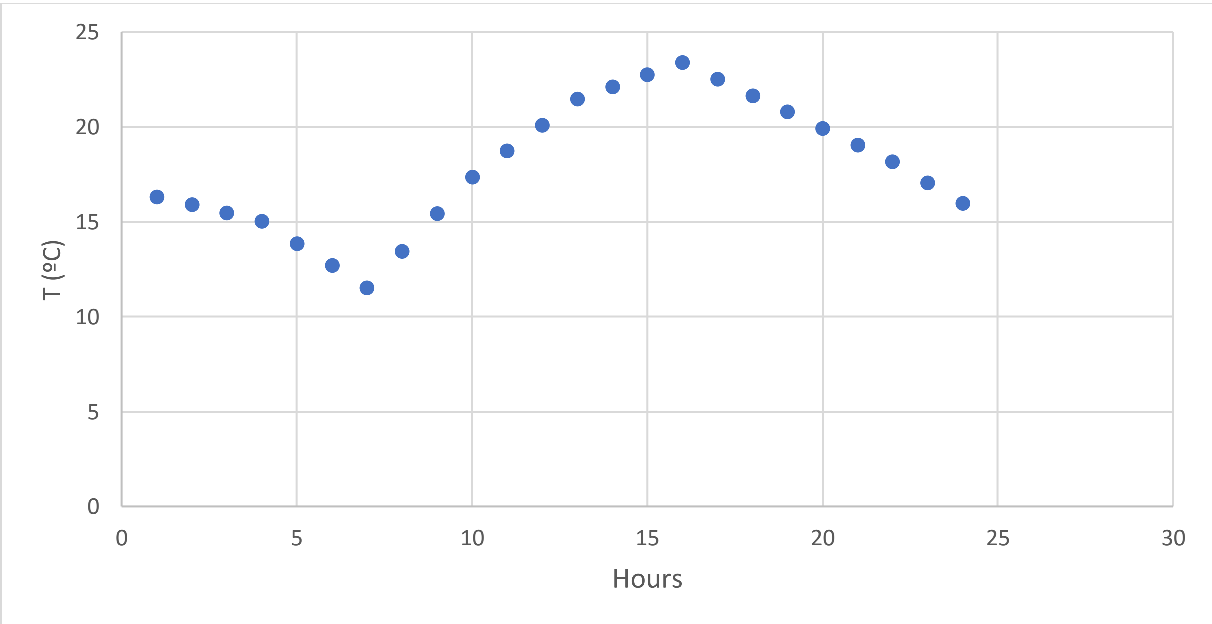

Figure 36. Annex II. Monthly Room Temperature (October)

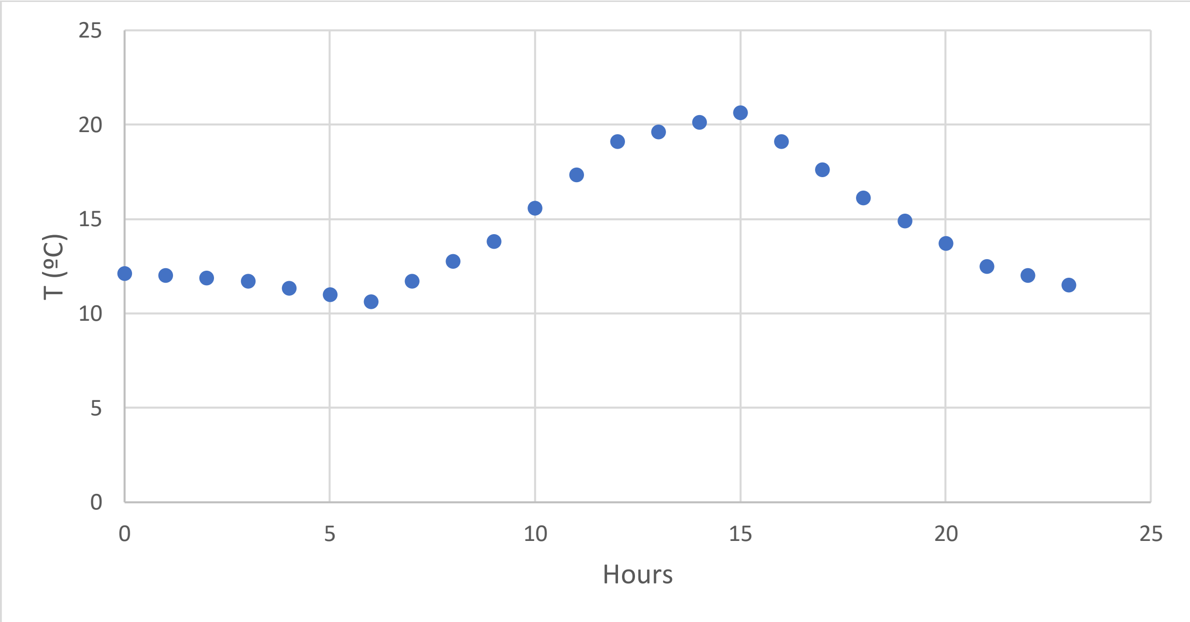

Figure 37. Annex II. Monthly Room Temperature (November)

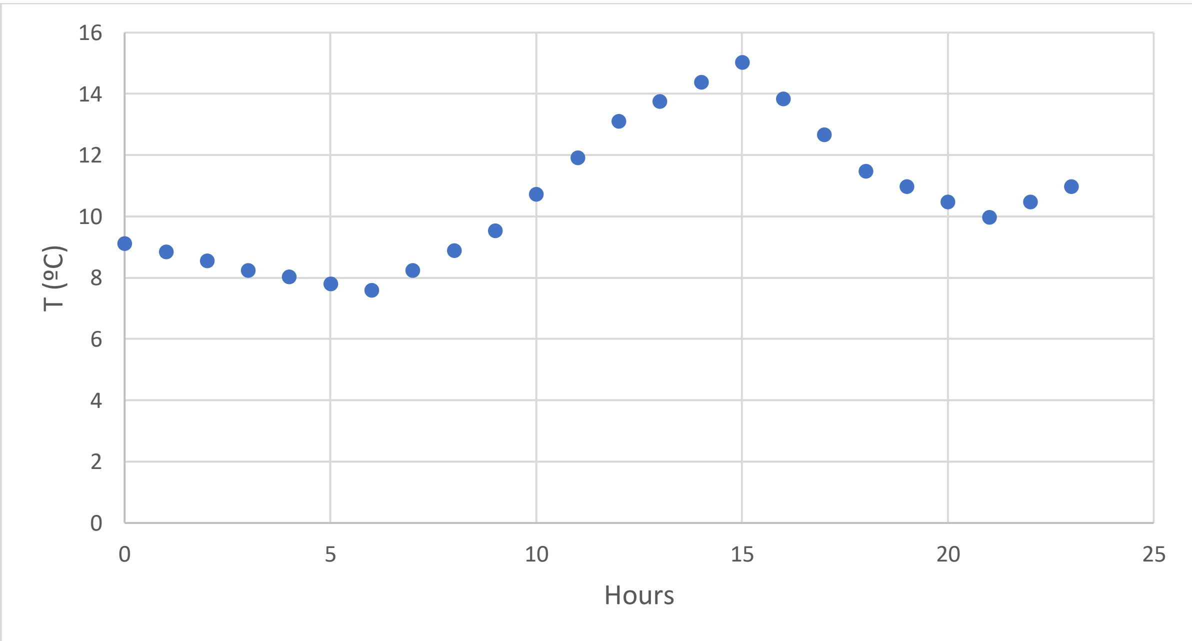

Figure 38. Annex II. Monthly Room Temperature (December)

8.3. Annex III (Monthly PV Cell Surface Temperature T_i, Central Day)

Table 9. Monthly Central Day T Surface

	Hours																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Base Surface Temperature (ºC)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,43	1,95	4,63	4,91	4,73	4,47	4,48	4,23	3,03	0,55	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,67	3,79	5,00	5,07	4,57	4,72	4,71	4,62	3,81	1,83	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,43	0,86	3,29	4,87	4,64	1,61	1,01	3,89	2,41	0,92	0,51	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,56	1,92	1,95	2,16	1,50	2,68	3,28	2,37	0,96	0,86	0,79	0,23	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,66	3,20	3,65	2,86	2,98	2,91	0,80	1,98	2,51	2,69	1,72	0,58	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	0,32	1,50	2,82	3,38	3,13	2,92	2,93	2,29	1,98	1,52	2,58	2,08	0,68	0,12	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	0,21	1,19	2,19	1,87	0,23	0,28	0,29	0,31	0,32	0,30	0,31	1,04	0,41	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	0,04	1,04	2,21	2,18	1,15	1,15	1,16	1,19	1,09	0,92	0,80	0,80	0,31	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,18	2,89	3,61	2,89	1,54	0,25	2,32	1,68	2,24	2,26	0,85	0,06	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,80	2,78	3,85	3,84	2,98	2,26	2,64	2,93	3,04	2,40	0,85	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,15	3,75	4,39	4,00	3,32	3,36	3,57	3,39	2,22	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,38	3,68	4,90	5,10	4,62	2,88	3,70	1,90	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Air Surface Temperature (ºC)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,43	1,98	5,36	6,73	7,28	7,31	6,04	5,39	3,23	0,55	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,68	3,96	5,84	7,16	7,94	7,30	6,84	6,07	4,17	1,86	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,37	0,75	3,06	5,81	6,17	1,43	0,86	4,26	2,27	0,76	0,36	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,56	1,97	2,04	2,29	1,57	3,05	4,09	2,62	1,00	0,89	0,81	0,24	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,69	3,54	5,26	6,63	3,79	5,21	7,30	6,13	5,04	3,81	1,95	0,61	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	0,33	1,58	3,27	4,61	5,71	5,63	4,29	2,75	2,31	1,72	3,34	2,40	0,73	0,13	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	0,22	1,31	2,94	4,40	5,49	6,08	6,12	6,04	5,42	4,48	3,52	2,11	0,59	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	0,05	1,13	2,82	4,28	5,12	5,57	6,32	3,04	2,05	1,66	1,23	1,15	0,43	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,20	3,19	5,06	6,44	7,23	7,61	5,68	6,17	5,23	2,84	0,92	0,07	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,80	2,93	4,66	6,05	6,97	7,18	6,53	5,78	4,45	2,77	0,89	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,19	4,08	5,63	6,61	6,95	6,64	5,84	4,37	2,38	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,38	3,81	5,57	6,76	5,45	3,00	4,05	1,95	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Water Surface Temperature (ºC)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,43	1,99	5,39	6,79	7,35	7,40	6,10	5,45	3,25	0,55	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,68	3,97	5,87	7,21	8,03	7,37	6,91	6,13	4,19	1,87	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,43	0,86	3,44	6,49	6,89	1,65	1,03	4,80	2,61	0,95	0,52	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,56	1,98	2,05	2,31	1,58	3,08	4,15	2,65	1,01	0,89	0,82	0,24	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,70	3,57	5,36	6,82	3,87	5,37	7,68	6,40	5,23	3,92	1,99	0,62	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	0,34	1,60	3,31	4,70	5,86	5,80	4,40	2,81	2,36	1,75	3,42	2,45	0,74	0,13	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	0,22	1,34	3,03	4,64	5,95	6,81	7,08	7,09	6,35	5,17	3,91	2,27	0,63	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	0,05	1,15	2,89	4,48	5,46	6,09	7,22	3,27	2,19	1,78	1,31	1,22	0,45	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,21	3,22	5,15	6,63	7,55	8,04	5,91	6,47	5,46	2,91	0,94	0,07	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,80	2,95	4,71	6,16	7,16	7,43	6,74	5,95	4,56	2,82	0,90	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,20	4,11	5,69	6,72	7,11	6,80	5,97	4,44	2,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,39	3,82	5,60	6,80	5,48	3,02	4,07	1,96	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00

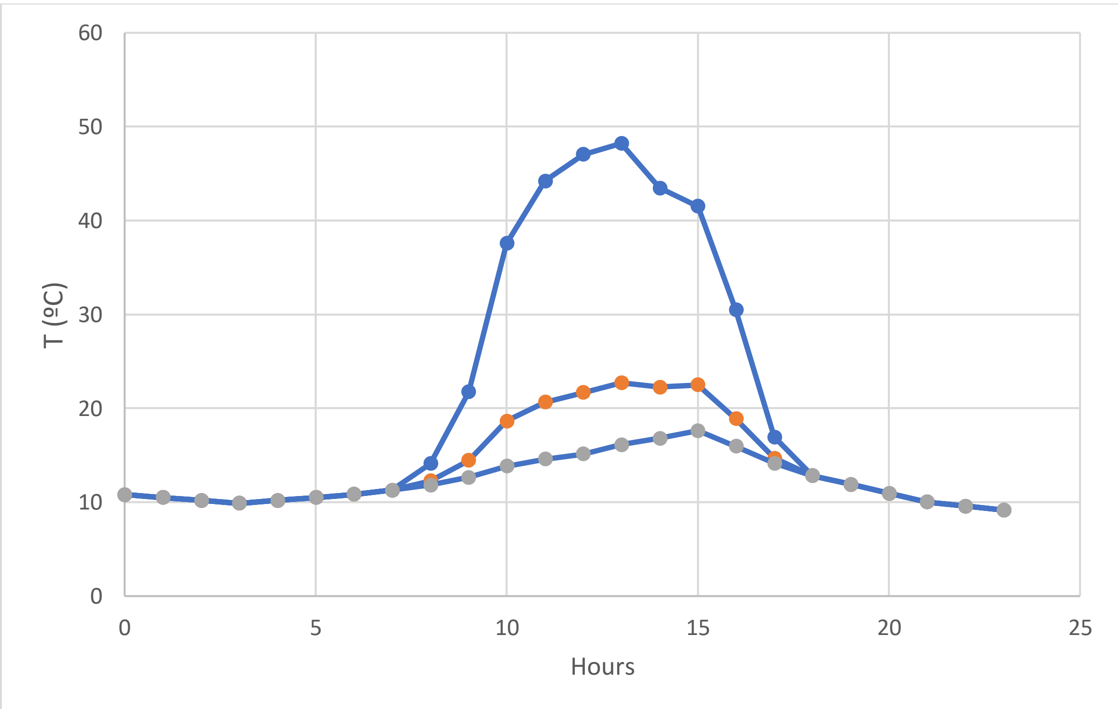

Figure 39. Annex III. Monthly PV Cell Surface Temperature Ti (January)

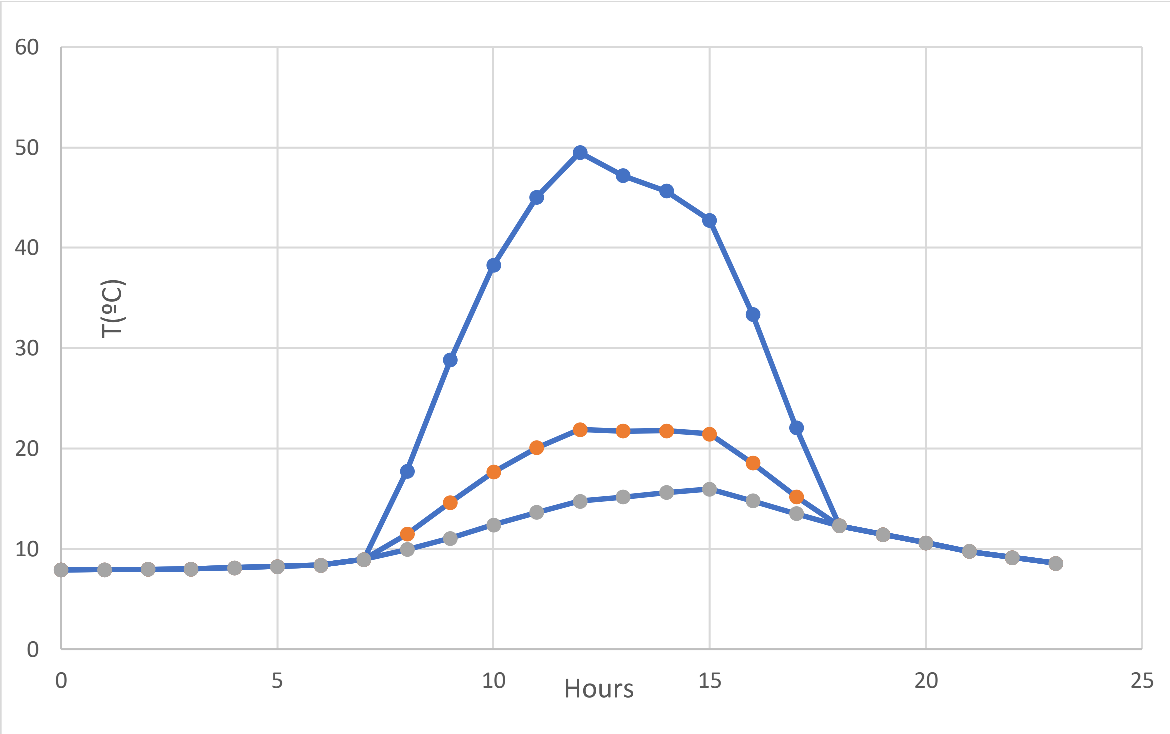

Figure 40. Annex III. Monthly PV Cell Surface Temperature Ti (February)

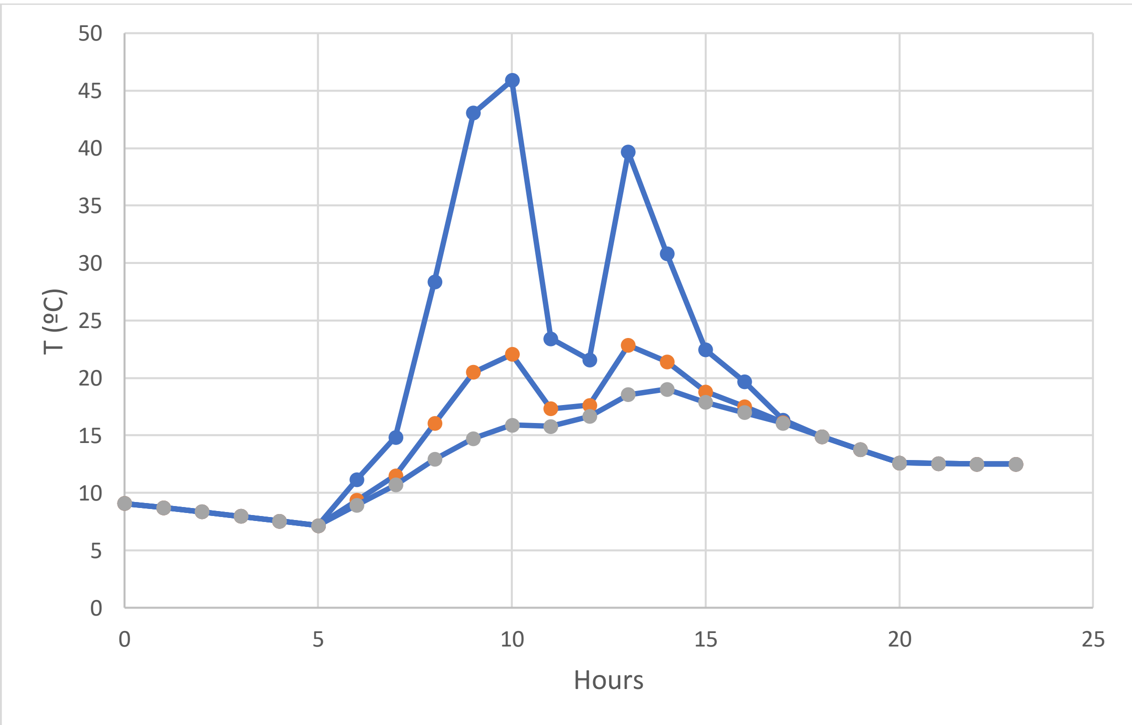

Figure 41. Annex III. Monthly PV Cell Surface Temperature Ti (March)

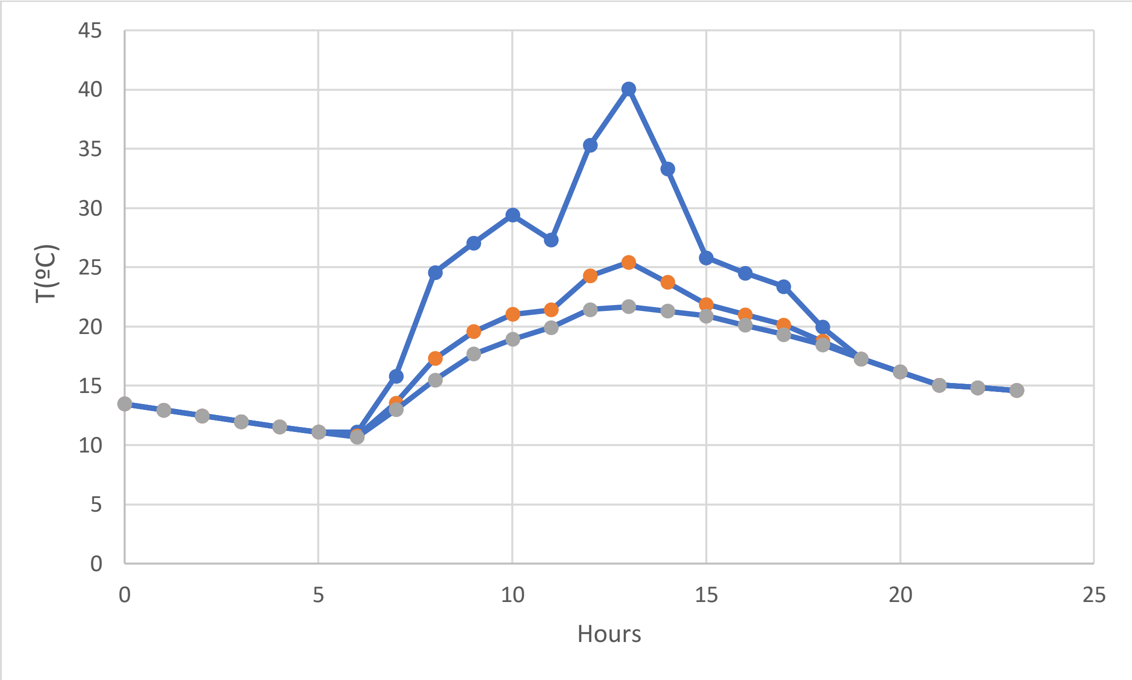

Figure 42. Annex III. Monthly PV Cell Surface Temperature Ti (April)

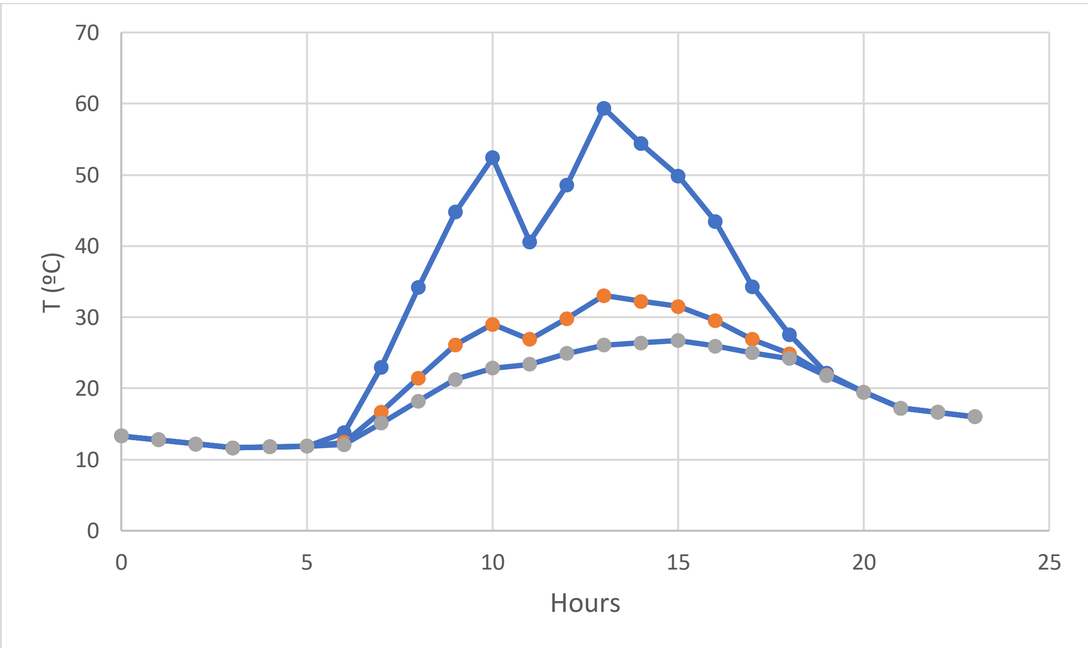

Figure 43. Annex III. Monthly PV Cell Surface Temperature Ti (May)

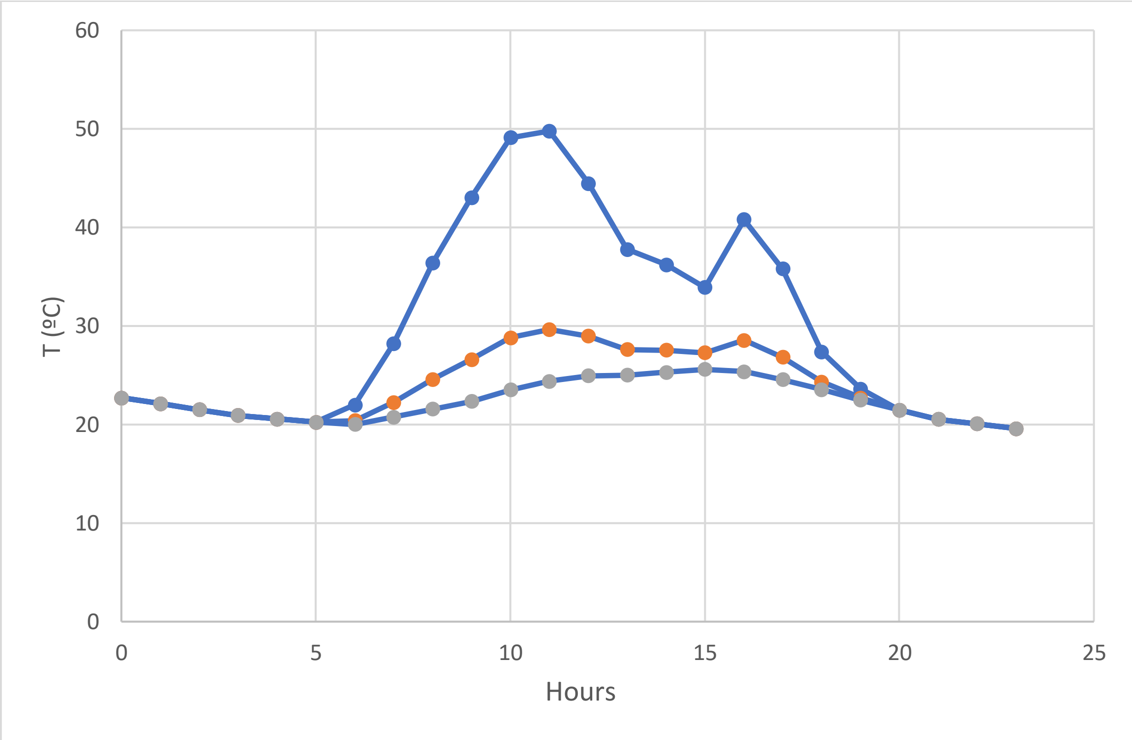

Figure 44. Annex III. Monthly PV Cell Surface Temperature Ti (June)

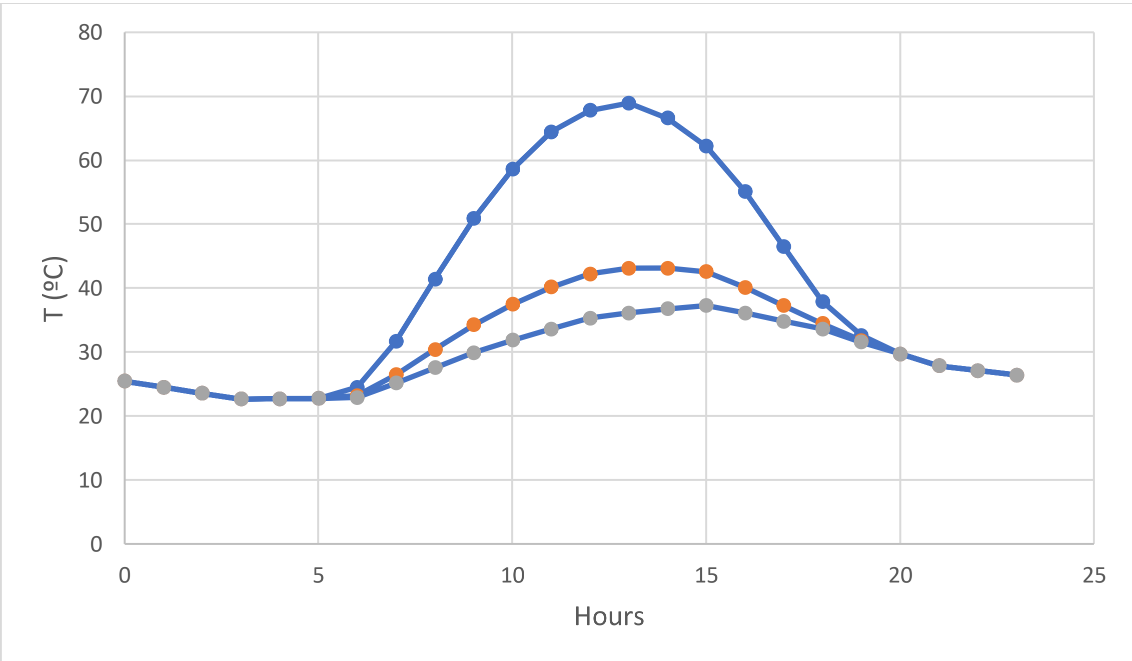

Figure 45. Annex III. Monthly PV Cell Surface Temperature Ti (July)

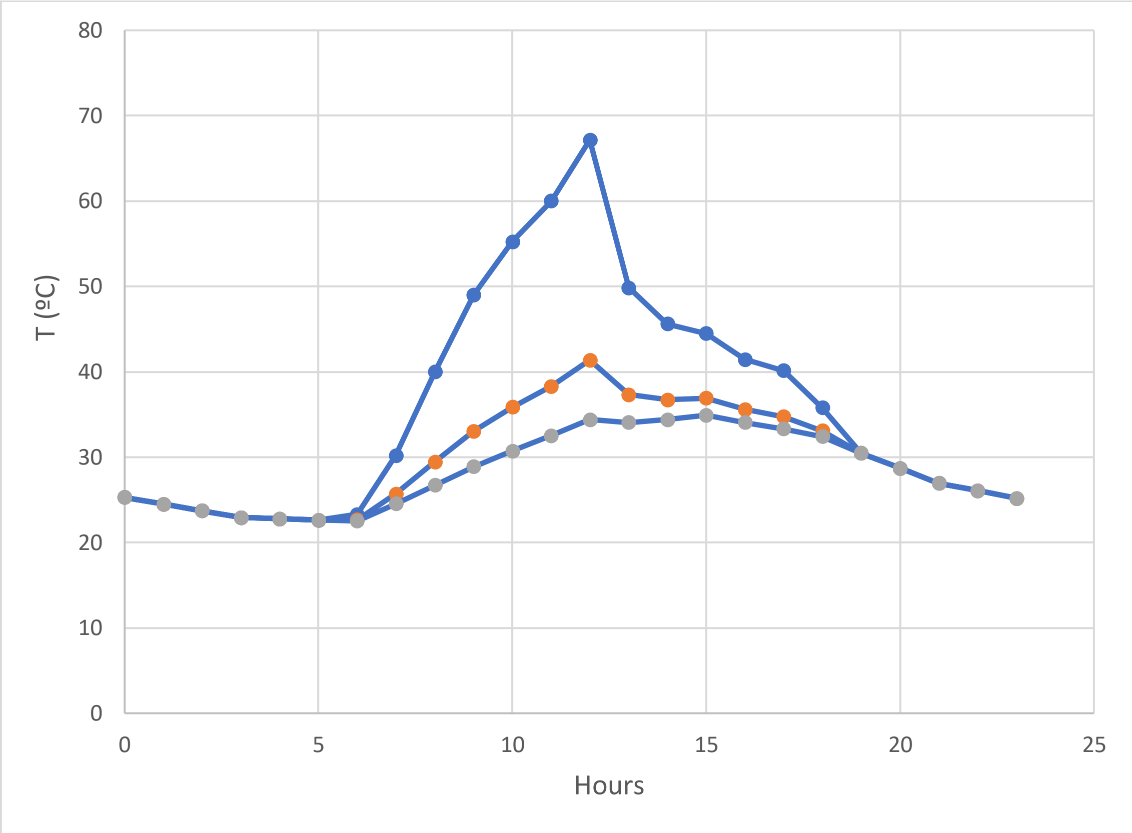

Figure 46. Annex III. Monthly PV Cell Surface Temperature Ti (August)

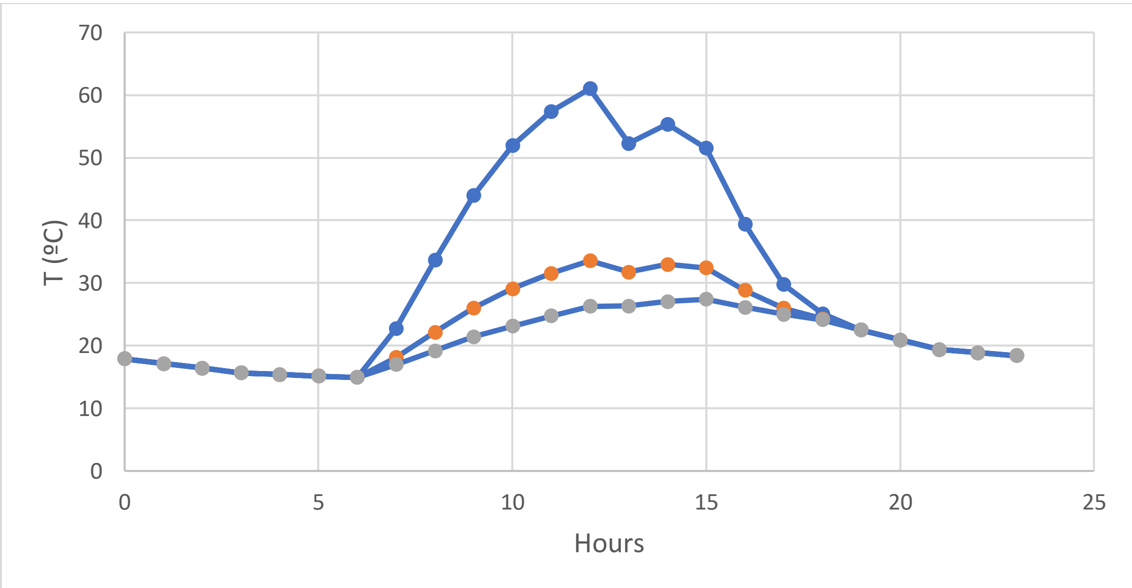

Figure 47. Annex III. Monthly PV Cell Surface Temperature Ti (September)

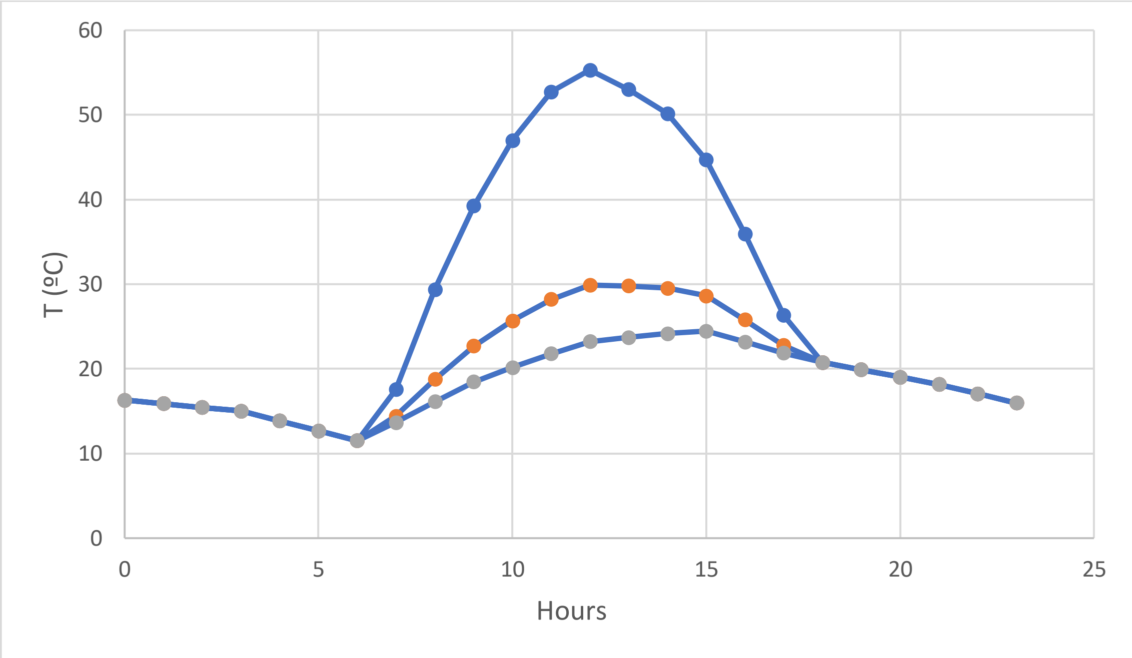

Figure 48. Annex III. Monthly PV Cell Surface Temperature Ti (October)

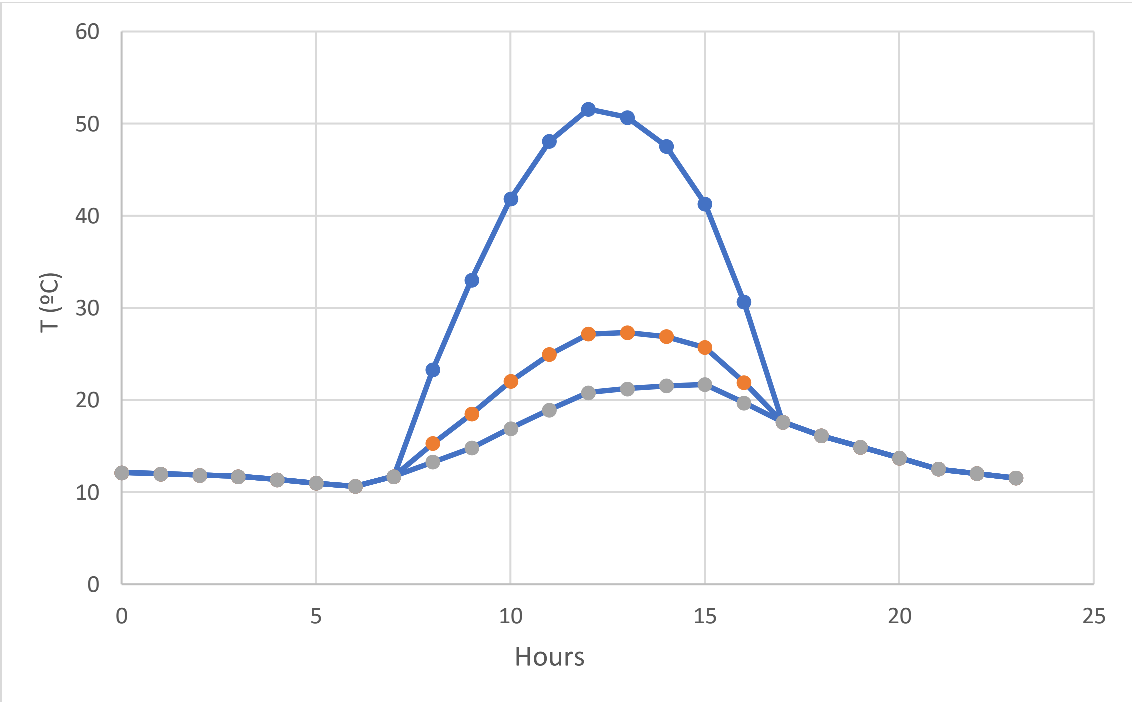

Figure 49.Annex III. Monthly PV Cell Surface Temperature Ti (November)

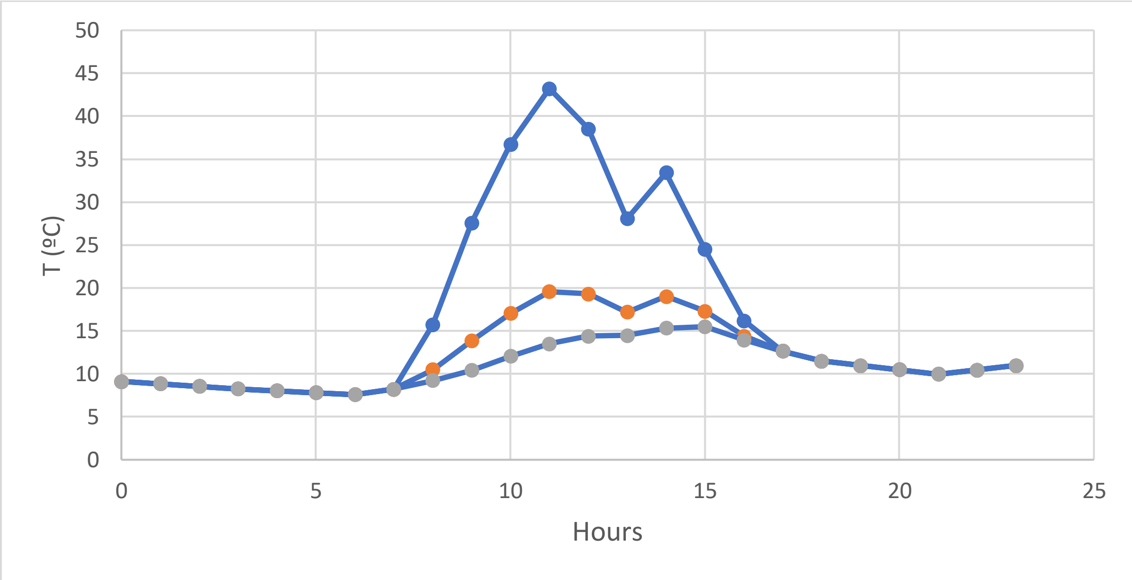

Figure 50. Annex III. Monthly PV Cell Surface Temperature Ti (December)

8.4. Annex IV (Monthly PV Cell Current I_i, Central Day)

Table 10. Monthly Central Day I Output

	Hours																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Base Current Output (A)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,43	1,95	4,63	4,91	4,73	4,47	4,48	4,23	3,03	0,55	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,67	3,79	5,00	5,07	4,57	4,72	4,71	4,62	3,81	1,83	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,43	0,86	3,29	4,87	4,64	1,61	1,01	3,89	2,41	0,92	0,51	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,56	1,92	1,95	2,16	1,50	2,68	3,28	2,37	0,96	0,86	0,79	0,23	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,66	3,20	3,65	2,86	2,98	2,91	0,80	1,98	2,51	2,69	1,72	0,58	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	0,32	1,50	2,82	3,38	3,13	2,92	2,93	2,29	1,98	1,52	2,58	2,08	0,68	0,12	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	0,21	1,19	2,19	1,87	0,23	0,28	0,29	0,31	0,32	0,30	0,31	1,04	0,41	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	0,04	1,04	2,21	2,18	1,15	1,15	1,16	1,19	1,09	0,92	0,80	0,80	0,31	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,18	2,89	3,61	2,89	1,54	0,25	2,32	1,68	2,24	2,26	0,85	0,06	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,80	2,78	3,85	3,84	2,98	2,26	2,64	2,93	3,04	2,40	0,85	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,15	3,75	4,39	4,00	3,32	3,36	3,57	3,39	2,22	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,38	3,68	4,90	5,10	4,62	2,88	3,70	1,90	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Air Current Output (A)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,43	1,98	5,36	6,73	7,28	7,31	6,04	5,39	3,23	0,55	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,68	3,96	5,84	7,16	7,94	7,30	6,84	6,07	4,17	1,86	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,37	0,75	3,06	5,81	6,17	1,43	0,86	4,26	2,27	0,76	0,36	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,56	1,97	2,04	2,29	1,57	3,05	4,09	2,62	1,00	0,89	0,81	0,24	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,69	3,54	5,26	6,63	3,79	5,21	7,30	6,13	5,04	3,81	1,95	0,61	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	0,33	1,58	3,27	4,61	5,71	5,63	4,29	2,75	2,31	1,72	3,34	2,40	0,73	0,13	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	0,22	1,31	2,94	4,40	5,49	6,08	6,12	6,04	5,42	4,48	3,52	2,11	0,59	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	0,05	1,13	2,82	4,28	5,12	5,57	6,32	3,04	2,05	1,66	1,23	1,15	0,43	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,20	3,19	5,06	6,44	7,23	7,61	5,68	6,17	5,23	2,84	0,92	0,07	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,80	2,93	4,66	6,05	6,97	7,18	6,53	5,78	4,45	2,77	0,89	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,19	4,08	5,63	6,61	6,95	6,64	5,84	4,37	2,38	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,38	3,81	5,57	6,76	5,45	3,00	4,05	1,95	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Water Current Output (A)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,43	1,99	5,39	6,79	7,35	7,40	6,10	5,45	3,25	0,55	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,68	3,97	5,87	7,21	8,03	7,37	6,91	6,13	4,19	1,87	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,43	0,86	3,44	6,49	6,89	1,65	1,03	4,80	2,61	0,95	0,52	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,56	1,98	2,05	2,31	1,58	3,08	4,15	2,65	1,01	0,89	0,82	0,24	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,70	3,57	5,36	6,82	3,87	5,37	7,68	6,40	5,23	3,92	1,99	0,62	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	0,34	1,60	3,31	4,70	5,86	5,80	4,40	2,81	2,36	1,75	3,42	2,45	0,74	0,13	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	0,22	1,34	3,03	4,64	5,95	6,81	7,08	7,09	6,35	5,17	3,91	2,27	0,63	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	0,05	1,15	2,89	4,48	5,46	6,09	7,22	3,27	2,19	1,78	1,31	1,22	0,45	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,21	3,22	5,15	6,63	7,55	8,04	5,91	6,47	5,46	2,91	0,94	0,07	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,80	2,95	4,71	6,16	7,16	7,43	6,74	5,95	4,56	2,82	0,90	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,20	4,11	5,69	6,72	7,11	6,80	5,97	4,44	2,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,39	3,82	5,60	6,80	5,48	3,02	4,07	1,96	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00

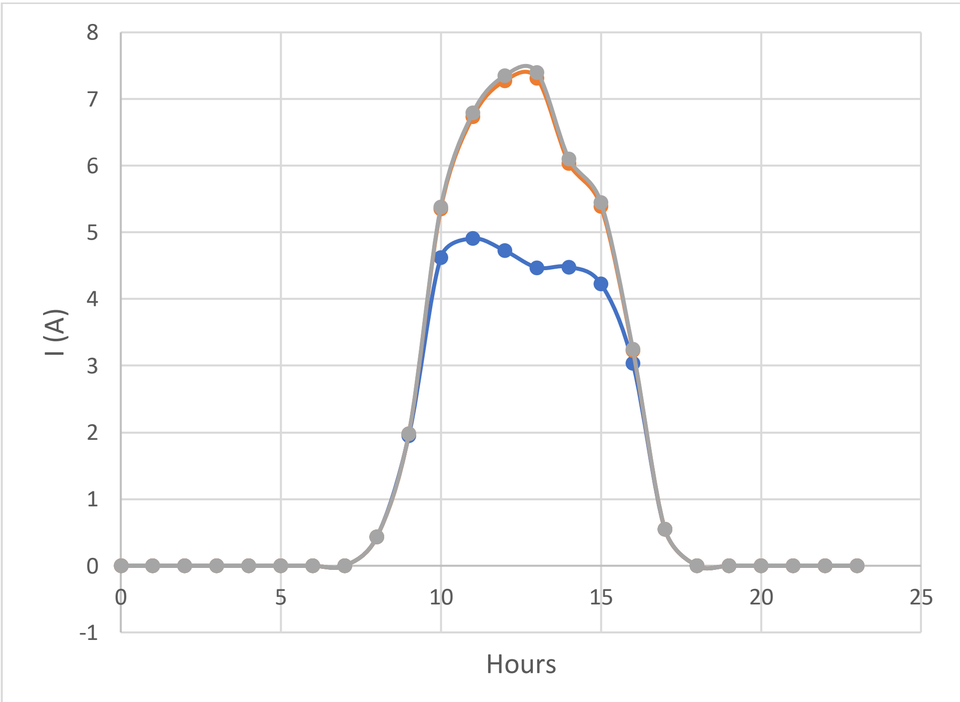

Figure 51. Annex IV. Monthly PV Cell Current Ii (January)

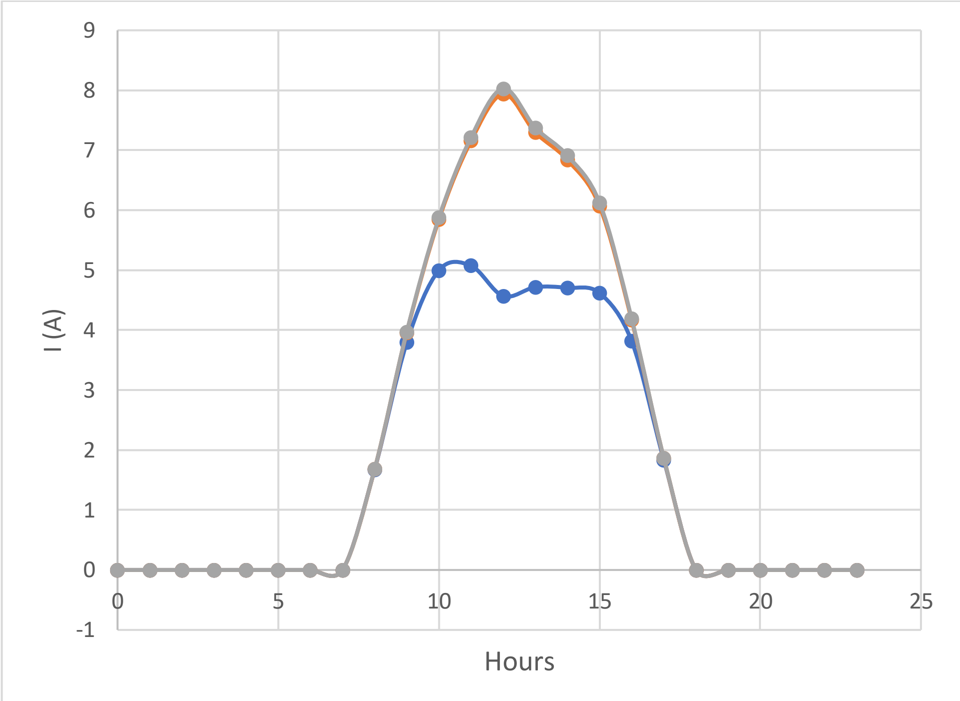

Figure 52. Annex IV. Monthly PV Cell Current Ii (February)

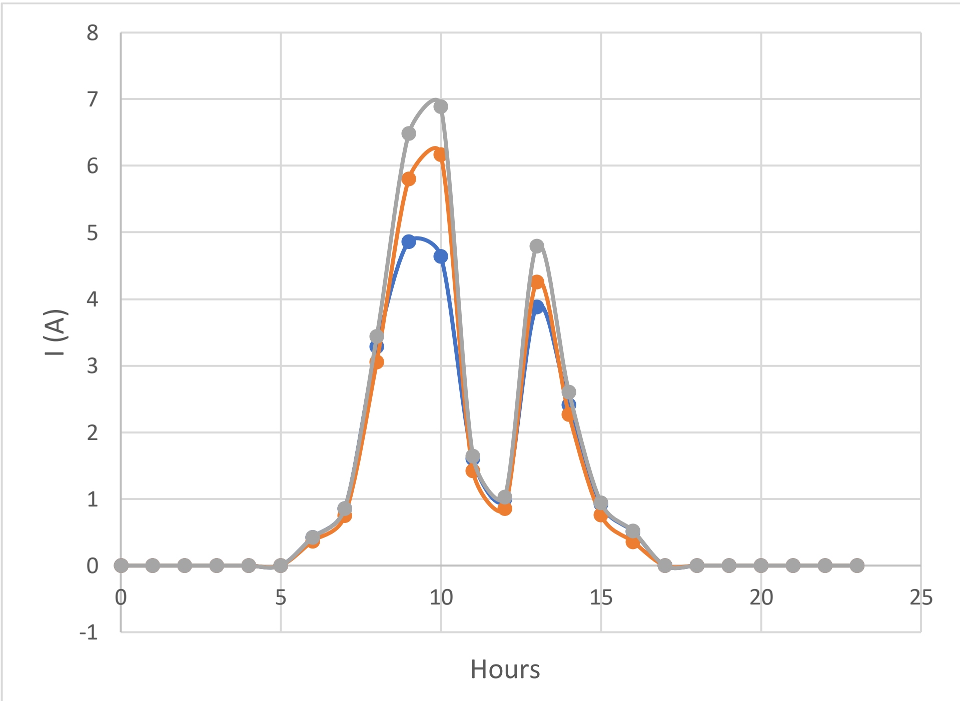

Figure 53. Annex IV. Monthly PV Cell Current Ii (March)

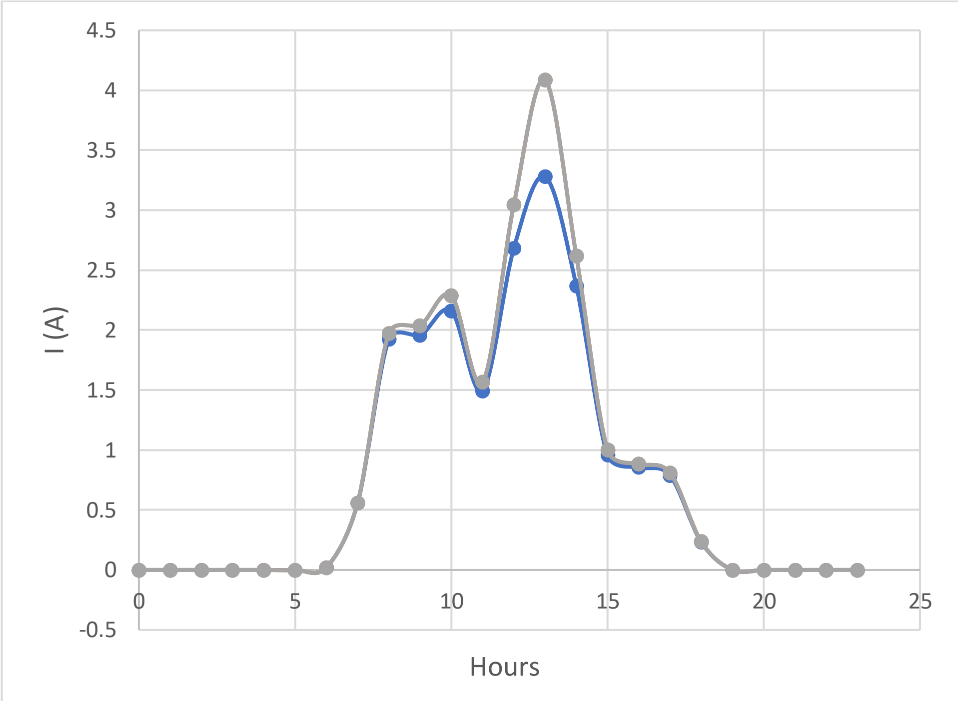

Figure 54. Annex IV. Monthly PV Cell Current Ii (April)

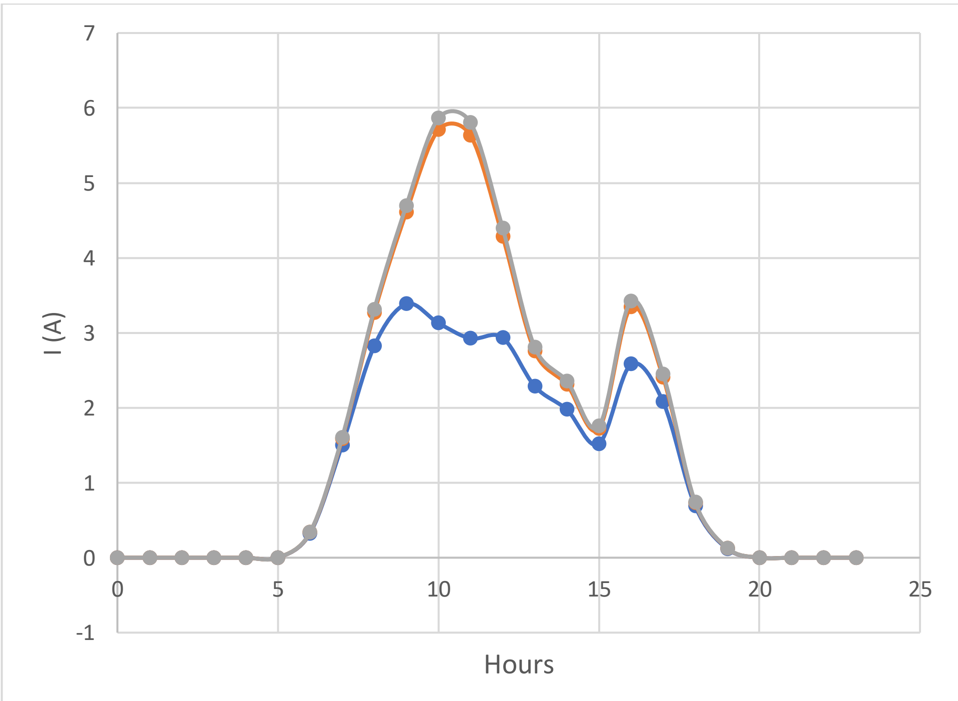

Figure 55. Annex IV. Monthly PV Cell Current Ii (May)

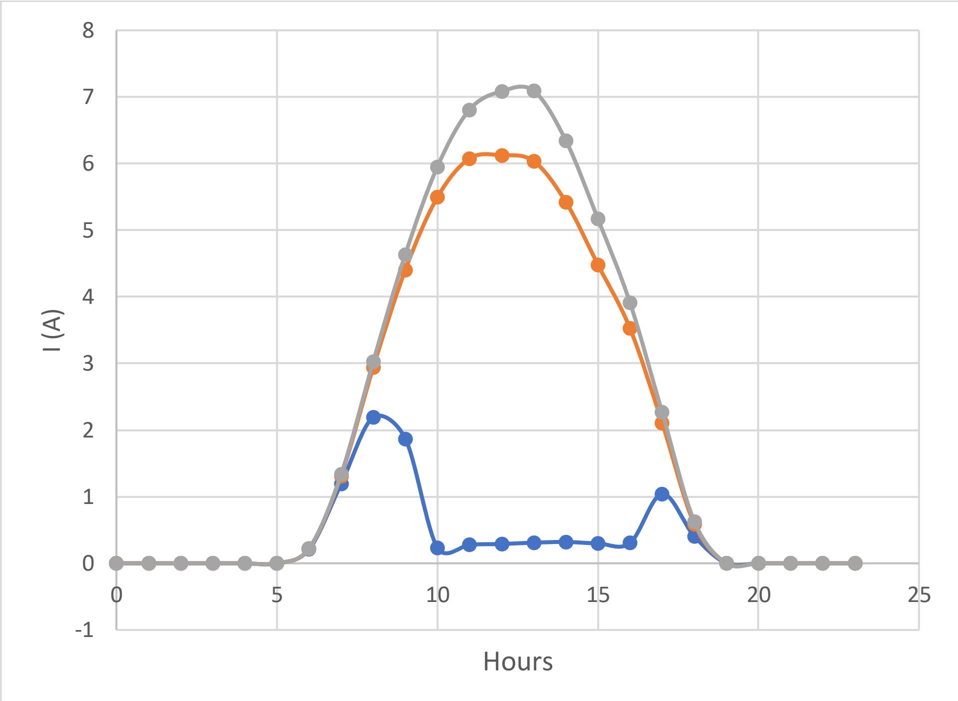

Figure 56. Annex IV. Monthly PV Cell Current Ii (June)

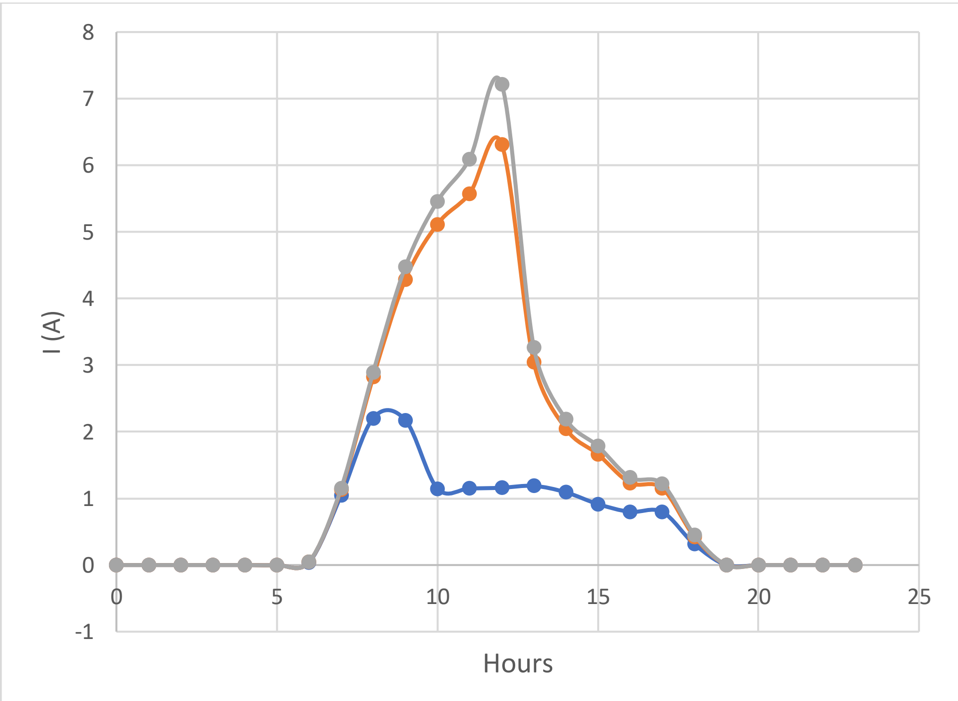

Figure 57. Annex IV. Monthly PV Cell Current Ii (July)

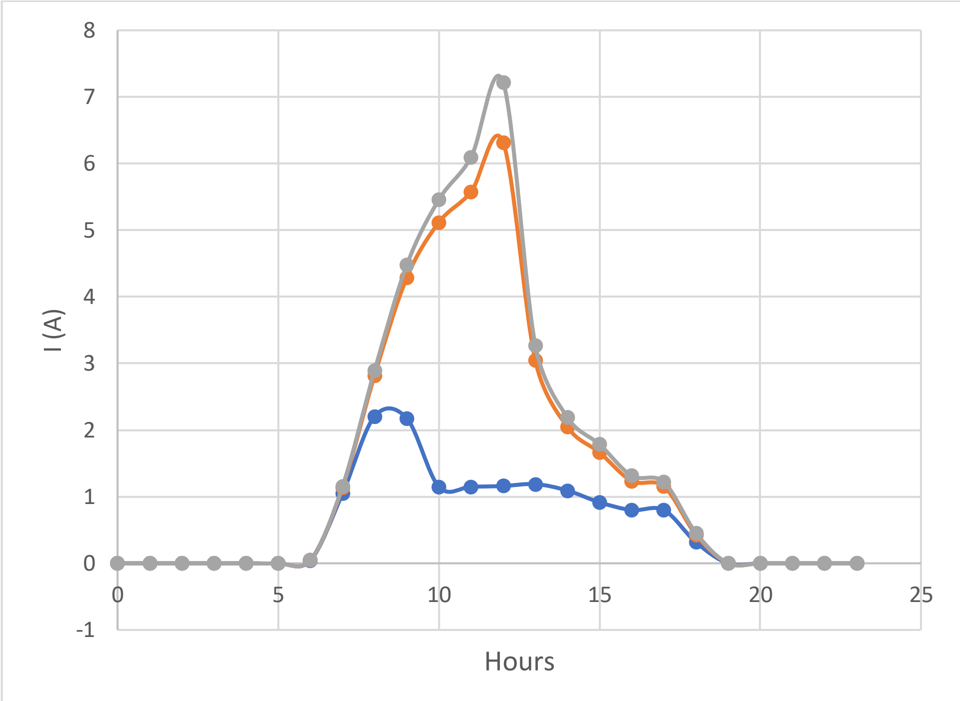

Figure 58. Annex IV. Monthly PV Cell Current Ii (August)

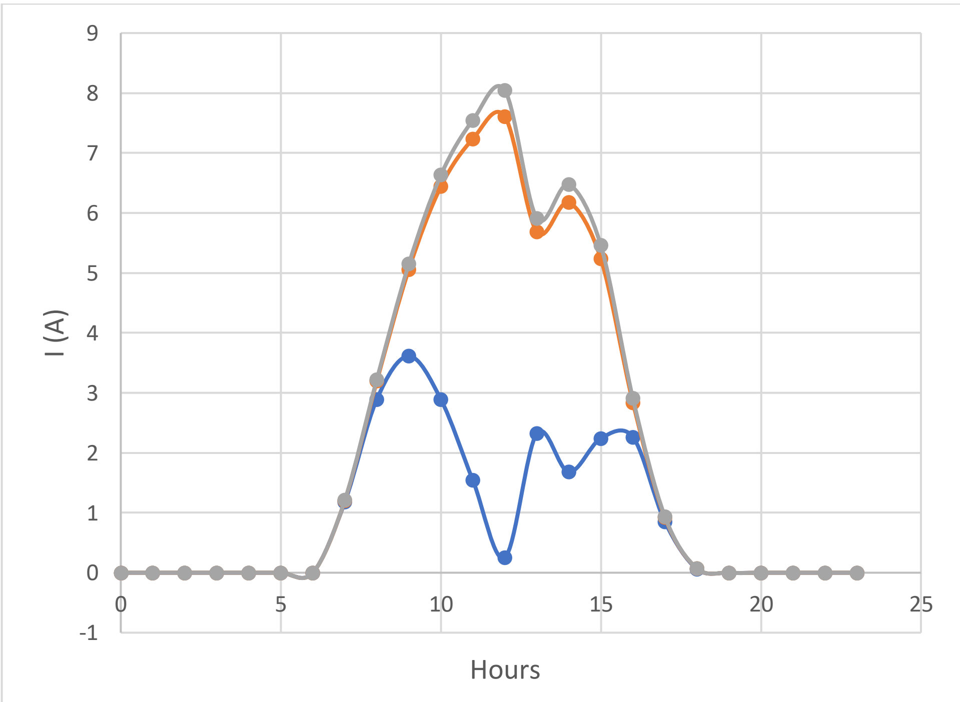

Figure 59. Annex IV. Monthly PV Cell Current Ii (September)

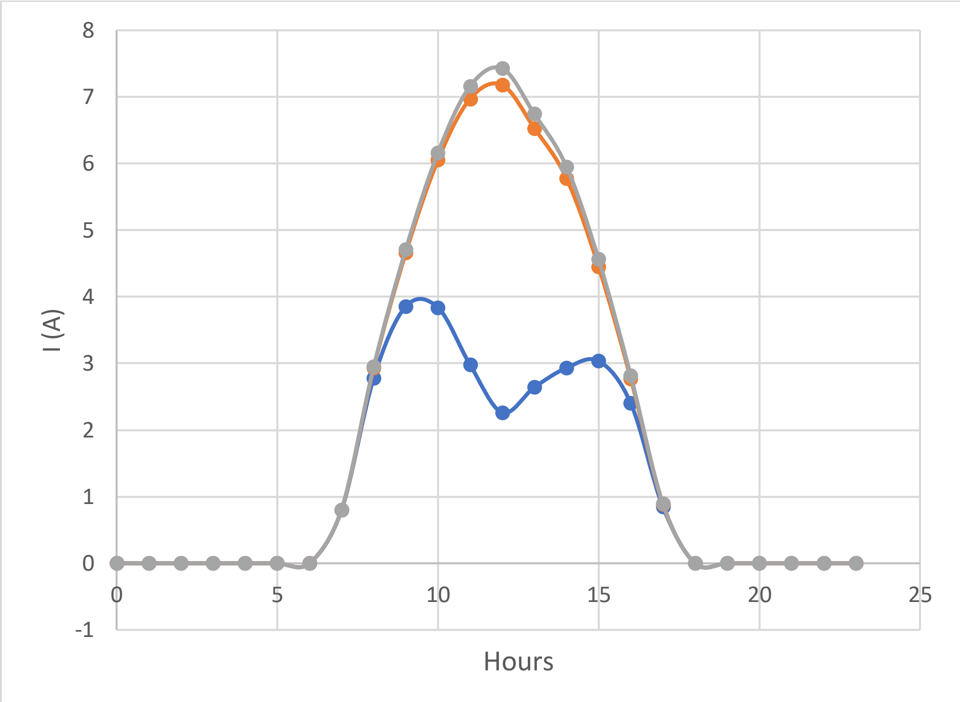

Figure 60. Annex IV. Monthly PV Cell Current Ii (October)

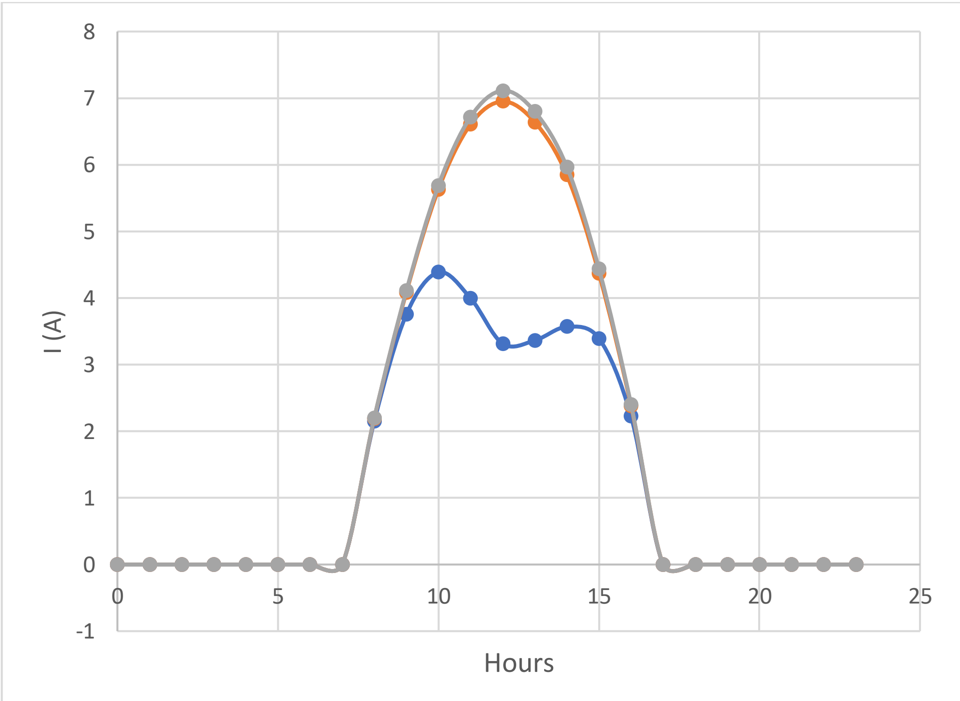

Figure 61. Annex IV. Monthly PV Cell Current Ii (November)

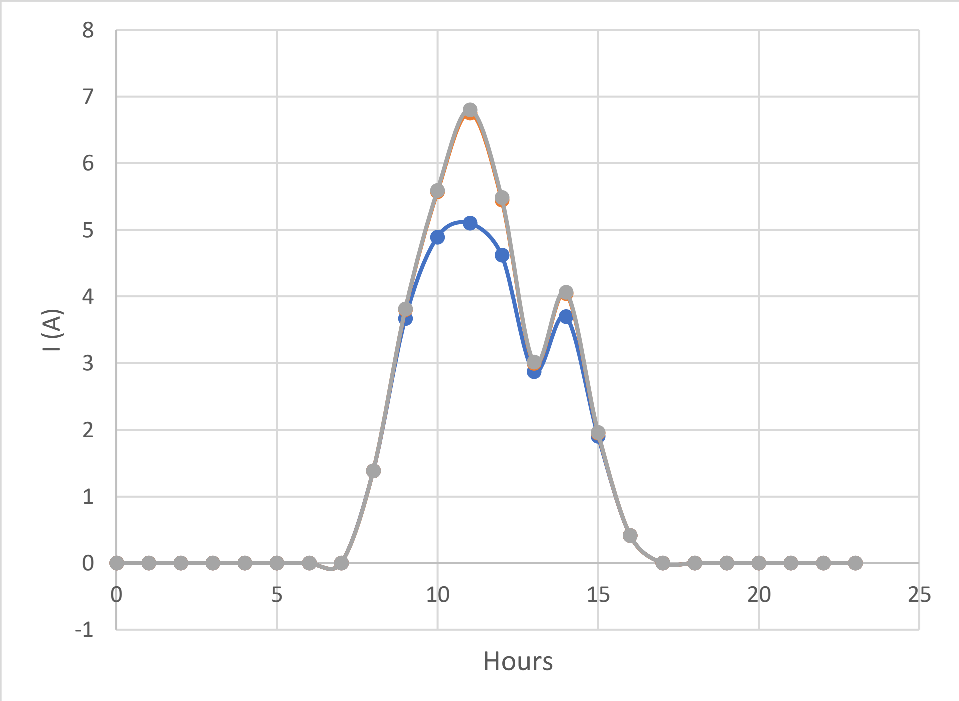

Figure 62. Annex IV. Monthly PV Cell Current Ii (December)

8.5. Annex V (Monthly Solar Array Power Output P_i, Central Day)

Table 11. Monthly Central Day P Output

	Hours																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Base Power Output (W)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	10,79	48,80	115,63	122,70	118,14	111,82	112,06	105,74	75,84	13,63	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	41,82	94,80	124,92	126,81	114,23	117,91	117,64	115,45	95,36	45,78	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	10,71	21,41	82,20	121,68	116,10	40,14	25,13	97,16	60,31	23,06	12,80	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,52	13,91	48,06	48,86	53,97	37,38	67,03	81,99	59,25	23,97	21,41	19,68	5,78	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	7,29	41,48	79,91	91,29	71,62	74,52	72,86	20,04	49,39	62,84	67,27	43,04	14,41	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	8,12	37,55	70,60	84,61	78,24	73,12	73,35	57,18	49,38	37,98	64,51	51,92	17,12	2,96	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	5,24	29,79	54,77	46,76	5,81	7,00	7,25	7,75	8,00	7,48	7,64	26,03	10,19	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	1,04	26,12	55,14	54,40	28,70	28,75	29,00	29,70	27,30	22,88	19,96	19,97	7,86	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	29,46	72,30	90,27	72,30	38,52	6,31	58,09	42,01	56,04	56,57	21,25	1,59	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	19,91	69,47	96,37	95,93	74,49	56,56	66,01	73,30	75,88	60,06	21,17	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	53,71	93,83	109,64	99,95	82,90	84,07	89,20	84,82	55,57	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	34,59	91,88	122,41	127,52	115,47	71,98	92,49	47,60	10,38	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Air Power Output (W)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	10,79	49,50	133,90	168,37	181,90	182,85	151,00	134,85	80,68	13,71	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	41,97	99,03	146,11	178,89	198,44	182,45	170,98	151,70	104,14	46,51	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	9,33	18,74	76,59	145,17	154,24	35,68	21,53	106,47	56,86	18,99	9,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,51	13,95	49,34	50,91	57,21	39,15	76,13	102,14	65,50	24,98	22,14	20,24	5,90	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	7,29	42,32	88,60	131,54	165,63	94,84	130,24	182,45	153,36	126,01	95,30	48,83	15,36	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	8,35	39,62	81,63	115,24	142,69	140,80	107,18	68,77	57,77	43,01	83,51	60,11	18,17	3,14	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	5,53	32,81	73,46	110,12	137,36	151,88	153,11	150,88	135,60	112,01	88,11	52,68	14,77	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	1,16	28,34	70,53	107,12	127,93	139,34	157,95	76,08	51,17	41,57	30,87	28,83	10,70	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	30,10	79,83	126,45	160,99	180,87	190,16	142,08	154,30	130,80	70,97	23,03	1,79	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	20,03	73,28	116,50	151,31	174,28	179,47	163,26	144,45	111,28	69,29	22,18	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	54,77	102,09	140,79	165,19	173,75	166,04	146,12	109,16	59,58	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	34,61	95,18	139,32	168,90	136,24	75,10	101,15	48,85	10,43	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Water Power Output (W)																							
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	10,82	49,63	134,67	169,81	183,80	185,11	152,62	136,31	81,14	13,76	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	42,04	99,29	146,82	180,31	200,67	184,37	172,75	153,13	104,71	46,66	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	10,69	21,46	86,09	162,23	172,31	41,24	25,71	119,89	65,22	23,71	13,05	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	0,51	13,99	49,56	51,24	57,67	39,48	77,10	103,75	66,27	25,21	22,32	20,39	5,94	0,00	0,00	0,00	0,00	0,00
May	0,00	0,00	0,00	0,00	0,00	0,00	7,31	42,49	89,37	133,95	170,51	96,65	134,19	192,06	160,12	130,78	97,91	49,72	15,59	0,00	0,00	0,00	0,00	0,00
June	0,00	0,00	0,00	0,00	0,00	0,00	8,42	40,00	82,73	117,43	146,57	145,08	109,96	70,16	58,92	43,83	85,47	61,20	18,41	3,20	0,00	0,00	0,00	0,00
July	0,00	0,00	0,00	0,00	0,00	0,00	5,61	33,38	75,65	115,92	148,82	170,22	177,11	177,25	158,63	129,19	97,72	56,63	15,74	0,00	0,00	0,00	0,00	0,00
August	0,00	0,00	0,00	0,00	0,00	0,00	1,20	28,78	72,37	111,90	136,47	152,33	180,43	81,81	54,75	44,61	32,84	30,47	11,34	0,00	0,00	0,00	0,00	0,00
September	0,00	0,00	0,00	0,00	0,00	0,00	0,00	30,26	80,59	128,72	165,76	188,68	201,04	147,80	161,81	136,42	72,68	23,42	1,86	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	20,09	73,69	117,76	154,03	178,98	185,66	168,58	148,82	114,05	70,38	22,42	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	54,94	102,64	142,23	167,94	177,82	169,93	149,21	110,96	60,12	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	34,66	95,39	139,91	170,10	137,12	75,43	101,75	49,07	10,47	0,00	0,00	0,00	0,00	0,00	0,00	0,00

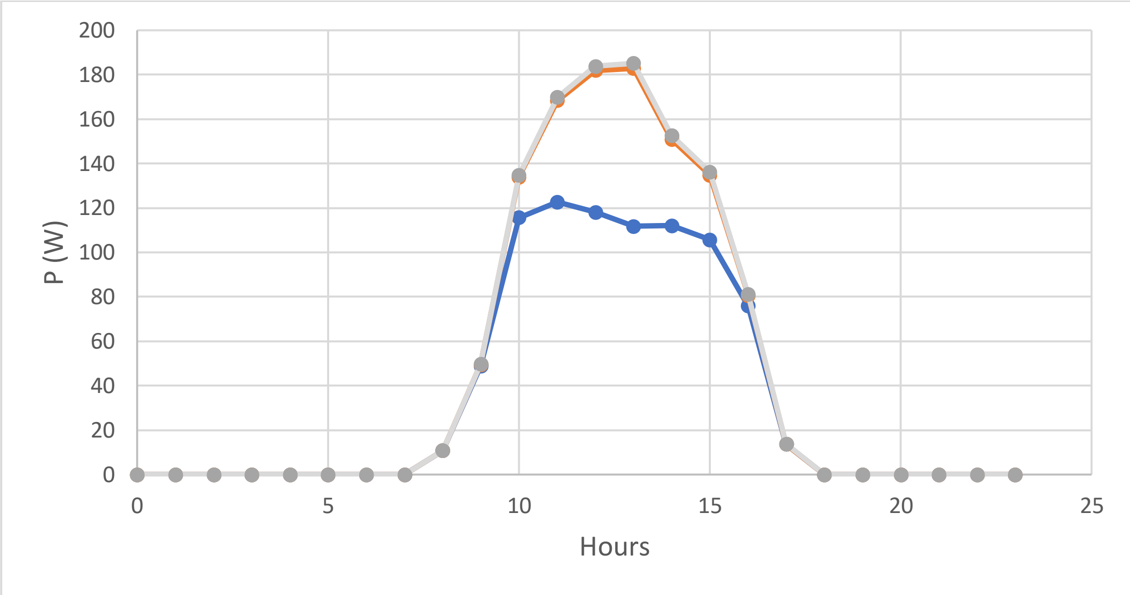

Figure 63. Annex V. Monthly Solar Array Power Output Pi (January)

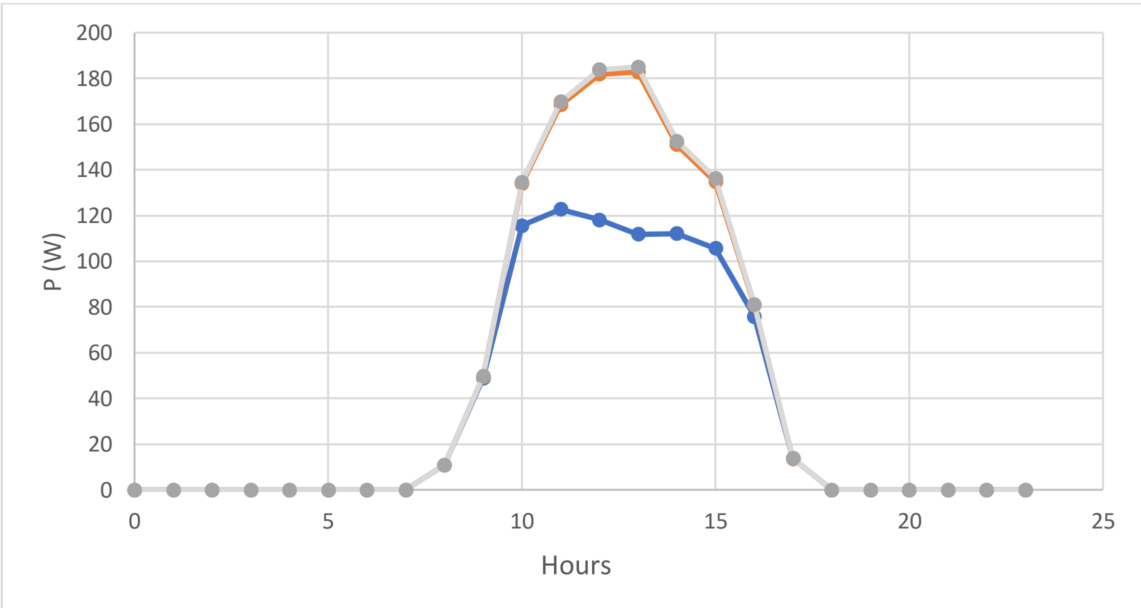

Figure 64. Annex V. Monthly Solar Array Power Output Pi (February)

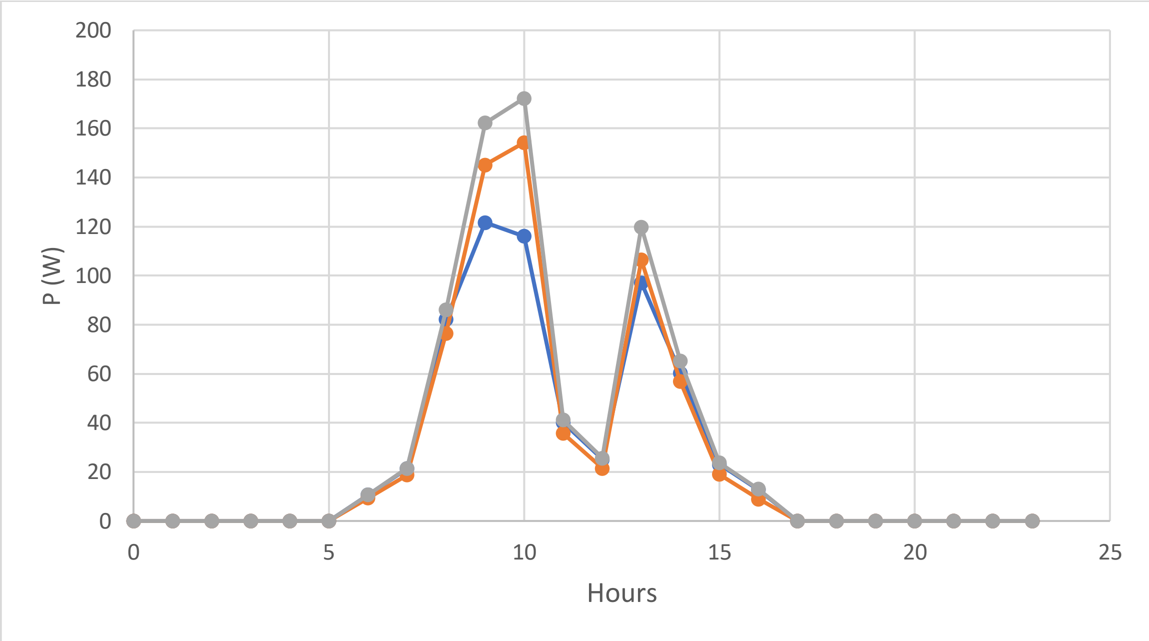

Figure 65. Annex V. Monthly Solar Array Power Output Pi (March)

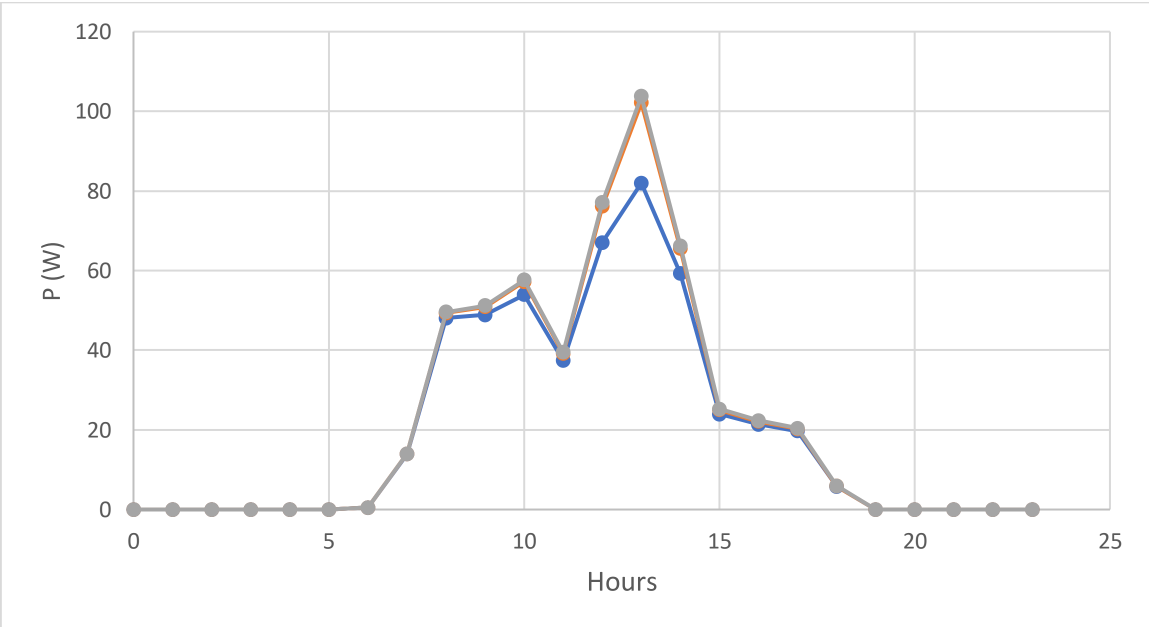

Figure 66. Annex V. Monthly Solar Array Power Output Pi (April)

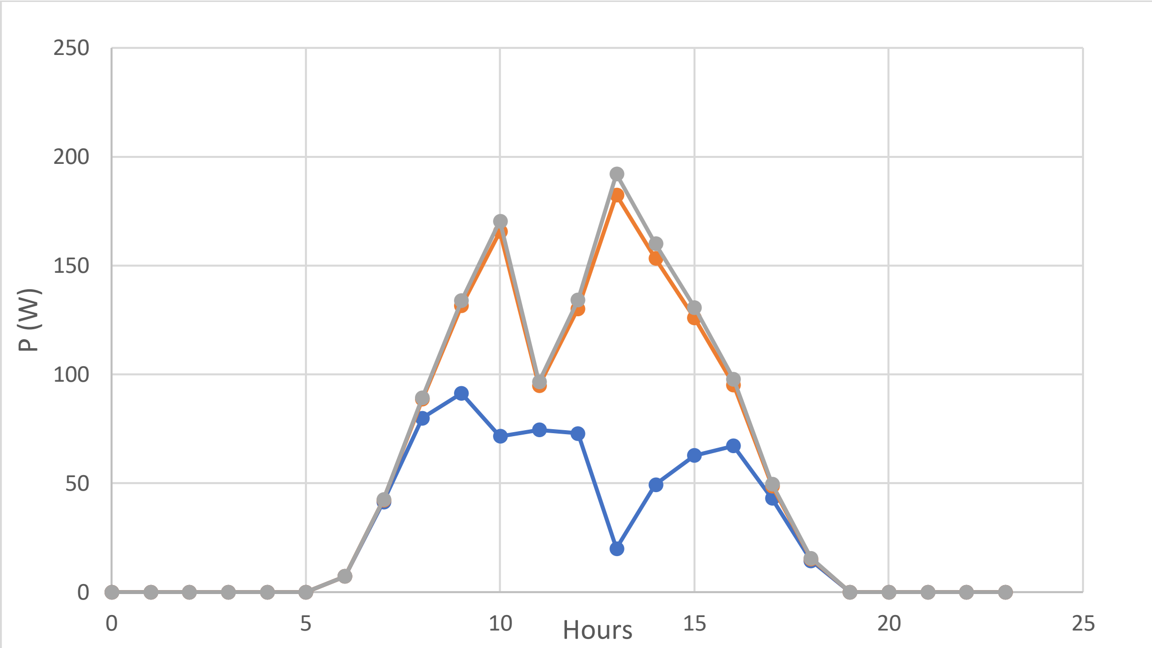

Figure 67. Annex V. Monthly Solar Array Power Output Pi (May)

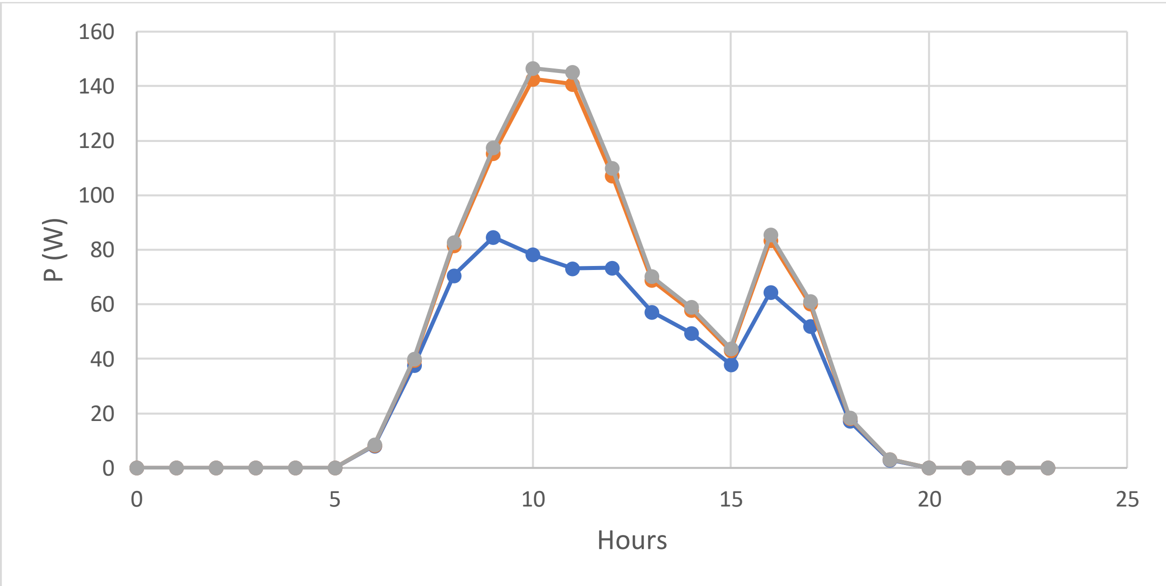

Figure 68. Annex V. Monthly Solar Array Power Output Pi (June)

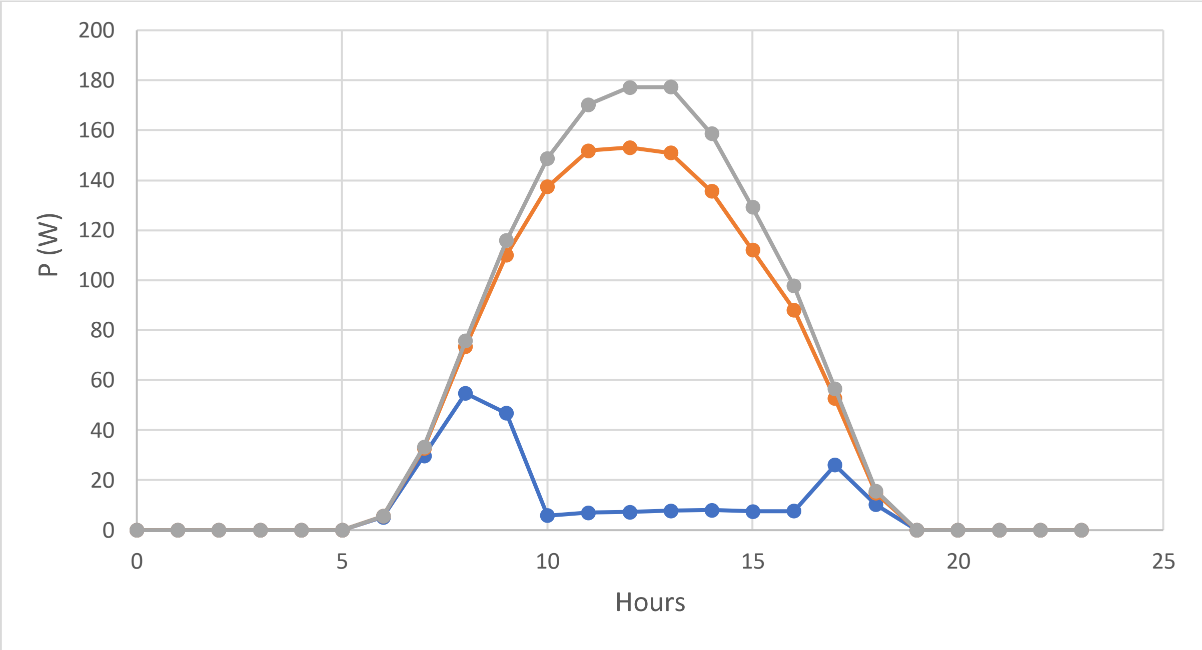

Figure 69. Annex V. Monthly Solar Array Power Output Pi (July)

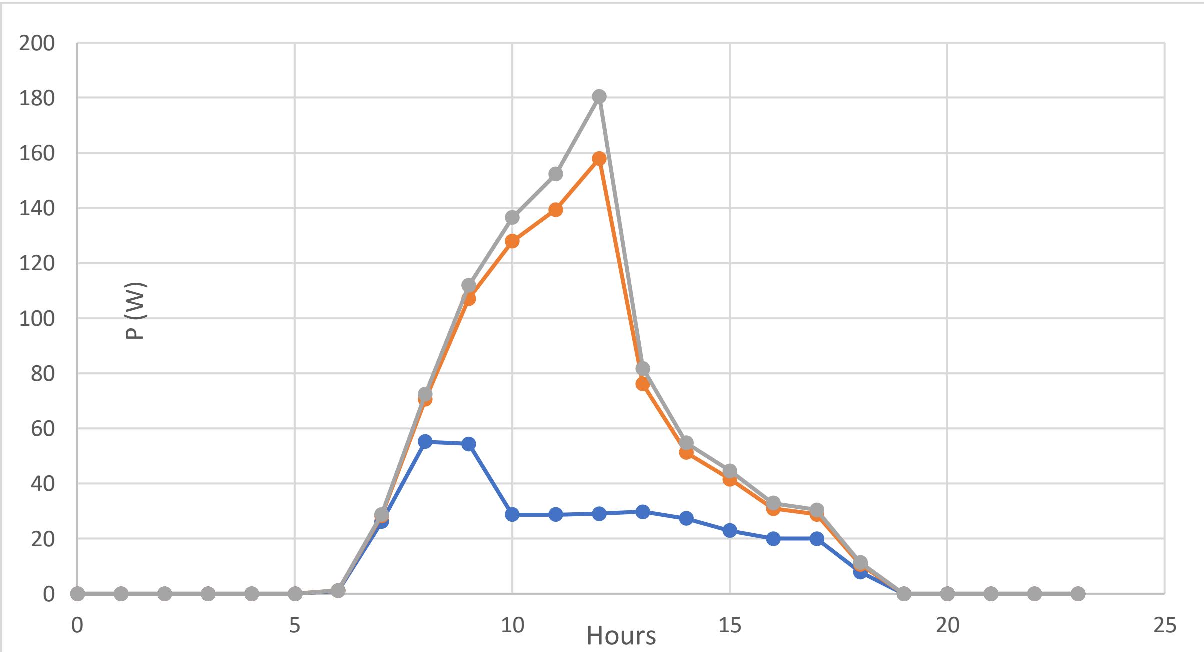

Figure 70. Annex V. Monthly Solar Array Power Output Pi (August)

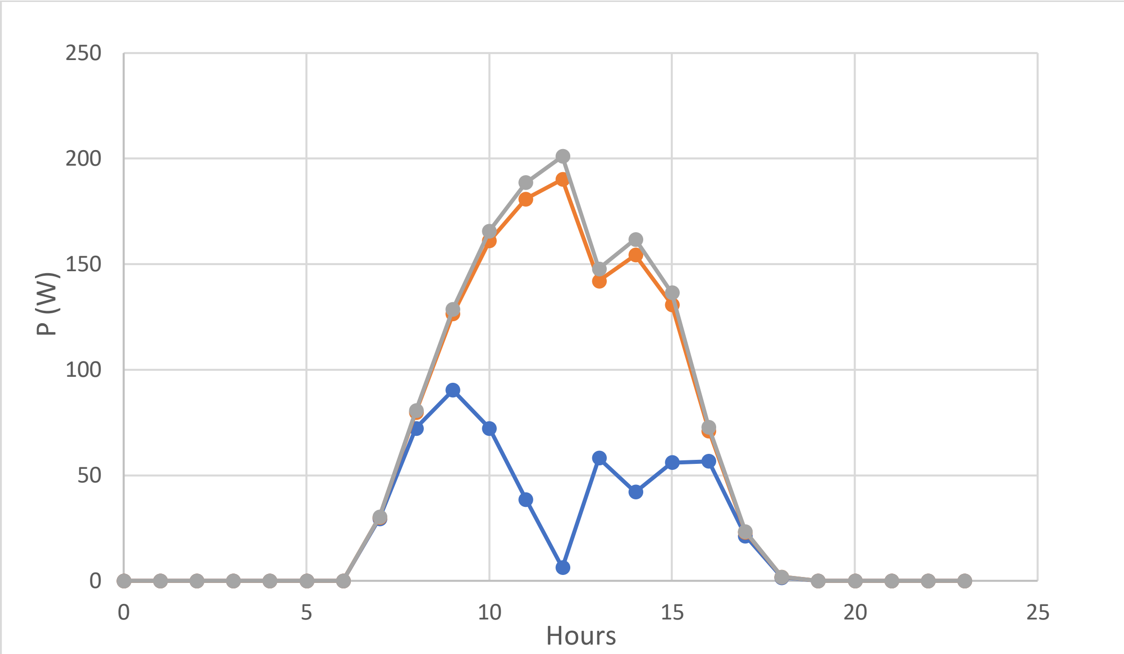

Figure 71. Annex V. Monthly Solar Array Power Output Pi (September)

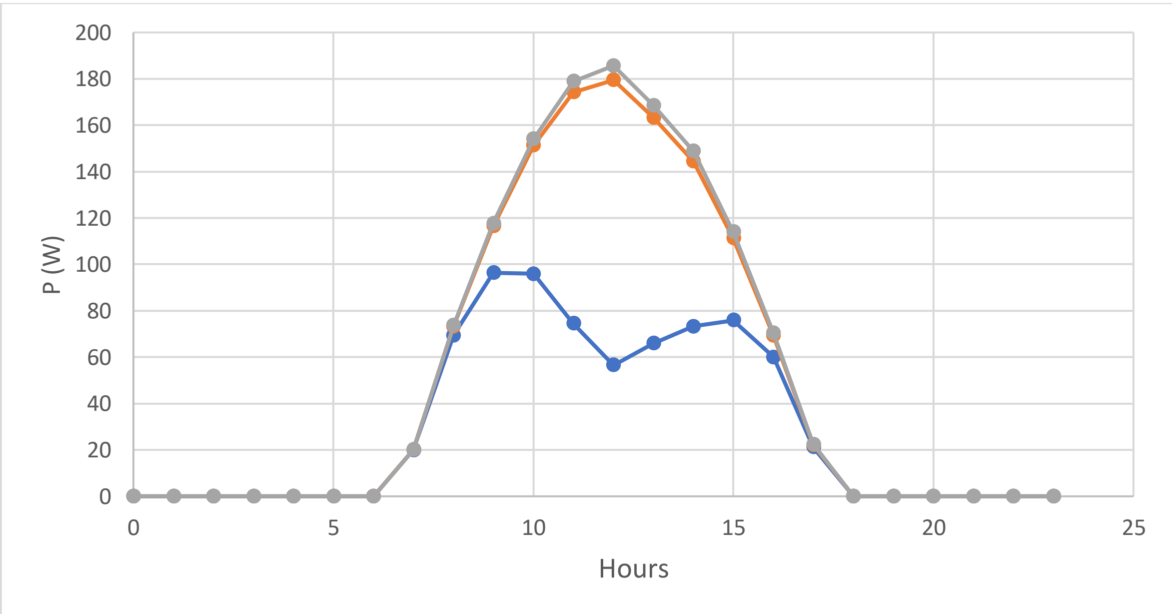

Figure 72. Annex V. Monthly Solar Array Power Output Pi (October)

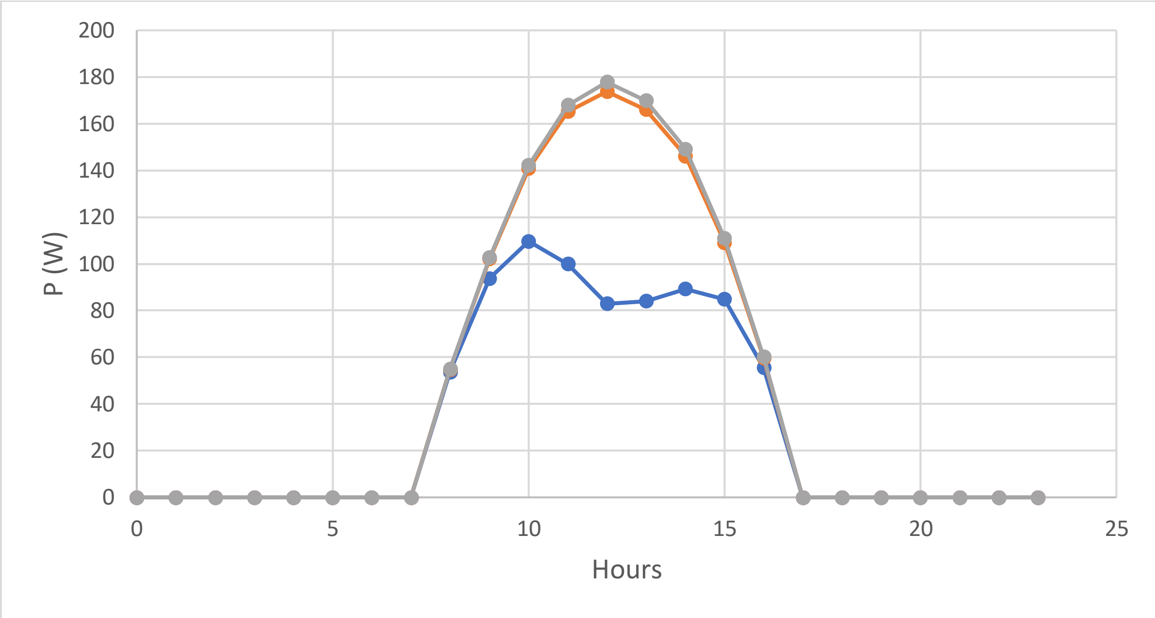

Figure 73. Annex V. Monthly Solar Array Power Output Pi (November)

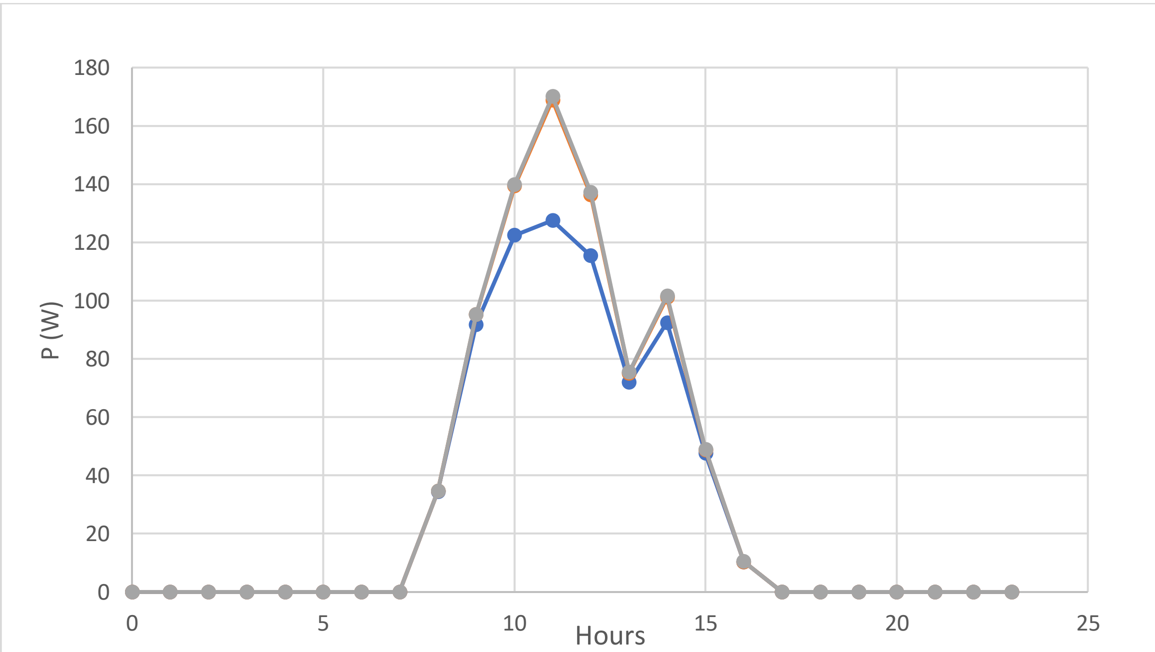

Figure 74. Annex V. Monthly Solar Array Power Output Pi (December)

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