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Sistemas de Energia - Solar Electric

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Introduction

Nowadays, renewable energy is seen as the main alternative to fossil fuels. The energy production technologies by solar radiation have been growing over the past years, its use has become more profitable and seen as a good choice for the future of our planet. During the production process of solar photovoltaic there is release of polluting gases through the extraction and mining of resources such as silicon (Si), in the electricity production phase there is no pollution of any kind, and it is only in the dismantling phase that pollution originating in this type of technology occurs again. Despite having environmental cost, the energy photovoltaic when compared with the energies from the burning of fossil fuels, does not have as significant environmental impact as those mentioned before, making this kind of technology a good investment in environmental terms. Huge amount of electricity is needed to meet the needs of the world's population making it still necessary to resort to the use of fossil fuel burning since renewables are not yet capable to produce all the global energy needed.

This work has the goal of idealizing two projects on an island that can respond to the energy needs of the population. The first project consists of the production of energy through the installation of photovoltaic panels of the roofs of the dwellings and the creation of photovoltaic power plant, the second project consists in the creation of a power plant through solar concentrating technologies.

Technologies

Solar Photovoltaic:

The photovoltaic technology is based on the conversion of solar radiation into electricity due to the absorption of photons by the semiconductor material of the solar cell. When the semiconductor material absorbs enough sunlight, electrons are dislodged from the material's atoms. The migration of electrons towards the front surface of the cell creates an imbalance of electrical charge between the cell's surfaces. This imbalance creates a voltage potential like the negative and positive terminals of a battery.

Concentrating Solar-thermal Power (CSP):

The Concentrating Solar-thermal Power (CSP) technologies uses mirrors in order to reflect and concentrate sunlight onto receivers that collect and convert solar energy into thermal energy. The thermal energy is then used to heat a fluid (steam) in order to rotate a turbine, producing electricity. Thermal energy can also be inexpensively stored which enables the power plant to adjust its energy generation according to the energy demand as well as being able to produce electricity when there is no sunlight.

Despite the positive impacts, these technologies face some environmental issues such as land usage which is a big problem especially for the CSP that requires much more land than the PV plant, the latter can be combined with agriculture for a more efficient way of using land, this is also known as *Agrophotovoltaics*. Regarding carbon footprint, the operation phase does not contribute to carbon dioxide production, however the materials used for the construction of such panels go through various forms of processing such as extracting and manufacturing, and these, as we know, cause negative impacts in the atmosphere.

The table below shows statistics regarding the population and housing of the island.

Population	Population/Area	Population/Housing	Total Area (km^2)	Roof Area (m^2)
50000	100	2,5	500	70

Table 1 - Initial given values

Beyond the values shown above, the global radiation of each hour during a whole year as well as the temperature, are known.

Month	Day	Hour	Temperature (ºC)	Global radiation (W/m^2)

1	1	12	12,7	29,98
1	1	13	12,9	30,37
⋮	⋮	⋮	⋮	⋮
12	31	23	13,1	0

Table 2 - Values for temperature and radiation

It is worth mentioning that the values of radiation are null during the night, and for the first day of the year only the data starting from the 12th hour is known.

For the concentrated solar power plant, the ratios regarding the direct and diffuse radiation are not established. Therefore, to obtain these values we use the *Photovoltaic Geographical Information system* (PVGIS) with Lisbon as the location. With this method the monthly ratios are no longer unknown:

Lisbon 2016	Diffuse/Global	Direct/Global
January	0,48	0,52
February	0,46	0,54
March	0,42	0,58
April	0,35	0,65
May	0,42	0,58
June	0,36	0,64
July	0,32	0,68
August	0,32	0,68
September	0,35	0,65
October	0,42	0,58
November	0,48	0,52
December	0,33	0,67

Table 3 - Monthly ratios for diffuse and direct radiation

Approach and Methodology

As for this sector the structure and procedures as well as the logic behind the calculations and assumptions will be discussed. The results in this project were made considering one week of each season, in order to show the annual variation and the dissimilarities between them. The table below shows the weeks chosen per each season as well as the months:

Season	Week	Month
Winter	8th - 14th	March
Spring	1st - 7th	April
Summer	8th - 14th	August
Autumn	8th - 14th	November

Table 4 - Weeks taken in considerations

It is important to note that, in order to facilitate the calculations, the values of global radiation are assumed to be constant during each hour.

Although the given data, some important values were still missing. Regarding the solar panels the following assumptions were made:

Power (W)	Area (m^2)	efficiency (%)	Cost (€)	Lifetime (years)
370	1,7272	0,214	344	25

Cost/Area (€/m²)			
Housing		**Power plant**	
Panel	Instalation	Panel	Instalation
199,3	133	191	48
Total (€/m²)			
332,3		239	

Tabela 7 - Solar Panel characteristics

For the cost distribution, in the housing sector, the total value per square meter was split 40% for the installation and 60% for the panel, as for the power plant these values changed to 20% and 80% respectively. The main reasoning behind this assumption is that generally, the labor for a photovoltaic implementation tends to cost more when done in several roofs than in one photovoltaic power plant.

Unfortunately, concentrated solar power plants are not that common compared to normal photovoltaic applications, hence the data made available is not extensive which brings a certain level of ambiguity to this topic. Although, we were able to establish some important characteristics for this power plant, enabling to proceed with further calculations. The latest data regarding the costs of such projects are related to 2019.

CSP Plant			
Power Installed (MW)	**Efficiency (%)**	**Total area (m²)**	**Cost per power installed (M€/MW)**
5	15	1 902 000	23,815

Table 6 - CSP Project characteristics regarding data from 2019

In order to study the potential of the solar photovoltaics and concentrating solar-thermal it was necessary to analyze the annual radiation data that was given. Primarily the daily average radiation was calculated for each month of the year (1), followed by the monthly average (2).

$$Daily\ average = \frac{\sum_{h=9}^{h=17} radiation}{9}\ [\text{kWh}] \quad (1)$$

$$Monthly\ average = \frac{\sum daily\ average}{n^{o}\ of\ days\ of\ that\ month}\ [\text{kWh}] \quad (2)$$

In order to obtain the island area, it was necessary to utilize the number of population and the respective ratio of population per square meter, according to equation (3).

$$Island\ area = \frac{People}{People/area} \times 10^{6}\ [\text{m}^2] \quad (3)$$

The number of houses built in the island was calculated based on the number of inhabitants and the ratio of people per house (4).

$$n^{o}\ of\ houses = \frac{People}{People/House} \quad (4)$$

From the number of houses calculated and the roof area available to install PV modules, it was possible to calculate the total roof area covered by photovoltaic modules (5)

$$Total\ roof\ area\ covered\ by\ PVs = n^{o}\ of\ houses \times Roof\ area\ covered\ by\ PV\ [\text{m}^2] \quad (5)$$

After that, the number of PV modules per roof was determined according to equation (6).

$$n^{o}\ of\ PVs\ by\ roof = \frac{Roof\ area\ covered\ by\ PVs}{PV\ area} \quad (6)$$

Knowing the number of PV modules installed in a roof as well as the unit cost of the module, it was possible to calculate de cost of the modules per house (7).

$$Cost\ by\ house = Cost\ of\ 1\ PV \times n^{o}\ of\ PVs\ by\ roof\ [€] \quad (7)$$

To calculate the electricity produced by the modules in a week of Summer, Winter and Spring, we started by calculate the daily radiation of a week from each season (8).

$$Average\ daily\ radiation = \frac{\sum daily\ average\ of\ the\ respective\ months\ of\ the\ season}{3}\ [kWh/m^2] \quad (8)$$

In order to perform a more correct analysis of the weekly production we decided to calculate the daily average radiation for each week of the year and then choose the value which was closer to the one calculated using equation 8.

The weekly electricity production for a week of Summer, Winter and Spring was calculated according to the equation (9).

$$Total\ weekly\ electricity\ production = \\ = daily\ radiation \times efficiency(\%) \times [1 - losses(\%)] \times nº\ off\ houses \times Roof\ area\ covered\ by\ PVs \times 7\ days\ [\text{kWh}] \quad (9)$$

The electricity produced per capita was calculated based on the total weekly electricity production and the number of inhabitants of the island, according to equation (10).

$$Electricity\ produced\ per\ capita = \frac{Total\ weekly\ electricity\ production}{People}\ [kWh/person] \quad (10)$$

The energy density is determined based on the values of the total electricity production and the area of the island according to equation (11).

$$Energy\ density = \frac{Total\ weekly\ electricity\ production}{island\ area}\ [kWh/m^2] \quad (11)$$

The annual global radiation was calculated by the sum of the daily radiation of the year (12).

$$Annual\ global\ radiation = \sum houry\ radiation\ \times 10^{-3}\ [kWh/m^2] \quad (12)$$

In order to calculate the annual energy produced by the PV mounted on the roofs per square meter, we used the annual global radiation, PV module efficiency and the losses regarding the inverter and the modules configuration, as presented in equation (13).

$$Energy\ produced\ by\ PVs\ on\ roofs = \\ = Anual\ global\ radiation \times efficiency\ (\%) \times [1 - losses(\%)]\ [kWh/m^2] \quad (13)$$

The total energy produced by PV modules was calculated based on the energy produced by a square meter of PV module and the total roof area covered by PV modules (14)

$$Total\ energy = energy\ produced\ by\ PVs\ on\ roofs \times roof\ area\ covered\ by\ PVs \times 10^{-3}\ [MWh] \quad (14)$$

The initial investment of PV modules on roofs was calculated based on the cost of the PV module and the cost of installation (15).

$$\text{initial investment} = (Cost\ by\ house \times nº\ of\ houses) + \frac{0.4 \times Cost\ by\ house \times nº\ of\ houses}{0.6}\ [€] \quad (15)$$

To calculate the number of photovoltaic modules required by the PV power plant, it was necessary to use the power produced by the plant and the power of a PV module (16).

$$nº\ of\ PVs\ in\ the\ plant = \frac{Power\ produced\ by\ the\ plant}{PV\ power \times 10^{-6}} \quad (16)$$

In order to determine the area of the power plant, it was utilized the number of PV modules of the power plant and the area occupied by the module itself (17).

$$Plant\ area = nº\ of\ PVs\ in\ the\ plant \times PV\ area\ [m^2] \quad (17)$$

To know the initial investment of the power plant, we had to consider the costs of installation as well as the cost of the PV module (18).

$$Initial\ ivestment = (nº\ of\ PVs\ in\ the\ plant \times PV\ cost) + \frac{0.2 \times nº\ of\ PVs\ in\ the\ plant \times PV\ cost}{0.8}\ [€] \quad (18)$$

For the final calculation, the energy cost for each energy systems were estimated according to the following equation (19) and (20). The monetary value regarding the operation and maintenance costs (d_{om}) was assumed to be 0,5% of the initial investment (I_T). The capital recovery factor was calculated with n, lifetime of the PV (25 years), and the discount rate (a).

$$C = \frac{I_T \times (i + d_{om})}{E_a} \ [€/kWh] \tag{19}$$

$$i = \frac{a\,(1+a)^n}{(1+a)^n - 1} \tag{20}$$

Discussion

Through the previous formulations we calculate the value of the total energy, power produced, total cost and the energy cost for the photovoltaic panels covering the roof of the island houses as we can see from the following table.

Solar photovoltaic panels covering the roofs

Roof área covered by PVs (km^2)	Energy produced (MWh/m^2)	Total energy (MWh)	Power produced (MW)	Installation cost (M€)	Energy cost (€/kWh)
1,4	0,265	372259	127	458,66	0,09

Table 7 – Calculated parameter of PV installation in roofs

We also calculated the plant area needed to produce the 5MW of power and the respective costs.

Municipal solar photovoltaic plant

Power installation (MW)	nº of panels in the plant	Plant area (km^2)	Installation cost (M€)	Energy cost (€/kWh)
5	13513	0,023	5,81	0,07

Table 8 – Calculated parameter of PV power plant

As we were expecting the power produced by the photovoltaic panels on the roofs is bigger than in the plant since the roof area covered by the PVs is must bigger than the area of the plant. The installation cost of panels on the roofs is more expensive than the installation on the plant, we used the same type of photovoltaic panels for both cases, because in the plant is done only once already in the houses, we must do in each of the house requiring more work. As consequence of the installation cost, the energy cost in the plant is cheaper than in houses.

For concentrating Solar-thermal power plant we have the same power installation as in the photovoltaic plant, but like we said before the concentrating solar-thermal power has a different mechanism compared with solar photovoltaic. As we can see, for the same power installation in this type of production we need to occupy a bigger area compared to solar photovoltaic plant, beyond that the installation cost is higher leading to the energy cost being higher.

Concentrating Solar-thermal power plant

Power installation (MW)	Energy produced (MWh/m^2)	Power produced (MW/km^2)	Plant area (km^2)	Installation cost (€/MW)	Energy cost (€/kWh)
5	0,012	5,02	0,124	23,815	0,12

Table 9 – Calculated parameter of CSP power plant

The figures in the *Attachments* segment show a better representation in terms of energy production of each technology in regard to the week chosen for each season of the year. (Attachments)

Conclusion

Analyzing the electricity generation from solar power solutions, we conclude that the Photovoltaic power plant has the lowest energy cost followed by the PV implementation on roofs while the concentrating solar-thermal power plant has the higher energy cost. It is important to emphasize that the energy cost of CSP might be lower since it was calculated based on estimates of other CSP systems and there were few data available. Regarding energy density both PV power plant and the

PV system on roofs have the biggest energy production per square meter, twice as much when compared with CSP. The energy production per capita has the highest value for the PV system mounted on the roofs, followed by the CSP and at last with the lower energy production per capita the PV power plant.

When comparing a week of energy production from each season, it is possible to observe that it exists seasonality in energy production for all solar-electric systems. The biggest energy production occurs in summer (when there are more hours of sunlight) while it drops a little in spring and hits the lowest energy generation in the winter for all the systems (which corresponds to the fewer hours of sunlight).

Regarding the implementation of photovoltaic energy, the optimal solution would be the installation of PV modules on roofs instead of a power plant since the area designated for the PV power plant could be used for other technologies, it is also important to refer that by having the power source close to the consumer we are able to reduce energy losses.

The cost needed to do the house covered by PVs is very high, many families may not have that money. This project was idealized for an island that as the possibility to have all these resources, in real life it would most likely be necessary to have government help for some families.

Bibliography

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5. Power Tower System Concentrating Solar-Thermal Power Basics | Department of Energy
6. LG370Q1C-V5 NeON ® R Solar Panel | LG US Solar
7. Environmental Impacts of Solar Power | Union of Concerned Scientists (ucsusa.org)

Attachments

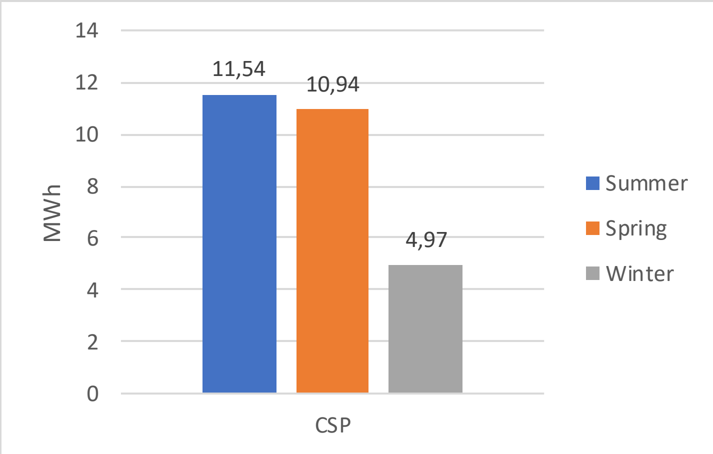

Figure 1 – CSP Energy Production

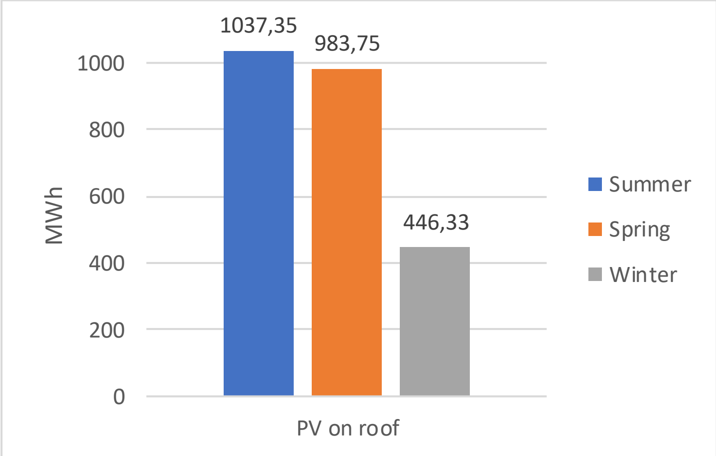

Figure 2 – PV Energy Production

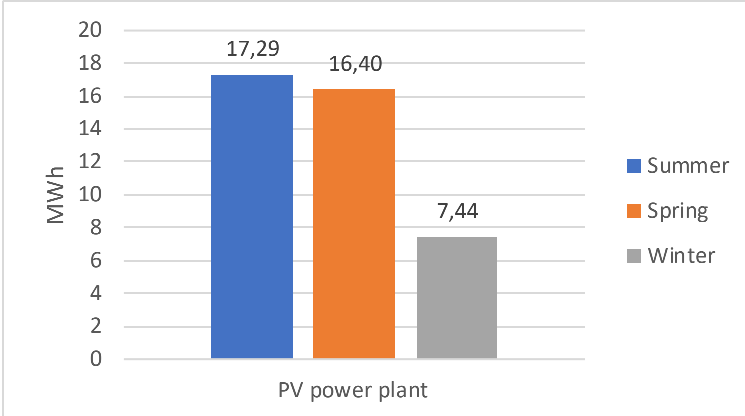

Figure 3 – PV power plant Energy Production

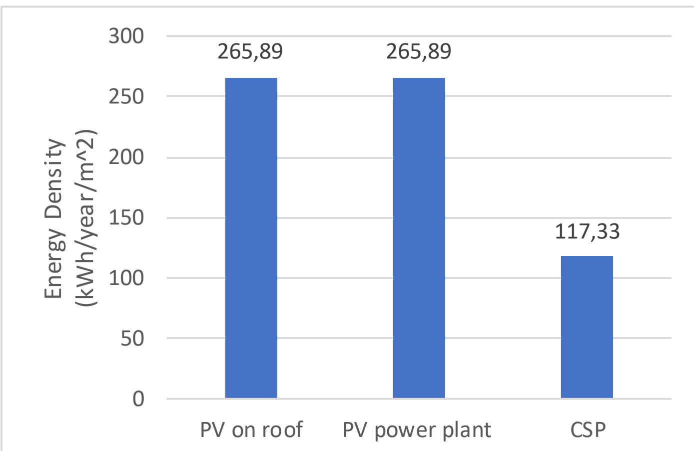

Figure 4 – Energy Density per application

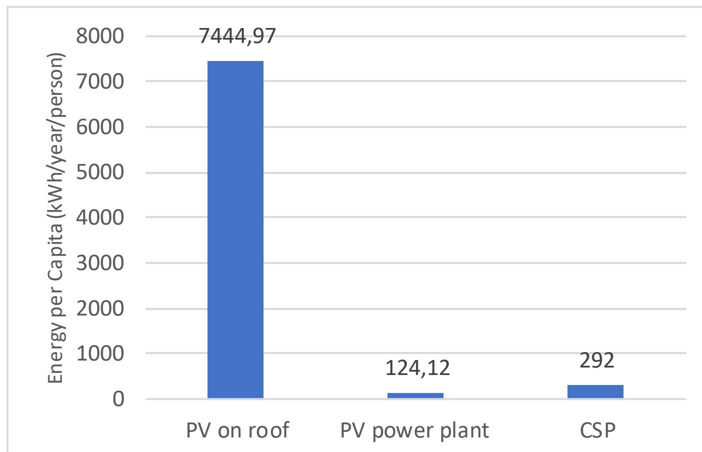

Figure 5 - Energy per capita per application

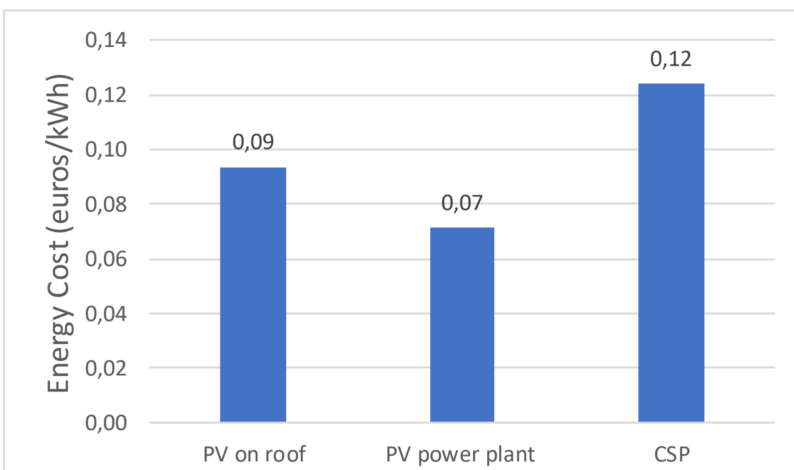

Figure 6 – Energy Cost per application