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Study of the application of solar cells in public lighting

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Abstract

As a result of climate change, there has been increasing interest in renewable energies. The state of the planet is worsening to such an extent that it is already seen as absolutely necessary to replace fossil fuels with other, more sustainable solutions. With this objective in mind, this research work aims to study a project that powers a public lighting system using photovoltaic energy. The study site is the Alameda Garden, where the project will have to supply 8,410 W. To this end, a study and framework are provided on the state and evolution of photovoltaic technology and the choice and characteristics of the implementation site. With the financial results, production, consumption, energy made available, and other factors that influence the viability of the project, the solutions presented are compared, giving an opinion on which is the best and the challenges that still exist and that can be tackled in the future. In the end, it is possible to conclude that the project is not financially viable on its own. Since it is not possible to sell energy to the grid, the project's only income is the energy saved during the night. Due to the characteristics of the loads to be powered, batteries are needed, which are expensive components; therefore, it is not possible to recover the investment after 20 years. Thus, it is concluded that in this project's types, one may also consider the social and environmental impacts besides the financial indicators.

Keywords: Optics, Optoelectronics, Photovoltaic energy, Public lighting, Renewable energies, Photovoltaic projects.

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1. Introduction

In recent years there has been an increase in the world's awareness of issues such as climate change. Extreme weather events, heat waves, droughts and other phenomena are becoming increasingly common all over the world. It is therefore necessary to start taking measures to combat these changes, which have a tendency to worsen [1].

With these concerns in mind, the European Union has set itself the goal of achieving a climate-neutral state by 2050. To this end, it is seen as necessary to drastically reduce greenhouse gas emissions. A long-term budget has been created to contribute to this climate action [2]. The European Commission has set an intermediate goal of reducing greenhouse gas emissions by 55% by 2030 [3].

This project aims to study the use of photovoltaic solar energy to support a public lighting system. Various factors will have to be taken into account, such as the hours of exposure to the sun, the energy produced in that time interval, the energy required during the night, among others. Based on the study of economic and environmental feasibility indicators, it will be assessed whether the investment in systems of this kind is justifiable.

2. Choice of Location

Portugal is one of the main countries in the world that uses renewable energy sources to meet its energy consumption. It currently ranks 5th in the world. In 2019, 51% of all the energy consumed in the country is renewable, according to data from REN [4].

From year to year, these figures are likely to increase further. By 2022, the share of renewable energy in mainland Portugal had already reached 54.5%. Photovoltaic energy, in particular, represents around 6.7% of the energy consumed by the country [5].

One of the reasons why photovoltaic energy is so widely used in Portugal is its geographical location. As will be seen below, photovoltaic energy production depends mainly on the irradiance and temperature levels of the project site. Portugal is one of the countries in the world with the best conditions when it comes to these two factors. According to the "Renewable Energy Country Attractiveness Index", Portugal ranks 23rd in the world in terms of attractiveness and opportunity for the use of renewable energies [6].

Portugal is one of the countries in Europe with the highest levels of irradiation throughout the year. Added to this is the fact that, due to its geographical location, it is one of the countries with the most annual hours of sunshine (between 2200 and 3100 hours), which means more production time.

There are countries closer to the equator where irradiation and hours of sun exposure are higher. However, in these places, temperatures are higher throughout the day, which is detrimental to the efficiency of the panels [3, 7, 8].

This concludes that Portugal has one of the best balances in terms of climatic conditions for photovoltaic production.

The site chosen for the project will be Alameda, where the Instituto Superior Técnico is located. Alameda Dom Afonso Henriques is a garden in Lisbon, built in honor of Portugal's first king. This is a small area, but it has a considerable number of lampposts installed, making it an ideal test site for the photovoltaic project. Depending on the results, it will be possible to extend the project to a larger area. There are increasing efforts by the Lisbon City Council to make the city "greener," which will make the project attractive in the eyes of the council.

3. Power of Photovoltaic Array

The maximum power value of a panel as a function of temperature and irradiance, $P_{max,,}$, is given by the expression 1 [3, 7, 8].

$$P_{max,T_{pv},G} = P_{max(NOCT)} \cdot \frac{G}{800} \cdot \left(1 + \Delta \cdot \left(T_{pv} - 20\right)\right) \qquad (1)$$

G and T_{pv} represent the irradiance that the panel receives and its temperature at each instant of time, respectively. Δ is the variation of maximum power with temperature. The value of the panel's temperature during operation, T_{pv}, is given by the relation 2 [3, 11, 12].

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

With T_{amb} representing the ambient temperature and T_{NOCT} the normal operating temperature of the cell.

4. Sizing and Implementation

In this section, the project is sized and the equipment selected. A few different options are analysed, so that in the end it will be possible to conclude on which is the most advantageous.

• Solution A - Installation of panels on the roofs of buildings surrounding the Alameda: The circuit diagram for this solution is shown in Figure 1. This solution seeks to use the free space on the roofs of buildings close to the garden. Since the buildings closest to the site belong to private entities, compensation must be offered for the use of the space. This could take the form of rent paid to the entity that owns the building (e.g. 2000€/month). An energy community could be created so that the building's meter is linked to the project's meter to power the luminaires. An energy community is an agreement between shareholders or entities that own properties next to the renewable energy project. The aim is for them to obtain environmental, economic or social benefits [9].

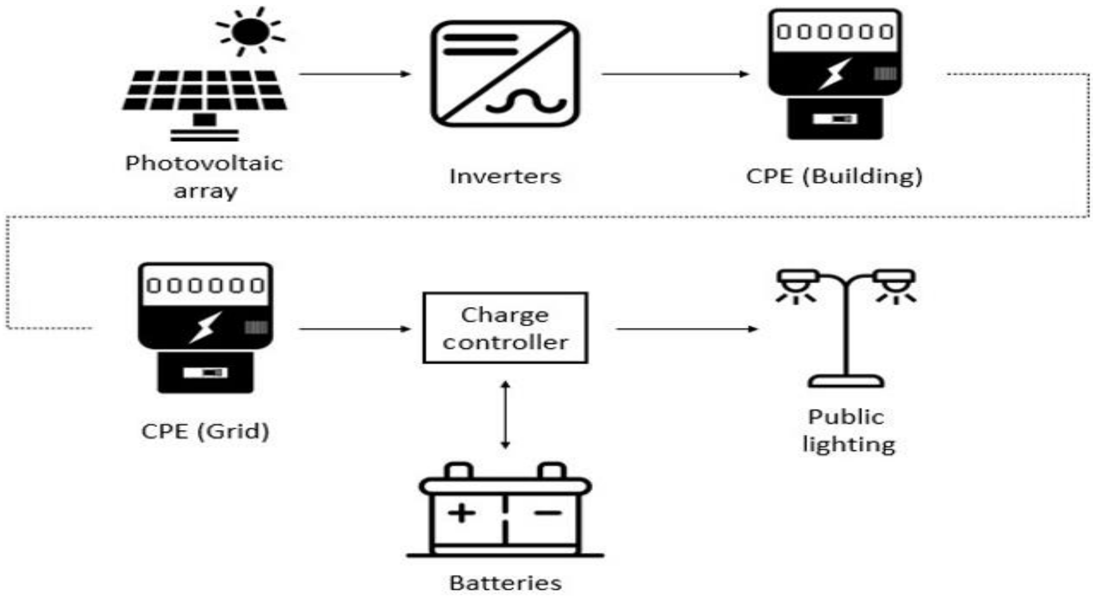

Figure 1.
Solution A.

This project has the particularity that the hours of energy production are completely out of sync with those of consumption. There are therefore two alternatives regarding what to do with the energy produced during the day. The first would be to sell the energy produced to the grid and then use those earnings to buy energy at night. The problem with this option is that currently, due to the excess of different sources wishing to send energy to the grid during the day, the energy it receives at various times exceeds that which is consumed, so there is no interest in buying energy, and the sale rates are zero. In some cases, it may even be necessary to pay to send energy to the grid. For this reason, this option has now been ruled out. The second alternative is to invest in a set of batteries. In this case, the energy produced during the day will be used to charge the batteries, and the excess, if any, will be sent to the grid. With this option, there would be no need to buy energy at night. This is the alternative that will be chosen.

• Solution B - Installing the panels in the Alameda Garden: This solution aims to distribute the photovoltaic panels along the Alameda Garden. The idea, subject to approval by the council, proposes using the panels as roofs that create areas of shade in the garden. This solution would be developed with the help of an architect in order to preserve the aesthetics of the Alameda. As with solution A, and for the same reasons, batteries will be used. The circuit diagram is shown in Figure 2. A house will be built for the batteries and inverters so that they can be protected. Its location will depend on negotiations with the city council.

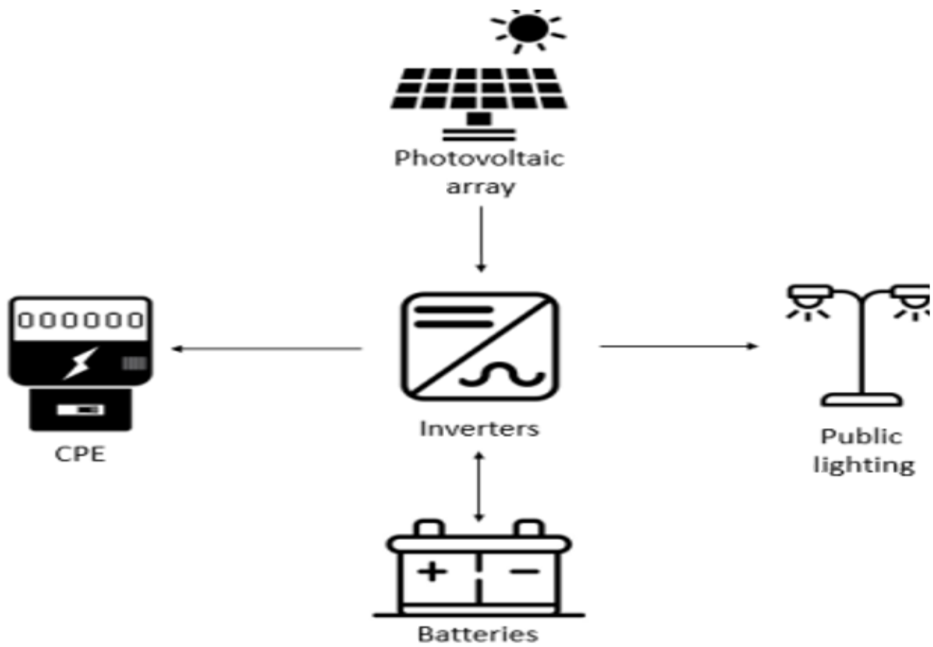

Figure 2.
Solution B.

• Solution C - Independent lamp posts: This solution seeks to install a lighting project in which each lamp post is an independent system. The energy needed to power the lamp (or lamps) on each pole will be produced and stored on the same pole. The panels will be installed at the top of the poles, with batteries on each pole as well. The diagram of this solution is shown in Figure 3.

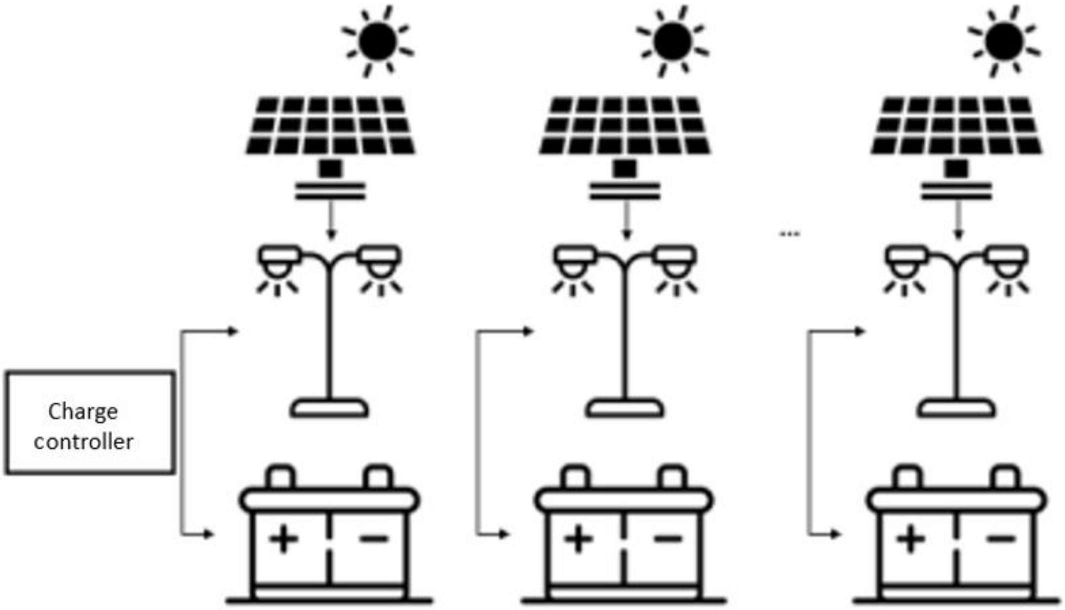

Figure 3.
Solution C.

4.1. Characterization of Energy Consumption

In order to correctly size the project, it is first necessary to study the loads to be fed. To do this, start by defining the area covered by the project.

Figure 4 shows the selected area. The marked area contains a total of 104 lamp posts, however, there are some lamp posts where there is more than one lamp (the loads to be fed). In order to save energy in the long term, it is proposed to replace the conventional light bulbs in the project area with Light-Emitting Diodes (LED).

Figure 4.
Lightning posts in Alameda.

According to Public Lighting Regulations [10] LED lamps of approximately 40-50W meet the necessary requirements for public lighting. The lamps selected for the project are those in 50W New Shoe [11] with 50W of power, and 5500 lm of luminosity and which are specifically designed for outdoor lighting.

The bulbs at the top of the fountain on the boulevard do not need as much power, so the 30 W bulbs of Philips [12] are selected.

4.1.1. Night Lighting Hours

The Lisbon Astronomical Observatory provides information on the times of sunrise and sunset on a daily basis. In this way, it is possible to analyse the evolution of nighttime hours throughout the year. This is important data for knowing when the project's loads need to be supplied. Figure 5 shows how this data varies.

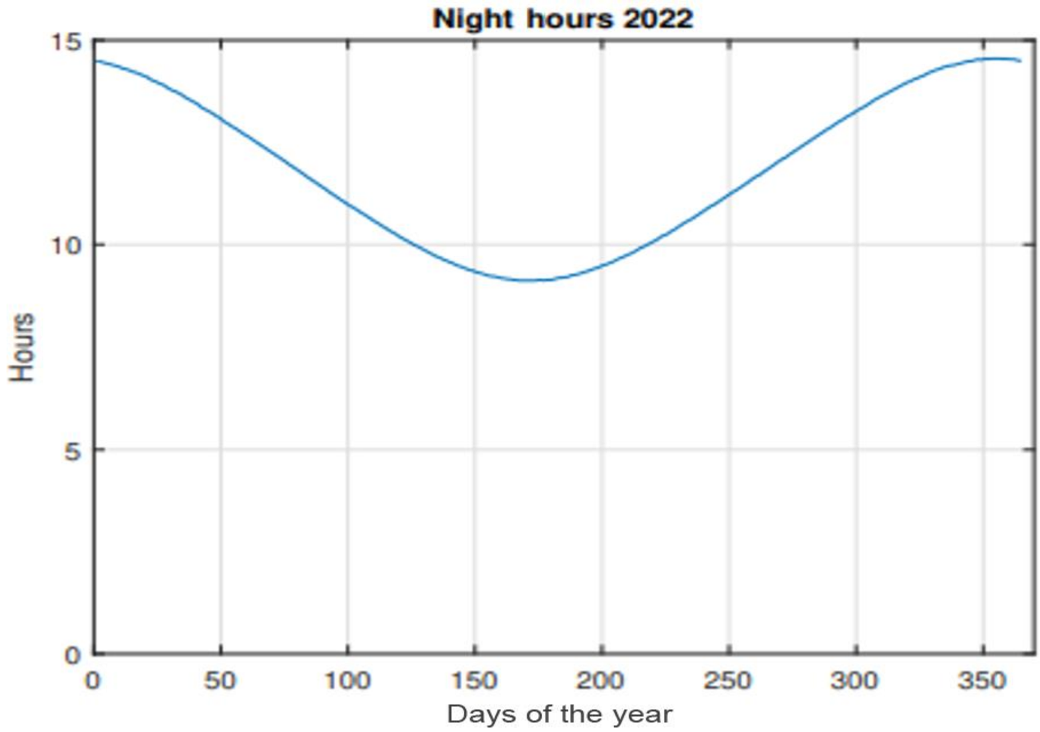

Figure 5.
Nigh hours in 2022.

As expected, the winter months have the longest nighttime periods. One can verify that throughout the year, the hours of sunshine increase until the summer months, then decrease again from June until the end of the year.

December is the month with the longest night. That night has 14 hours and 13 minutes without sunlight. This will be the critical case that will have to be taken into account when sizing the battery bank.

With this information, one can determine the energy consumption. The power of the total loads to be supplied is calculated by expression 3, where P_{LED} is the power consumed by a given LED and N_{lamps} the number of used devices. The study uses 152 lamps of 50W and 27 of 30W, giving a total of 8410W.

$$P = P_{LED} \times N_{lamps} \qquad (3)$$

Combining the data on the number of nighttime hours with the total power of the set of poles, according to expression 4, gives the graph in Figure 6 of the energy consumed throughout the year.

$$E(t) = P_{lamp} \cdot \Delta t \qquad (4)$$

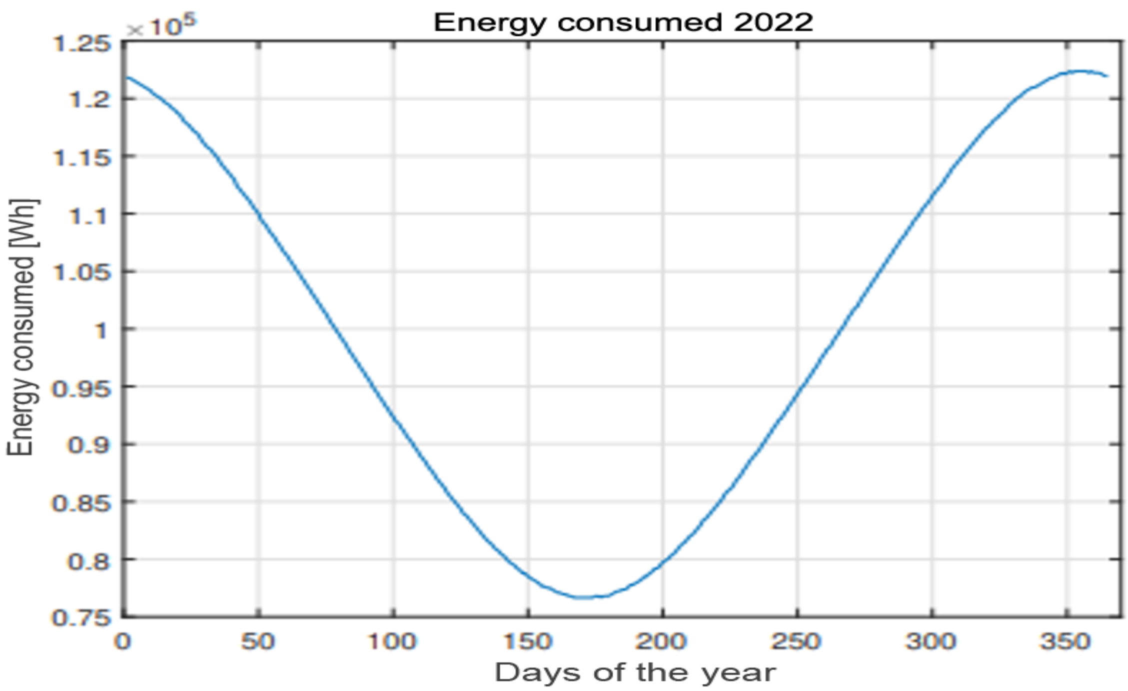

Figure 6.
Energy consumed over the year 2022.

The month of December is when the most energy is consumed, with a peak energy requirement of 122400 Wh.

4.2. Climate Data

Using the PVGIS tool (Photovoltaic Geographical Information System) in its website, it is possible to collect information about the climate data of the site under study. This is crucial for project sizing.

4.2.1. Irradiance

For the Lisbon area, it is possible to estimate the average irradiance per hour for each month of the year. This data is represented in Figure 7. As expected, the higher values of irradiance are in the months of summer.

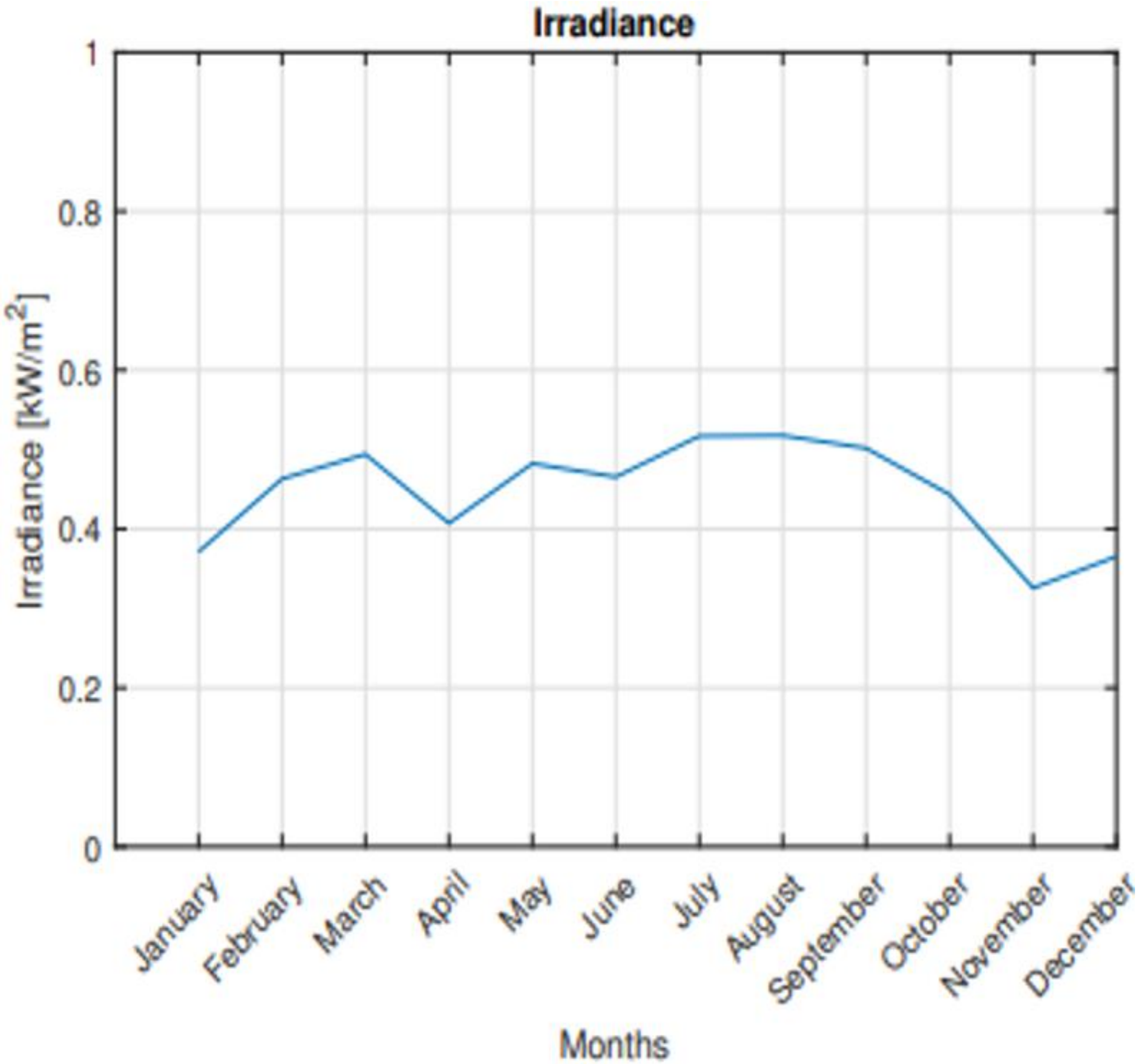

Figure 7.
Average irradiance per hour in Lisbon in 2020.

4.3. Temperature

Data is also collected from Figure 8, referring to the average temperature for each month. It can be concluded that the summer months are the ones with the highest temperatures. January is the month with the lowest temperatures.

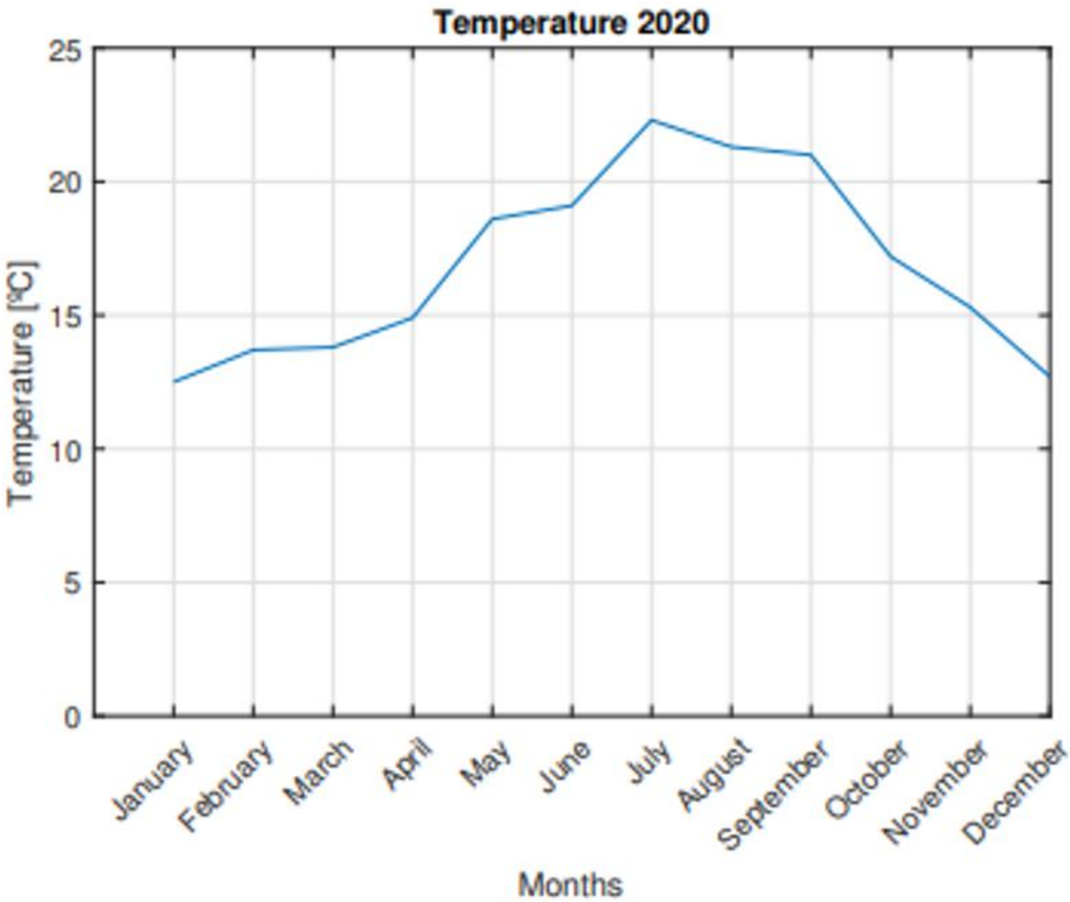

Figure 8.
Average monthly temperature in Lisbon in 2020.

5. Sizing the Photovoltaic System (Critical Case)

In order to calculate the power to be produced by the photovoltaic system and, consequently, the number of panels required, the number of hours of sunshine each day must be taken into account.

Using data from the Lisbon Astronomical Observatory, it is obtained average values for each month, which are shown in the Table 1. The difference between the average number of hours of sunshine and the maximum for each month is also shown, and it can be seen that there are no large deviations between the average and the extreme for each month.

Firstly, the sizing will be done for the critical case, which in this project corresponds to the shortest day of the year, in December, with 9.45 hours of sunshine. This will ensure that all the energy consumed during the year can be produced, without the need to buy it.

The energy needed to be produced by the photovoltaic system (for the critical day of the year), when considering an approximate efficiency of 90%, inherent in the components between the panels and the loads, is given by 5.

$$E_{generator} = \frac{E_{critical}}{\eta_{system}} = \frac{122400}{0.90} = 136000Wh \quad (5)$$

Table 1.
Sun hours per month.

Month	H_s	**Variance**
January	9.81	0.30
February	10.76	0.51
March	11.96	0.63
April	13.23	0.60
May	14.30	0.46
June	14.84	0.14
July	14.57	0.37
August	13.63	0.58
September	12.43	0.60
October	11.18	0.58
November	10.08	0.41
December	9.51	0.06

5.1. Photovoltaic Module Selection

As previously mentioned, there are currently several solar panel technologies.

The first photovoltaic cell technology consists of a crystalline silicon structure and, although it is the oldest technology, it has undergone constant development which has kept it extremely competitive. Within this technology, there are two main types: monocrystalline panels and polycrystalline panels [13].

Monocrystalline panels are the most common on the market, as they have high efficiencies, long lifetimes and competitive prices. On the other hand, polycrystalline panels have lower costs, but lower efficiencies compared to monocrystalline panels.

Since the space for implementing the panels is limited in this project, it is assumed that it will be advantageous to opt for monocrystalline technology which, because it has a higher efficiency, will require a smaller area for implementation.

It analysed the installation of Phono Solar 550W Twin Plus monocrystalline panels [14] which have a unit cost of 209.13 €.

Based on the Equations 1 and 2, together with the data from the technical data sheet of the selected panel, an average value of the power produced each month by each panel is estimated. The graph in Figure 9 illustrates how the power produced by 1 of these panels varies throughout the year.

The tendency for production to be higher in the summer months is confirmed. For December, it is concluded that each panel produces an average of 184.1 W.

Since in Lisbon and in the month of December the shortest day had 9.45 hours of sunshine, as already seen, the minimum number of panels of this model required to meet the system's needs (critical case) is given by 6.

$$n_{panels} = \frac{E_{generator}}{P_{panel} \cdot H_s} = \frac{136000}{184.1 \cdot 9.45} \approx 79 \qquad (6)$$

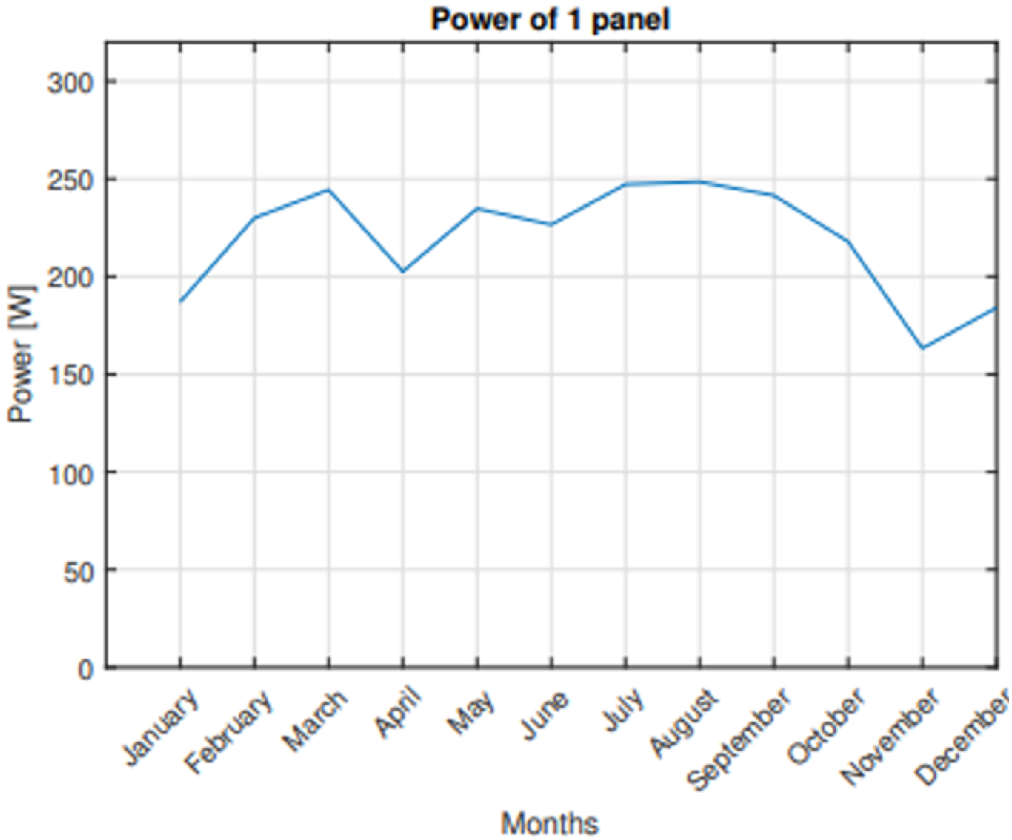

Figure 9.
Power output of 1 panel Phono solar 550w twin plus.

Photovoltaic modules are relatively inexpensive components, so it is possible to slightly oversize their quantity in order to guarantee the necessary production for any case. In addition, panels suffer some degradation over time, which affects their production capacity. Manufacturers usually indicate that over a period of 25 years (the lifetime of the panels), production can drop by up to 80%. Studies show that these degradation values can be even higher [15].

Assuming a 20% decrease in production, to produce the same as 79 panels under ideal conditions, a minimum of 95 panels would be needed.

For these reasons, 96 panels will be considered (an even number is more appropriate for the configuration/disposition of the panels), which will have an associated purchase cost of 20076.48€.

Figure 10 contains a graph where one can compare the energy produced by the photovoltaic array and that consumed by the loads.

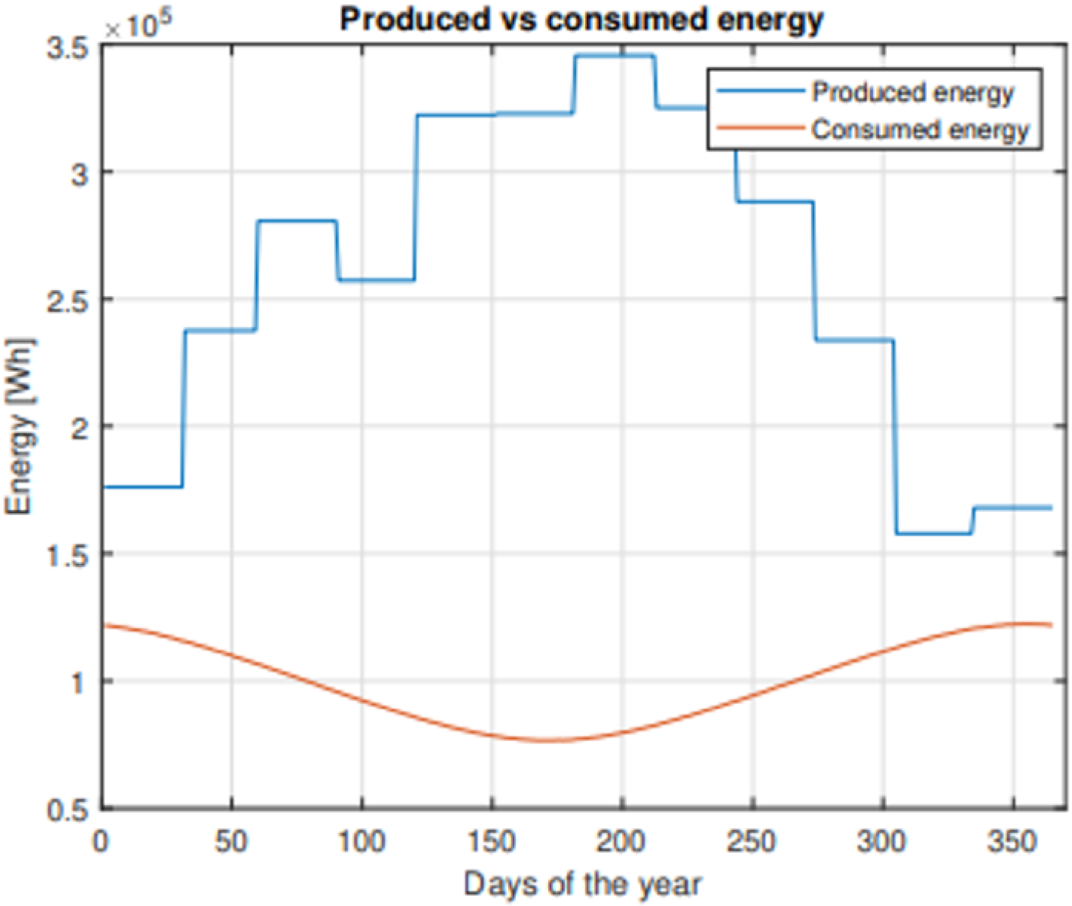

Figure 10.
Energy produced and energy consumed by the system.

As one can observe, in order to ensure sufficient production for the critical day, there is an inevitable oversizing of the number of panels for the rest of the year. This oversizing is especially noticeable in the summer months, when the energy produced is more than three times that consumed.

5.2. Solution A

5.2.1. Panel Installation Area

As already mentioned, one of the alternatives being studied is to install panels on the roofs of the buildings surrounding the Alameda Garden.

The roofs face south and have an inclination of approximately 35º, which is favorable for solar production. For this reason, the panels will be installed with the slope of the roof. This means that there is no need for a large distance between rows to avoid the projection of shadows between panels.

5.2.2. Sizing the Panels' Inverter

The selection of the inverter to use depends on the size of the loads in the circuit and how many are being used simultaneously in the worst case. In this project, the only loads to be powered are the lamps in the chandeliers which, since they all work at the same time, simplify sizing.

The total power of the lamps in the circuit is 8410W. A set of inverters must be selected to support this value. The inverter selected is the "Sunny Boy 4.0", whose technical data sheet is in Sunny Boy [16]. This model has an associated unit cost of 1128€.

The inverter has the following specifications:

- Maximum input voltage = 600V;
- • MPPT range = [140,500] V;
- Maximum input current = 15 A per MPPT (there are 2);
- Maximum input power = 7500 Wp;
- Nominal output power = 4000 W.

In order to connect the 96 installed panels to the inverter, it will be necessary to divide the set of panels into 4 inverters of this model, one for each roof. Each inverter will have 24 panels at its input (2 in parallel of 12 in series). Each set of 24 panels, with the configuration shown, will have 498.6V, 26.48A, and 5961.6W (in the month of highest production, August). As each inverter has 2 MPPTs, each series of 12 panels will be connected to 1 Maximum Power Point Tracker (MPPT). It is possible to see that, in this way, no specification is exceeded.

- Maximum input voltage = 600V > 498.6V;
- MPPT range = [140,500] V, 140V < 498.6V < 500V;
- Maximum input current = 15 A (x2) > 13.24 A (x2);
- Maximum input power = 7500 Wp > 5961.6 W;
- Nominal output power = 4000 W > 8410 4 W.

5.2.3. Battery Sizing and Inverters

The battery bank must be sized to ensure that it can store the energy needed to be consumed during any night of the year. In this way, the night when the most energy is consumed must be taken into account. This is in December and 123200 Wh are consumed.

The model chosen for the battery is the "AXIstorage Li 7S" [17] compatible with SMA inverters. This model is made of lithium-ion technology (which has been mentioned before as the best option) and has a capacity of 6.3 kWh, with a DOD of 80%. Its unit cost is 3459€.

It is good practice to size the battery bank so that it has an autonomy of more than one day, in order to prepare the system for periods when energy production is reduced.

In this case, it is considered an autonomy of 2 days. Thus, the energy that the battery must store is given by 7.

$$E_{batteries} = \frac{E_{critical} \cdot autonomy}{\eta_{battery} \times DOD}$$

$$= \frac{122400 \cdot 2}{0.97 \times 0.80} = 315464Wh \qquad (7)$$

As the selected battery stores up to 6300 Wh, the number needed to store all the energy is obtained by 8.

$$n_{batteries} = \frac{E_{batteies}}{E_{bat}} = \frac{315464}{6300} \approx 50 \qquad (8)$$

In this way, 50 batteries of this model will be used, which equates to 315000 Wh of energy that can be stored. The purchase of these components will cost 172950€.

It will also be necessary to use the "SUNNY TRIPOWER STORAGE 60" inverter [18] which will connect the batteries to the grid. This model costs 3799€ per unit.

The batteries in this model have a nominal voltage of 55.5 V. Given the limitations of the inverter's technical data sheet, 4 inverters will be used, with 2 of them associated with 12 batteries in series and the other 13 (totaling 666 V and 721.5 V, respectively). The inverters are therefore associated with an investment of a further 15196€.

Figure 11 shows the evolution of the state of the batteries over the course of a year.

Only the energy that can be extracted from the batteries is shown, taking into account the depth of discharge (DOD) of 80%. With this sizing, the batteries are always full at the beginning of each night, preparing the system for unforeseen events throughout the year.

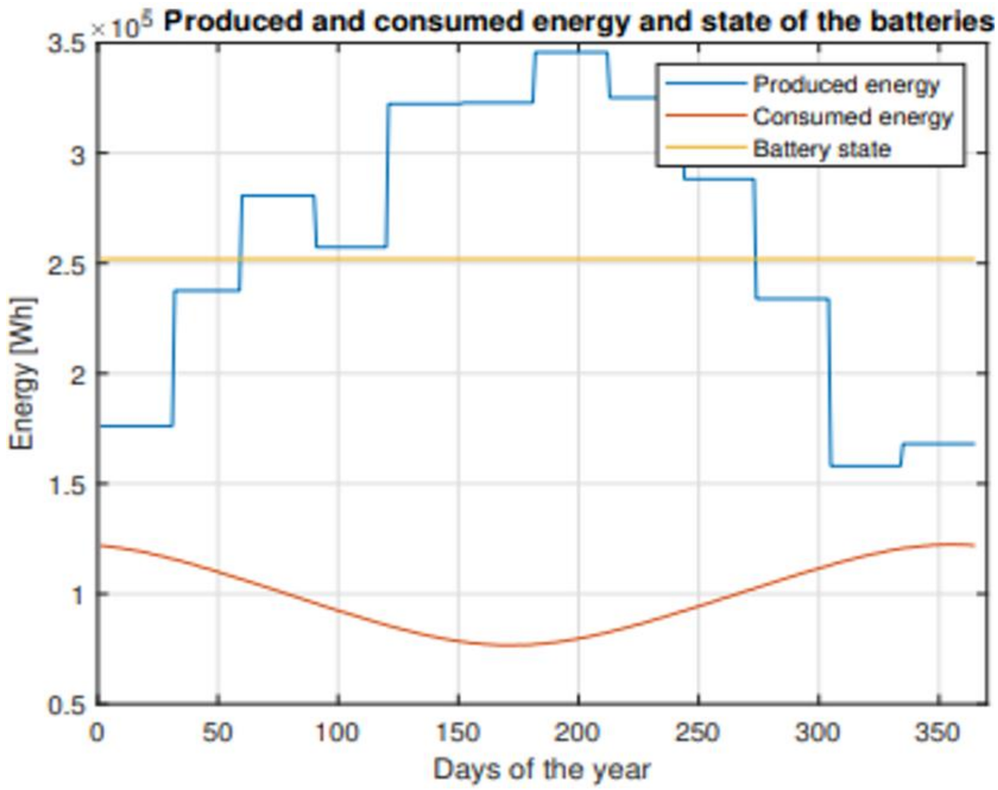

Figure 11.
State of batteries evolution.

5.2.4. Total Costs

By negotiation with the entities that own the buildings, a rent will be agreed for the use of the roofs and a space to install the inverters. For now, a figure of €2,000 per month will be considered.

One also has to take into account the cost of the structures on which the panels are installed on the roofs. For these, after comparing solutions on the market, a total of €2,000 will be considered.

The Table 2 shows that this solution requires an initial investment of more than 320000€.

Table 2.
Costs solution A.

Component	Cost
LEDs	9757.05€
Panels	20076.48€
Batteries	172950.00€
Inverters-pv	4512.00€
Inverters-bat	15196.00€
Structures	2000.00€
Rent	96000.00€
Total	320491.53€

5.2.5. Licensing

To get such a project approved, the following contacts are necessary to perform to seek approval:

• DGEG (Directorate-General for Energy and Geology) - Submit the application for the creation of a Production Unit for Self-Consumption. Obtain an operating certificate;

• Lisbon City Council - Obtain a license to install and use;

• E-Redes - Request an opinion and inform of the construction of the project, checking the availability of the network;

• ANAC (Autoridade Nacional de Aviação Civil – National Civil Aviation Agency) - Request an opinion because the installation may be in an area that affects air traffic;

5.3. Solution B

As already explained, in this solution the panels are installed in the Alameda Garden. The structures where they will be installed will be oriented to the south and at an inclination of 35º. The sizing of the photovoltaic array is identical to that of the previous solution, so it is necessary to distribute 96 panels over the available space.

The 96 panels will be divided into 4 sets, each with 2 rows of 12 panels in series.

5.3.1. Sizing of Inverters and Batteries

Due to the similarity between the two cases, the sizing of the inverters and batteries will also be identical to that of solution A.

The batteries and their inverters, since in this case it is no longer possible to keep them in the buildings, must have a place where they can be protected. A "technical house" will be built next to the garden so that the equipment can be stored.

5.3.2. Total Costs

The total costs for the implementation of this solution are presented in Table 3. Note that Table 3 does not include the construction costs of the structures to be installed in the middle of the garden to place the panels, nor the house to store the batteries and inverters. This is because the characteristics of these structures will have to be discussed with the city council and the architects.

Table 3.
Costs solution B.

Component	Cost
LEDs	9757.05€
Panels	20076.48€
Batteries	172950.00€
Inverters-pv	4512.00€
Inverters-bat	15196.00€
Total	222491.53€

5.4. Solution C

For this alternative, 3 different types of insulated systems will have to be sized, one for each type of pole.

• Type 1 - Pole with 50 W lamp;

• Type 2 - Pole with 4 x 50 W lamps;

• Type 3 - Pole with 30 W lamp; As already mentioned, the panels will be installed on top of the lampposts.

5.4.1. Type 1 Post

Similar to what has already been studied, the energy consumed over the year for a 50 W light bulb is obtained.

For this case, the critical day energy is 727.5 Wh. Following the same principles used for previous solutions, the "Longi Solar LR6-60PB-300M" panel [19] is selected, with a unit cost of 112.0€.

Assuming a 2-day autonomy, the battery bank must be able to store 1901.88 Wh, according to 7. In this case, the amount of energy needed to be stored is lower, so it is not justified to use the batteries selected for the previous cases. The battery model chosen is GC LiFePo4 battery 2560Wh [20] which can store up to 2560Wh, so 1 battery of this model will be installed in each pole of this type. It costs 982.77 euros per unit.

5.4.2. Type 2 Post

In this case, the energy required is higher, which is why it is chosen to use 2 panels of the "Phono Solar 550W Twin Plus monocrystalline" model. Again, according to 7, the battery bank must store 7607.76 Wh. It is determined a total of 3 Green Cell batteries on each pole.

5.4.3. Type 3 Post

For this case, with lower power loads, the model selected is the "VICTRON BLUESOLAR SOLAR PANEL 140W 12V MONOCRYSTALINE" [21] with a unit cost of 184.84€.

The batteries must store up to 1217.17 Wh. 1 Green Cell battery will be used.

This solution requires a large number of components compared to solutions A and B since each lamp will need its own panel, inverter and battery pack. As concluded earlier, a large number of batteries makes the project unfeasible. Therefore, further study of solution C will be discontinued.

6. Sizing Solution A and B (Average Case)

The problem with sizing the system to meet the critical case is that there is a large excess of energy produced in the summer months. This excess energy, since it is not profitable to sell, will just be sent to the grid and can be considered waste.

With this constraint in mind, it may be more advantageous to reduce the amount of energy to be produced and stored, in order to reduce the investment in components.

Instead of the critical case studied above, it is proposed to consider only an average case (in which an attempt will be made to ensure that the system is independent for nights lasting the average length of the year). In this way, during the summer months, there will be enough energy in the batteries to power the lamps at night, while in the winter months, the batteries will be used until they run out, and the rest will be purchased from the grid.

The sizing process carried out for solutions A and B are repeated. Referring to the Table 1, the average nighttime hours throughout the year in Lisbon ($Hs_{average}$) are 11.78h, considering also 9 and 10.

$$E_{average} = P \times H_{s_{average}} = 8410 \times 11.78 = 99069.8Wh \quad (9)$$

$$E_{generator} = \frac{E_{average}}{\eta_{system}} = \frac{99069.8}{0.90} = 110077.56Wh \quad (10)$$

In 11, the hours of sunshine on the shortest day of the year is also taken into account. It is decided to purchase 72 panels since this number of panels can be distributed over just 3 roofs and 3 "Sunny Boy 4.0" inverters, each with 24 associated panels (2 parallel panels of 12 in series).

$$n_{panels} = \frac{E_{generator}}{P_{panel} \cdot H_s} = \frac{110077.56}{184.1 \cdot 9.45} \approx 63 \quad (11)$$

The following specifications are validated:

• Maximum input voltage = 600V > 498.6V;
• MPPT range = [140,500] V, 140V < 498.6V < 500V;
• Maximum input current = 15 A (x2) > 13.24 A (x2);
• Maximum input power = 7500 Wp > 5961.6 W;
• Nominal output power = 4000 W > 8410 4 W.

The energy produced and consumed for this case is shown in Figure 12.

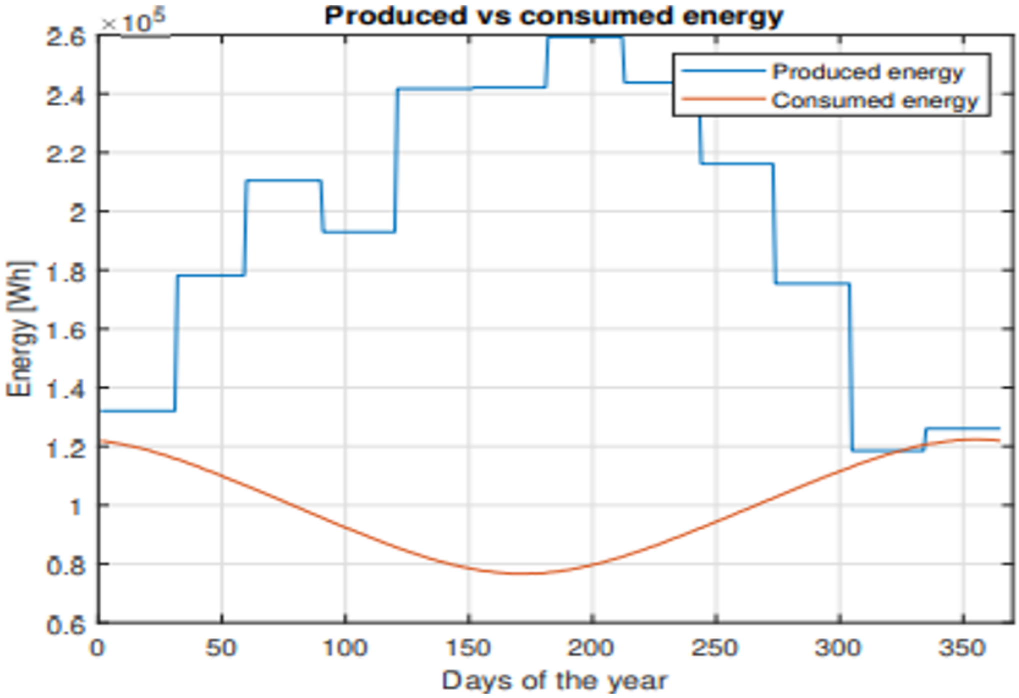

Figure 12.
Energy produced and energy consumed by the system.

Expression 12 give us the energy needed in the battery system. As the selected battery stores up to 6300 Wh, the number needed to store all the energy is obtained by 13.

$$E_{batteries} = \frac{E_{average} \cdot autonomy}{\eta_{battery} \times DOD} = 255334.5Wh \qquad (12)$$

$$n_{batteries} = \frac{E_{batteries}}{E_{bat}} = \frac{255334.5}{6300} = 40.5 \qquad (13)$$

40 batteries will be obtained, resulting in 252000 Wh of stored energy and an investment of 138760€. These will be distributed among 3 "SUNNY TRIPOWER STORAGE 60" inverters (one with 14 batteries in series and the others with 13).

The evolution of the batteries over the course of the year is shown in Figure 13. One can verify that the batteries are no longer always full, and it is even necessary to buy energy on the last days of the year.

Considering Table 4, the initial investment for this solution is 177955.41€, lower than that of the solutions for the critical case.

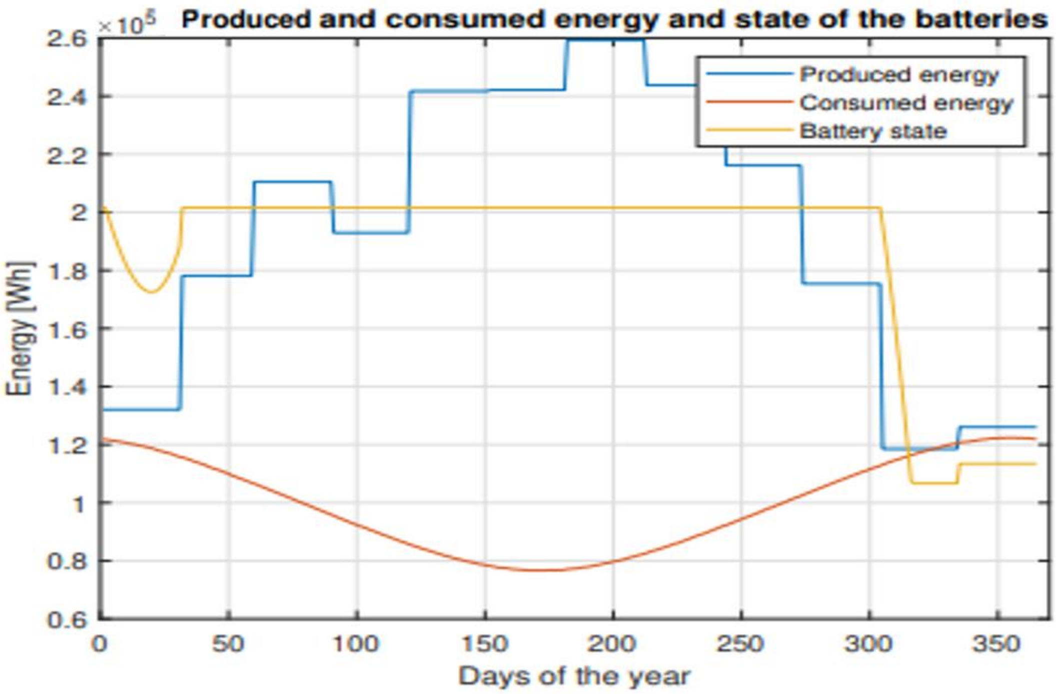

Figure 13.
State of batteries evolution.

Table 4.
Costs average solution.

Component	Cost
LEDs	9757.05€
Panels	15057.36€
Batteries	138360.00€
Inverters-pv	3384.00€
Inverters-bat	11397 .00€
Total	177955.41€

7. Financial Analysis

The financial analysis will be carried out for the next 20 years, as this is the lifetime of the batteries. After this time, various components of the system will have to be replaced, since the panels themselves will have degraded considerably by then.

The cost of buying electricity will be 0.15€/kWh, according to the prices charged by Energias de Portugal (EDP) in Portugal in 2023.

Periodic maintenance of the various components of the photovoltaic system will also be taken into account. This is essential to safeguard the performance and durability of the components. A value of 0.5% of the initial project investment can be considered for these maintenance costs [22].

7.1. Solution A (Critical and Average)

As can be seen from Table 5, the project is not viable, since after 20 years, the period in which the replacement of components has to begin, it is still a long way from recovering the investment.

As explained before, the analysis considering the lowest investment must be carried out. The results are shown in Table 6.

In this case, the return point is closer to be reached, but still quite far away. Although the return on investment is lower than in the critical case, since the initial investment is lower, this solution is seen as preferable.

The 2 options are, however, seen as extremely nonviable, since although they comply with the technical specificities of the project, they are quite far from bringing financial benefits.

The Net Present Value (NPV) of both solutions is quite negative. There is also no Internal Rate of Return (IRR) that would make the NPV positive.

In addition, it is also studied what would happen if it were actually possible to sell surplus energy to the grid. A value of 0.11€/kWh is considered, which is lower than the value of buying from the grid. The results for solution A (critical case) are in Table 7.

In this case, there are already positive cash flows for a few years. However, as can be concluded, the project remains non-viable, thanks to the high investment that needs to be made in the components, mainly the batteries.

This means that one could consider increasing production in order to increase sales revenue, thus making the project viable.

7.2. Solution B

The results for solution B are very similar to those for solution A. Like solution A, the project has a very negative NPV, both for the critical case and the medium case. For this reason, the same conclusion arises: profit is only achieved if the production increases to sell extra energy.

8. Comparison between Solutions

Solutions A and B are very similar in terms of size, production, and financial return. What sets them apart is the location and conditions of implementation. Since the chosen location is in an urban and emblematic area, which is quite built up, both solutions have their challenges. Solution A’s main obstacle is the license to use the roofs of private buildings. For the project to be approved, there will have to be an agreement with all the owners of the buildings in question, something that is not expected to happen without difficulty.

Solution B only requires approval from the Lisbon City Council. However, since the aim is to change the landscape of an emblematic city garden, there may be obstacles to implementing the project.

Solution C is the easiest of all to approve. It only depends on the approval of the city council and does not have the landscape problems of solution B. However, as already mentioned, it requires a much higher investment than the others, which makes it unfeasible.

With all these factors in mind, solution B is considered to be the most favorable. It does not depend on private entities and condominium owners, so it will be easier to approve than A. Through talks with the city council and input from architects, it should be possible to reach an agreement to implement the project without damaging the landscape.

9. Conclusion

This study has led to the conclusion that, with the current technology and energy sales policy in Portugal, it is not financially viable to develop an independent, self-sustaining photovoltaic energy system for street lighting. This study, as mentioned earlier, presents the major problem that the hours of production are entirely disconnected from the hours of consumption, so it is not possible to use the energy produced directly. The possibility of storing energy or selling it is therefore considered. Currently, selling energy to the grid is extremely complicated, for the reasons explained during the study. The only option left is to store the energy in batteries, which are very expensive components. After a financial analysis, it is concluded that there could be no return on the high investment required for the project. The fact that a project like this is not viable is attributed to the high barrier to selling energy to the grid in Portugal today. With the great effort currently being made to invest in renewable energies and make the planet greener, it does not make sense that there is not this incentive for private companies to actually take this step. However, the electrical grid has to be stable, and for that reason, grid companies are limiting decentralized energy production. The bottom line is that this type of project can never be carried out for financial purposes. Environmental and social impacts must also be considered. On top of that, the main promoters of projects like this must be governments or city councils. Additionally, energy communities must be easier to project in the public domain, i.e., public services managed by the same body can exchange energy and benefit from the same renewable power source.

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Table 5.
Financial analysis for critical case solution A.

Year	Panel degradation (%)	Produced energy (Wh)	Cost of energy saved (€)	Cost of energy bought (€)	Maintenance (€)	Cash flow (€)	NPV (€)
0	-	-	-	-	-	-320492	-320492
1	0	94800000.00	5434.50	0	10636.72	-5202.22	-325376
2	0.80	94041600.00	5434.50	0	10636.72	-5202.22	-329963
3	1.60	93289267.20	5434.50	0	10636.72	-5202.22	-334269
4	2.40	92542953.06	5434.50	0	10636.72	-5202.22	-338313
5	3.20	91802609.44	5434.50	0	10636.72	-5202.22	-342110
6	4.00	91068188.56	5434.50	0	10636.72	-5202.22	-345676
7	4.80	90339643.05	5434.50	0	10636.72	-5202.22	-349023
8	5.60	89616925.91	5434.50	0	10636.72	-5202.22	-352167
9	6.40	88899990.50	5434.50	0	10636.72	-5202.22	-355118
10	7.20	88188790.58	5434.50	0	10636.72	-5202.22	-357889
11	8.00	87483280.25	5434.50	0	10636.72	-5202.22	-360492
12	8.80	86783414.01	5434.50	0	10636.72	-5202.22	-362935
13	9.60	86089146.70	5434.50	0	10636.72	-5202.22	-365229
14	10.40	85400433.53	5434.50	0	10636.72	-5202.22	-367384
15	11.20	84717230.06	5434.50	0	10636.72	-5202.22	-369406
16	12.00	84039492.22	5434.50	0	10636.72	-5202.22	-371306
17	12.80	83367176.28	5434.50	0	10636.72	-5202.22	-373089
18	13.60	82700238.87	5434.50	0	10636.72	-5202.22	-374764
19	14.40	82038636.96	5434.50	0	10636.72	-5202.22	-376336
20	15.20	81382327.86	5434.50	0	10636.72	-5202.22	-377812

Table 6.
Financial analysis for average case of solution A (Lowest investment).

Year	Panel degradation (%)	Produced enenergy (Wh)	Cost of energy saved (€)	Cost of energy bought (€)	Maintenance (€)	Cash flow (€)	NPV (€)
0	-	-	-	-	-	-252355	-252355
1	0	71100000.00	5361.50	72.99	8429.92	-3141.41	-255305
2	0.80	70531200.00	5353.50	81.05	8429.92	-3157.47	-258089
3	1.60	69966950.40	5345.40	89.11	8429.92	-3173.63	-260716
4	2.40	69407214.80	5335.80	98.75	8429.92	-3192.87	-263198
5	3.20	68851957.08	5323.60	110.91	8429.92	-3217.23	-265546
6	4.00	68301141.42	5311.40	123.10	8429.92	-3241.62	-267768
7	4.80	67754732.29	5299.20	135.30	8429.92	-3266.02	-269870
8	5.60	67212694.43	5287.00	147.50	8429.92	-3290.42	-271858
9	6.40	66674992.88	5274.80	159.70	8429.92	-3314.82	-273788
10	7.20	66141592.93	5262.60	171.89	8429.92	-3339.21	-275517
11	8.00	65612460.19	5250.40	184.08	8429.92	-3363.60	-277200
12	8.80	65087560.51	5238.20	196.28	8429.92	-3388.00	-278719
13	9.60	64566860.02	5226.00	208.48	8429.92	-3412.40	-280296
14	10.40	64050325.14	5213.80	220.67	8429.92	-3436.79	-281719
15	11.20	63537922.54	5201.60	232.87	8429.92	-3461.19	-283065
16	12.00	63029619.16	5189.40	245.06	8429.92	-3485.58	-284338
17	12.80	62525382.21	5177.20	257.26	8429.92	-3509.98	-285541
18	13.60	62025179.15	5165.00	269.45	8429.92	-3534.37	-286678
19	14.40	61528977.72	5152.90	281.65	8429.92	-3558.67	-287754
20	15.20	61036745.90	5140.70	293.85	8429.92	-3583.07	-288771

Table 7.
Financial analysis for average case of solution A (Critical case).

Year	Panel degradation (%)	Produced enenergy (Wh)	Cost of energy saved (€)	Cost of energy sold (€)	Cost of energy bought (€)	Maintenance (€)	Cash flow (€)	NPV (€)
0	-	-	-	-	-		-320492	-320492
1	0	94800000.00	5434.50	5413.60	0	10636.72	211.38	-320293.05
2	0.80	94041600.00	5434.50	5370.29	0	10636.72	168.07	-320144.88
3	1.60	93289267.20	5434.50	5327.33	0	10636.72	125.10	-320041.31
4	2.40	92542953.06	5434.50	5284.71	0	10636.72	82.49	-319977.19
5	3.20	91802609.44	5434.50	5242.43	0	10636.72	40.21	-319947.84
6	4.00	91068188.56	5434.50	5200.49	0	10636.72	-1.73	-319949.03
7	4.80	90339643.05	5434.50	5158.89	0	10636.72	-43.33	-319976.92
8	5.60	89616925.91	5434.50	5117.62	0	10636.72	-84.61	-320028.04
9	6.40	88899990.50	5434.50	5076.68	0	10636.72	-125.55	-320099.27
10	7.20	88188790.58	5434.50	5036.06	0	10636.72	-166.16	-320187.78
11	8.00	87483280.25	5434.50	4995.78	0	10636.72	-206.45	-320291.05
12	8.80	86783414.01	5434.50	4955.81	0	10636.72	-246.42	-320406.79
13	9.60	86089146.70	5434.50	4916.16	0	10636.72	-286.06	-320532.95
14	10.40	85400433.53	5434.50	4876.83	0	10636.72	-325.39	-320667.69
15	11.20	84717230.06	5434.50	4837.82	0	10636.72	-364.41	-320809.38
16	12.00	84039492.22	5434.50	4799.12	0	10636.72	-403.11	-320956.56
17	12.80	83367176.28	5434.50	4760.72	0	10636.72	-441.50	-321107.91
18	13.60	82700238.87	5434.50	4722.64	0	10636.72	-479.59	-321262.28
19	14.40	82038636.96	5434.50	4684.86	0	10636.72	-517.37	-321418.65
20	15.20	81382327.86	5434.50	4647.38	0	10636.72	-554.85	-321576.12