Autonomous System of Renewable Energy Generation Applied to Agricultural Consumers

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***Abstract*—This dissertation is based on the need to develop an autonomous system of renewable energy generation applied to agricultural consumers. For this purpose, the installation of a photovoltaic solar system is the key solution for the autonomous system studied in this thesis. In this context, several alternatives of photovoltaic solar systems (consisting of solar panels, controller, inverter and, hypothetically, batteries) are studied.**

Firstly, the implementation of an autonomous system, capable of generating all the energy consumed by the exploration unit, is studied. Subsequently, due to the economic impracticability of this solution, the implementation of two types of photovoltaic systems is analysed: a system composed only of photovoltaic panels and another composed of photovoltaic panels and batteries. As a complement to the analysed hypotheses, it is studied the installation of the aforementioned systems with the possibility of selling the surplus to the grid, in order to anticipate the return period of the already simulated solutions.

The results show that, energetically, the best type of system to be implemented consists of the autonomous photovoltaic solar system, a system whose implementation is discarded due to the high return period it presents, resulting in an economically inviable solution. Economically, the photovoltaic solar system without the installation of batteries presents a better performance than the other hypotheses studied. Regarding the sale of surplus to the grid, if it is possible to obtain licensing for this activity, it is always a plus in what concerns the type of system to be implemented within this dissertation.

***Index Terms*—Autonomy, economic analysis, photovoltaic solar system, renewable energy.**

I. INTRODUCTION

THE production of electricity has a significant worldwide environmental impact, in particular due to the energy production through fossil fuels, such as coal and natural gas. The main harm associated with the production of electricity from non-renewable sources is the emission of gases into the atmosphere, which enhance and are responsible for the formation of acid rain, the destruction of ozone layer and the greenhouse effect and consequent global warming of the planet. Another problem related with the use of this type of fuel for electric energy production refers to the possible exhaustion of these resources, since the rate at which the are being used is quite superior to the rate at which they are produced, raising sustainability problems for future generations [1].

The use of the Sun as a source of energy and its use to generate energy has an economic and environmental surplus value, which are reflected in some advantages, such as the fact that the Sun is an inexhaustible source of energy and the non-release of harmful gases in the environment during energy conversion.

The theme of this dissertation comes from this need to replace fossil fuels with renewable energy sources. By implementing an autonomous system for generating energy from renewable sources, it is guaranteed the sustainability of this system in terms of energy, ensuring that there is no release of harmful gases to the environment and that there is an inexhaustible source of energy that allows the operation of it.

In addition to the climatic reasons that encourage the installation of renewable energy systems, there is interest from the owner of the exploration unit under study to analyze the application of photovoltaic panels in agricultures, particularly crops that are exploited in the unit, and optimize the on-site energy generation/storage process by implementing a photovoltaic solar system scaled taking into account the specific consumption needs of the site under study.

II. SOLAR GEOMETRY

To understand how energy is captured from the Sun, it is necessary to predict its location relative to the collector. For this, it is fundamental, for a solar system, to define the main angles that rule the solar orientation. Some of these angles can be observed in the figure 1:

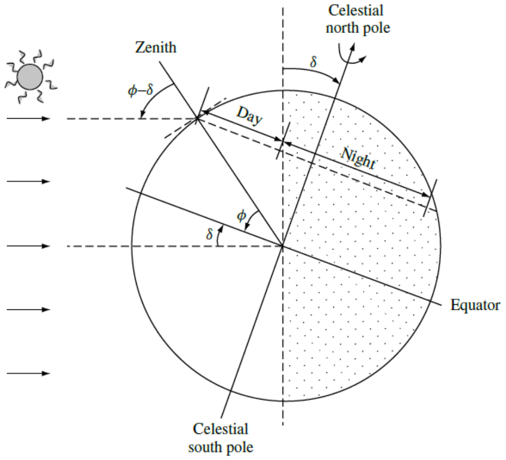


Fig. 1. Relative Earth-Sun position in a day of winter in the Northern Hemisphere (extracted from [2])

In the figure 1 we can see represented the latitude angle, ϕ, and the declination angle, δ, which is created by the inclination of the polar axis and is defined by [3]:

$$\delta = 23.45 \sin\left(360° \cdot \frac{284+N}{365}\right) \tag{1}$$

where N is the day's number of the year. It is also represented in the figure 1 the zenith angle, θ_z and is defined as the angle between the horizontal plane containing the observer and the Sun line.

In the figure 2 are represented the angles related to the receiver position.

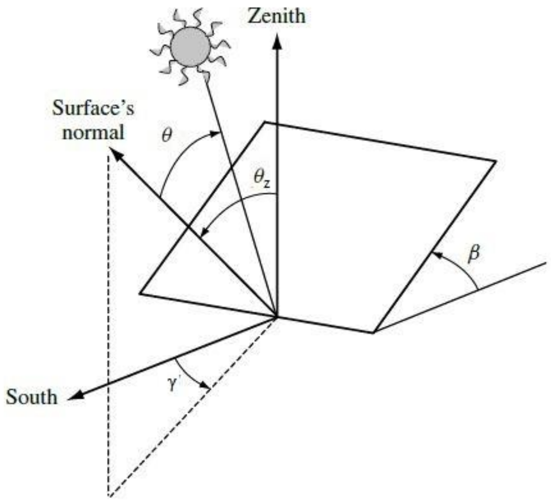


Fig. 2. Receiver position and sun's rays incidence angle (extracted from [2]).

As can be seen in figure 2, β refers to the inclination of a plane placed at Earth's surface and γ refers to the surface's azimuth angle, which represents the deviation between the projection of the Sun in the horizontal plane and the surface in the longitude of the observer.

From the angles already described, it is possible to determine the hour angle from solar time, ω,

$$\omega = \left(\frac{t_{solar}}{60} - 12\right) \cdot 15° \tag{2}$$

where t_{solar} is the solar time, in hours. The incidence angle, θ, which can be seen in figure 2, represents the angle between the sun's rays and the normal plane of the surface where these rays strike [4].

III. SOLAR ENERGY

Once defined the angles between the Earth and the Sun, it is essential to determine how much radiation hits a sloped plane placed on the Earth's surface. In equation (3) we can see the expression that determines the amount of irradiance that hits the Earth's surface, G [2]:

$$G = G_0\, k_t \tag{3}$$

where k_t is the clearness index and G_0 is the extraterrestrial solar irradiance that hits a flat surface tangent to the atmosphere. Being G the the radiation that hits a flat surface, G_β represents the radiation that reaches a tilted surface and it can be decomposed into three parcels, as shown in the figure 3: the diffuse irradiance, $G_{b\beta}$; the beam irradiance (direct irradiance), $G_{d\beta}$; and the ground-reflected irradiance, also known as albedo, $G_{r\beta}$ [5].

$$G_\beta = G_{b\beta} + G_{d\beta} + G_{r\beta} \tag{4}$$

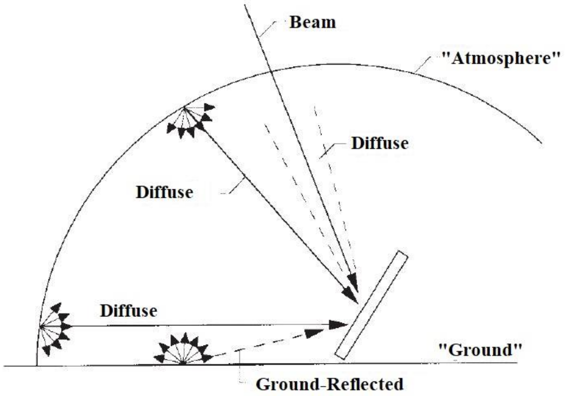


Fig. 3. Beam, diffuse and ground-reflected radiation on a tilted surface.

From (4), one can deduct the radiation a solar panel installed on the Earth's surface receives [3]:

$$G_\beta = (G_b + G_d A_i) \cdot R_b + G_d(1 - A_i)\left(\frac{1+\cos(\beta)}{2}\right) \left[1 + f sen^3\left(\frac{\beta}{2}\right)\right] + G\,\rho_g\left(\frac{1-\cos(\beta)}{2}\right) \tag{5}$$

where A_i is an anisotropic index that determines the atmosphere transmittance relative to the direct irradiance, f represents a modulating factor to account for cloudiness, R_b is the ratio of total radiation on the tilted surface to that on the horizontal surface and ρ_g is the terrestrial albedo [3].

IV. SOLAR PANELS

When analyzing a model of photovoltaic panel, there are certain parameters that must be taken into account, such as the tests that are done in NOCT, which is the acronym for "Nominal Operating Cell Temperature" and these are the conditions that reflect the characteristics of the solar panel more realistically.

These conditions correspond to an irradiance of 800 W/m^2, panel surface temperature of 45 (+/- 3) ºC, wind speed of 1 m/s and ambient temperature of 20 ºC. To estimate the maximum power generated by photovoltaic panels under NOCT conditions, there are certain expressions that need to be considered. The first, represented by equation (6), determines the panel temperature, T_{PV}, based on the panel incident radiation, G_β, and at ambient temperature, T_{amb}.

$$T_{PV} = T_{amb} + \frac{G_\beta}{800}(T_{NOCT} - 20) \tag{6}$$

The other expression (7), determines the power generated by each panel and is given by:

$$P_{PV} = P_{max,NOCT} \cdot \frac{G_\beta}{800}(1 + \alpha(T_{PV} - T_{NOCT})) \qquad (7)$$

where α is the temperature coefficient of the solar panel.

V. CASE STUDY CHARACTERIZATION

As the main objective of this dissertation is to study the implementation of an autonomous system of renewable energy applied to agricultural consumers, it was necessary to find an adequate case study to analyze the implementation of the system in a real exploration unit. For that purpose, a real case-study was given by Francisco Parente, owner of an exploration unit in Cartaxo, Portugal, where five types of agricultural crops are harvested: pears (98500 m^2), blueberries (23000 m^2), nectarines (21000 m^2), plums (7700 m^2) and apricots (18000 m^2).

A. Location and Climate

The farm on which the system's implementation will be studied is located in Cartaxo, Santarém, Portugal being its coordinates 39º08'28,8''N, 8º48'37,6''W.

It is located in the Ribatejo region, where the climate is of the tempered type, moderately rainy and with predominant winds from North/Northwest during Spring and Summer, and from North/East during Autumn and Winter. There, Summer is hot, dry and with very few cloudy days. On the opposite side we have Winter, which is fresh, rainy and with some cloudy days. During the year, the temperature varies from 6ºC to 32ºC and rarely is lower than 1ºC or higher than 40ºC [6]. The annual average air temperature is around 16,5ºC [7].

From the information available at PVGIS (Photovoltaic Geographical Information System) database, the values for the monthly clearness index for that location were obtained, table 1 [8].

TABLE I. MONTHLY AVERAGE CLEARNESS INDEX

Jan	Feb	Mar	Apr	May	Jun
0,49	0,55	0,59	0,58	0,63	0,67
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0,70	0,70	0,66	0,59	0,55	0,50

B. Irrigation system

This farm has an automated drip irrigation system, composed by two main hydraulic pumps, being the first one, from now on referred as Pump 1, responsible for pumping the water from water borehole in the farm to a water storage tank with a capacity of 800 m^3 and the second one responsible for pumping the water from the water storage tank to the crops.

To know the power consumption of each water pump described previously, the hydraulic power, P_H, needs to be determined, being its expression obtained by [9]:

$$P_H = H \cdot Q \cdot g \cdot \rho \qquad (8)$$

where H is the head of the pump, Q is the flow rate, g is the acceleration due to gravity and ρ is the fluid density.

From (8), one can obtain the electric power of a pump, P_e, whose formula is given by [9]:

$$P_e = P_H / \eta \qquad (9)$$

where η is the pump efficiency.

Since each parcel of cultivated land has its own needs in terms of water, the flow rate and, consequently, the power consumption, is different for each of these parcels. In table 2 the power consumption of each pump and parcel can be observed.

TABLE II – FLOW RATE AND ELECTRIC POWER CONSUMPTION FOR EACH PARCEL AND FOR PUMP 1.

Parcel	Q [m^3/h]	P_e [kW]
Blueberries	20,2	7,21
Apricots and Nectarines	17,7	7,16
Plums and Pears (P3)	14,4	6,72
Pears (P2 and P4)	23	7,30
Pump 1	51	20,99

C. Load Profile

Once determined the power consumption of the main pumps installed in the irrigation system of the exploration unit, it is possible to predict the monthly load profile of it, based on the irrigation periods stipulated by the farm owner. Since the simulations will be mainly aimed at the months of April and July, I only will show the irrigation periods and load profile of these months, and they can be observed in figures 4 to 7.

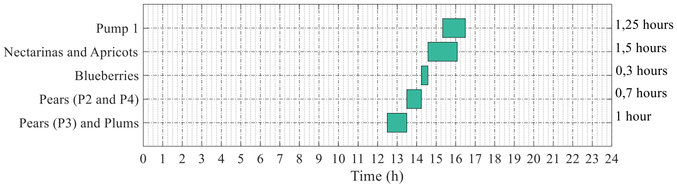


Fig. 4. Irrigation periods, for each crop, on April.

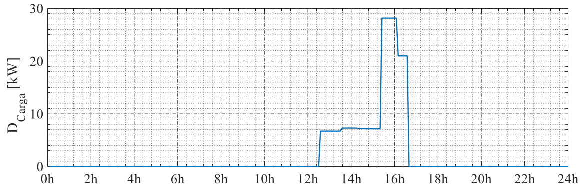


Fig. 5. Load profile of the farm on April.

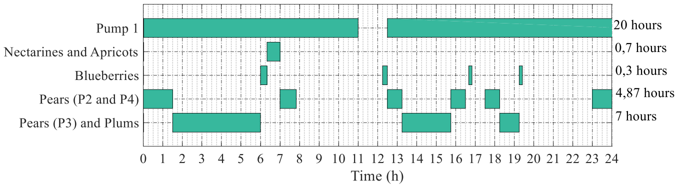


Fig. 6. Irrigation periods, for each crop, on July

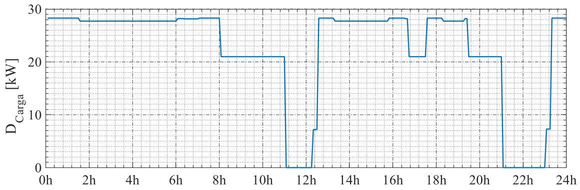


Fig. 7. Load profile of the farm on July

VI. AUTONOMOUS PHOTOVOLTAIC SYSTEM

A. Parameters

The first hypothesis considered is the installation of an autonomous system. For that purpose, a multi-objective algorithm was used, based on the NSGA-II algorithm.

The aim of this simulation is to evaluate the evolution of some decision variables, namely the number of installed batteries, n_{bat}, the number of installed solar panels, n_{PV}, and the inclination and orientation of them, and since it is an analysis in terms of energetic autonomy of the system, where energy saving is more important than saving money, one of the objective functions is the investment made, I, whose expression is given by:

$$I = n_{PV} \cdot C_{PV} + n_{bat} \cdot C_{bat} \tag{10}$$

where C_{PV} and C_{bat} are the costs of solar panels and batteries, respectively.

The other objective function is the autonomy rate, AR, which is defined as the percentage of annual consumed energy, E_{annual}, that is generated by the photovoltaic panels, E_{PV}.

$$AR = E_{PV}/E_{annual} \tag{11}$$

In this simulation, in order to allow the existence of solutions whose total autonomy rate is 100%, meaning all of the energy consumed in the farm is generated by the installed solar panels, the maximum limits for the number of installed photovoltaic panels and batteries were defined as very high values, and they are shown in table 3.

TABLE III. DECISION VARIABLES AND PARAMETERIZED LIMITS IN SIMULATION.

Variable	**N$_{PV}$**	**N$_{bat}$**	**β [º]**	**γ [º]**
Min	1	0	0	-90
Max	350	150	180	90

In addition to the decision variables and objective functions defined, the optimization was programmed to simulate 100 generations of samples with 150 elements per generation. No constraints were set on this simulation.

B. Results

Once the parameters were defined, the optimization was done and the graph of figure 8, representative of the investment, in euros, as a function of the autonomy rate, in %, was obtained. In this figure are represented the 150 samples referring to the last generation.

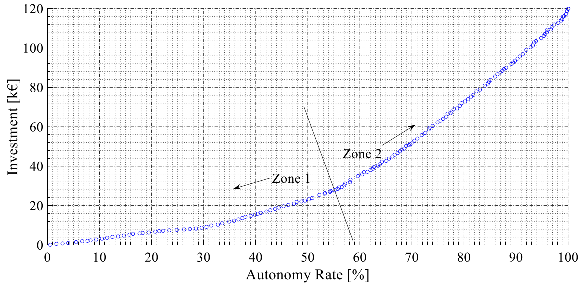


Fig. 8. Last generation of the simulated scenario.

From the scatter plot shown in figure 8, it is possible to draw some conclusions about the characteristics of the system under analysis. At first glance, the existence of two distinct and well-demarcated zones, around the 55% rate of autonomy. Until this transition point, investment grows at a moderate pace as the rate of autonomy increases. After this same point, a significantly higher investment is required to achieve the same increase in the autonomy rate. Naturally, since there are night and dawn watering periods in the months corresponding to peak consumption, the installation of a system composed only of photovoltaic panels is insufficient to guarantee total autonomy of the exploration unit under study. As such, from that transition point already mentioned, the simulation for the autonomy study of the system begins to predict the installation of batteries in a way to allow the increase the autonomy rate. Otherwise, it would not be possible to obtain any totally autonomous result (i.e., 100% autonomy rate).

With the purpose of analyzing the system from the point of view of autonomy, the first sample of the last generation whose autonomy rate is 100% ($n_{PV} = 301$; $n_{bat} = 149$; $\beta = 6{,}74^{\circ}$ and $\gamma = 49{,}37^{\circ}$) is taken into account. Its behavior is evaluated in two distinct months of energy demand by the operating unit, April and July.

On April, by observing the graphs shown in figure 9, it can be concluded that the solution under study is enough to meet the needs of the farm, since at all times the power consumed is less than the power generated by the photovoltaic panels. Naturally, the curve representing the state of charge of the batteries remains immutable with time, once it is never necessary to resort to the energy stored there to meet the needs of the operating unit. Therefore, in moments of less demand in terms of consumption, the number of photovoltaic panels installed is enough to meet the needs to the same.

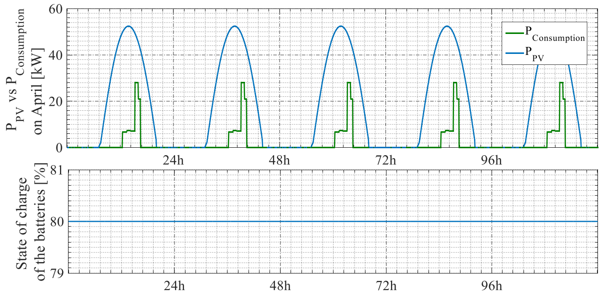


Fig. 9. Load profile versus power generated by solar panels and state of charge of the batteries, for five days, on April.

In quantitative terms, out of a total of 51,58 kWh consumed on a typical day of the month of April, about 51,58 kWh (i.e., all energy consumed) were saved due to the consumption of the same energy from the photovoltaic panels.

The figure 10 shows the results corresponding to the power generated from the installation of the 301 photovoltaic panels, together with the state of charge of the 149 batteries installed for July. It is observed that to supply the night-watering needs, which are characteristic of the peak consumption, the power generated by the photovoltaic panels when it reaches its maximum is much higher than the load curve. This difference allows the batteries to charge up to the maximum, resulting in a state of charge curve that never reaches the minimum stipulated (with the minimum being 20%, the batteries reach 23%). This way, the autonomy of the farm is guaranteed.

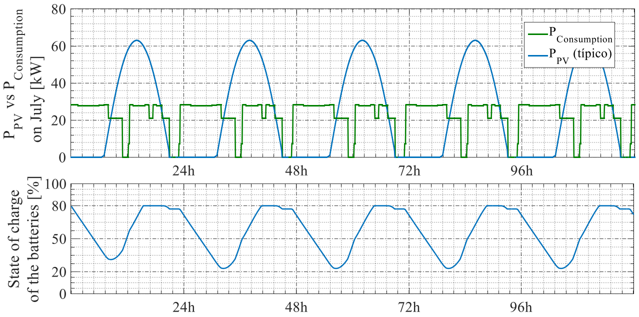


Fig. 10. Load profile versus power generated by solar panels and state of charge of the batteries, for five days, on July.

In quantitative terms, of a total of 532,11 kWh consumed on a typical day of July, all of it is saved using the components installed for this purpose. The energy consumed directly from the photovoltaic panels is 269,25 kWh (about 50,6% of the total power consumed) and the remaining 262,86 kWh (about 49,4% of the total power consumed) comes from the energy stored in the batteries throughout the day.

Once the performance of the system in periods of different requirements in terms of energy consumption was analyzed, the next step is to study the implementation of this system in energy and financial terms, throughout one year. The figure 11 shows the evolution of the annual saved energy, consumed energy and wasted energy.

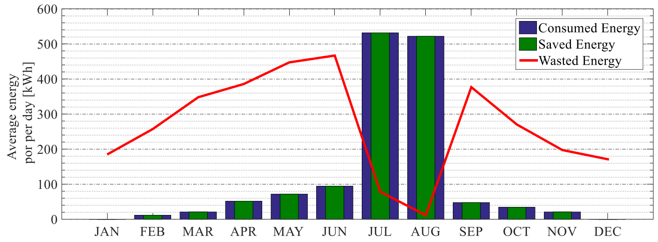


Fig. 11. Annual evolution of the saved energy, consumed energy and wasted energy.

As expected and according to what has been demonstrated in the previous section, all the energy consumed during the year is spared due to photovoltaic panels and batteries installed, because of a 100% autonomy rate.

These results have reached the objectives proposed from the energy point of view, however, from the financial point of view, it is observed that the money saved at the end of a typical year reaches about € 4111 saved, in duality with the required investment of € 119800 to install the system in analysis. These values result in a payback of invested money of about 29,1 years, which is considered not economically viable in the installation of such systems.

VII. PHOTOVOLTAIC SYSTEM WITHOUT BATTERIES

A. *Parameters*

Once the installation of an autonomous photovoltaic system was analyzed, it was concluded that from the financial point of view there are better options to consider when installing such systems. As such, we proceed to study the implementation of different solutions starting by the photovoltaic solar system composed only of photovoltaic panels, without considering the installation of batteries.

From now on, the simulations carried out will be studied from a financial perspective and, for that purpose, the objective functions to be optimized are different: instead of investment and autonomy rate, the new objective functions are the payback period, r, and the money saved annually.

The money saved annually is calculated by means of the energy produced by the photovoltaic panels, which is consumed directly by the operating unit or stored in the batteries for later use, and the excess energy produced that can be sold to the grid as surplus. Its expression is given by:

$$Saved\ Money = E_{pv} \cdot p_{tariff} + E_{surplus} \cdot p_{surplus} \qquad (12)$$

where $E_{surplus}$ is the money sold to the grid as surplus, p_{tariff} is the energy price according to the contracted tariff and $p_{surplus}$ is the energy price at the moment it is sold to the grid as surplus. The payback period expression is given by:

$$r = \frac{I}{Saved\ Money} \qquad (13)$$

In terms of decision variables, this simulation has the same as the one studied in the previous chapter, with exception to the number of batteries installed. In the table 4 are shown the minimum and maximum limits defined for each variable.

TABLE IV. DECISION VARIABLES AND PARAMETERIZED LIMITS IN SIMULATION.

Variable	N_{PV}	β [º]	γ [º]
Min	1	0	-90
Max	200	180	90

In addition to the decision variables and objective functions defined, the optimization was programmed to simulate 100 generations of samples with 150 elements per generation. No constraints were set on this simulation.

B. Results

Once the parameters were defined, the simulation was run and the graph of figure 12, representative of the investment, in euros, as a function of the autonomy rate, in %, was obtained. In this figure are represented the 150 samples referring to the last generation.

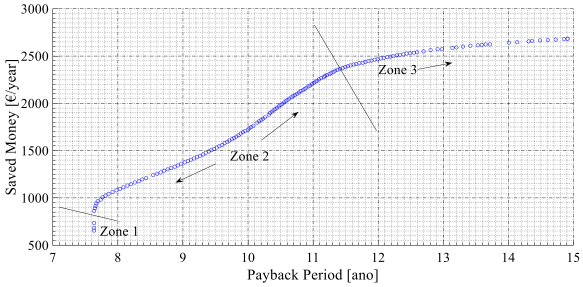
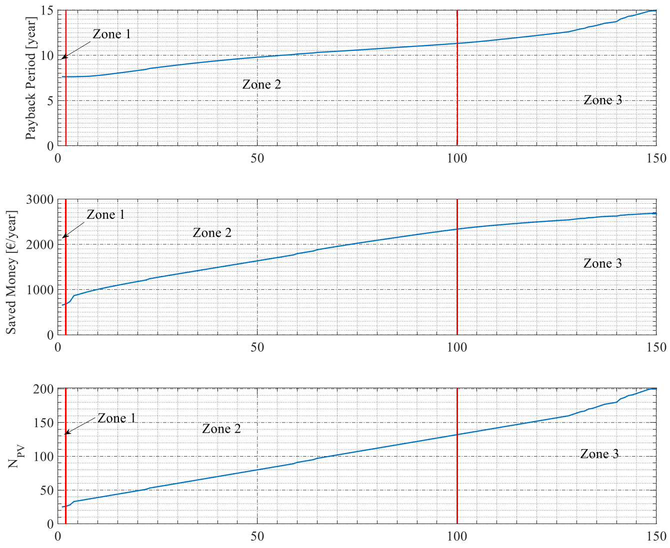
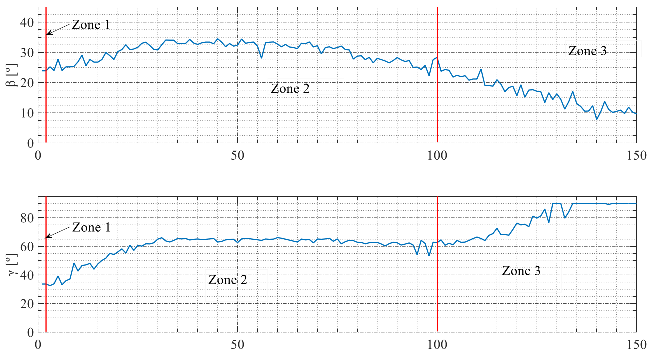


Fig. 12. Last generation of the simulated scenario.

From the dispersion graph shown in figure 12 it is possible to analyze some characteristics of this system composed only of photovoltaic panels. It is noted that from € 2350 saved annually, there is a significant increase in the payback period compared to the money saved annually.

For a better analysis of the evolution of the defined parameters we observe in figures 13 to 17 both the decision variables and the objective functions in ascending order of the payback period.





Figs. 13-17. Objective functions and decision variables of all samples of last generation.

As expected, the number of installed photovoltaic panels is also proportional to the payback period and the money saved annually, because the greater number of panels is installed, the more solar energy is produced and consequently, more money is saved annually. However, despite the constant increase in the number of photovoltaic panels, it is possible to see a stabilization in the money saved annually from the € 2350. The opposite behavior is verified in the payback period, at the point it is around 11,4 years. This goes according to what was written earlier on figure 12.

As for the angular values of inclination and azimuthal orientation, they remain relatively constant at 30º and 60º, respectively. However, in the samples corresponding to Zone 3, a change in azimuth and slope values is observed: from this point, the azimuthal orientation of the panels increases as much as possible (90º), that is, with the panels facing West, where it stabilizes. As for the inclination of the panels, it gradually decreases from the 100th sample (corresponding to the installation of 140 photovoltaic panels) up to 10º, where it stabilizes. In Portugal, the typical solution consists of a slope of the panels of about 30º and are usually oriented towards South, resulting in a 0º azimuth. However, the results obtained for the farm in study differ significantly from the typical values. This phenomenon is due to the typical load curve of the consumer, which is mostly concentrated in the afternoon.

In summary, Zone 1 corresponds to the initial moment from which no important conclusion can be drawn; Zone 2 corresponds to the set of values most suitable for the simulated system and Zone 3 corresponds to the set of samples from which, if the number of photovoltaic panels is increased, the money saved annually grows less, while the payback period increases more significantly.

Considering a set of values from a sample of Zone 2 ($n_{PV} = 80$; $\beta = 32,37^{\circ}$ and $\gamma = 62,59^{\circ}$) is necessary to make the annual analysis of the implementation of this system in terms of energy and finances. Based on observation of the figure 18, it is evident the inefficiency of the installation of the system composed only of photovoltaic panels during the period of greatest consumption. While in most months of the year the saved energy is almost enough to meet the consumption needs of the exploration unit, during the peak of consumption, the energy consumed by the farm raises significantly, accentuating the difference between the saved energy and the energy consumed. This is because at peak consumption months there are night and dawn irrigations, corresponding to times of the day the energy produced by the panels is null, and it is necessary to use energy supplied by the grid during these periods.

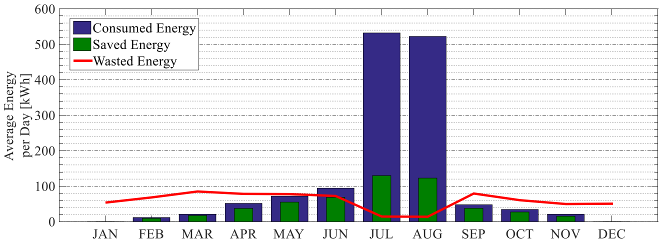


Fig. 14. Annual evolution of the saved energy, consumed energy and wasted energy.

Regarding the energy wasted during the year, we verify that in the months of less consumption there is a great amount of energy that is produced by the photovoltaic panels that is lost. The opposite phenomenon occurs in the periods corresponding to the peak months, where a larger slice of the energy produced is used, thus reducing the values of wasted energy during that period.

Quantifying these amounts of energy, results in a total of 43,42 MWh consumed and only 15,95 MWh saved, corresponding to about 36,7% of the total energy consumed annually.

With this solution, with an investment of € 16000, an annual saving of around € 1635 is achieved, resulting in a payback period of 9,8 years.

VIII. PHOTOVOLTAIC SYSTEM WITH BATTERIES

A. *Parameters*

The type of system to be analyzed in this chapter will be a system composed of photovoltaic panels as a source of energy and batteries as an energy storage system, such as the system analyzed in the chapter VII, with the difference that this time it will be studied from an economic perspective instead of an autonomy point of view. The decision variables under study will be the same as in the referred system, with a difference for the objective functions, which are now the payback period (13) and the money saved annually (12). In the table 5 are shown the minimum and maximum limits defined for each variable.

TABLE V. DECISION VARIABLES AND PARAMETERIZED LIMITS IN SIMULATION.

Variable	**N_{PV}**	**N_{bat}**	**β [º]**	**γ [º]**
Min	1	0	0	-90
Max	200	50	180	90

In addition to the decision variables and objective functions defined, the optimization was programmed to simulate 100 generations of samples with 150 elements per generation. No constraints were set on this simulation.

B. *Results*

In figure 19 is shown the graph that reproduces the objective functions, one in function of the other.

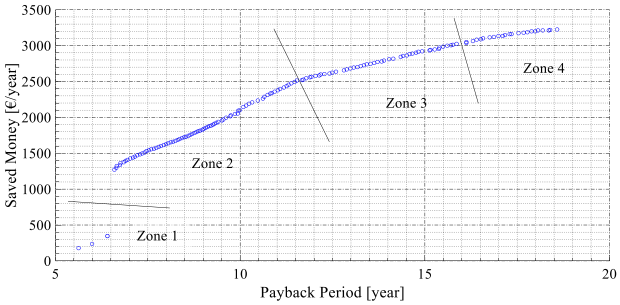
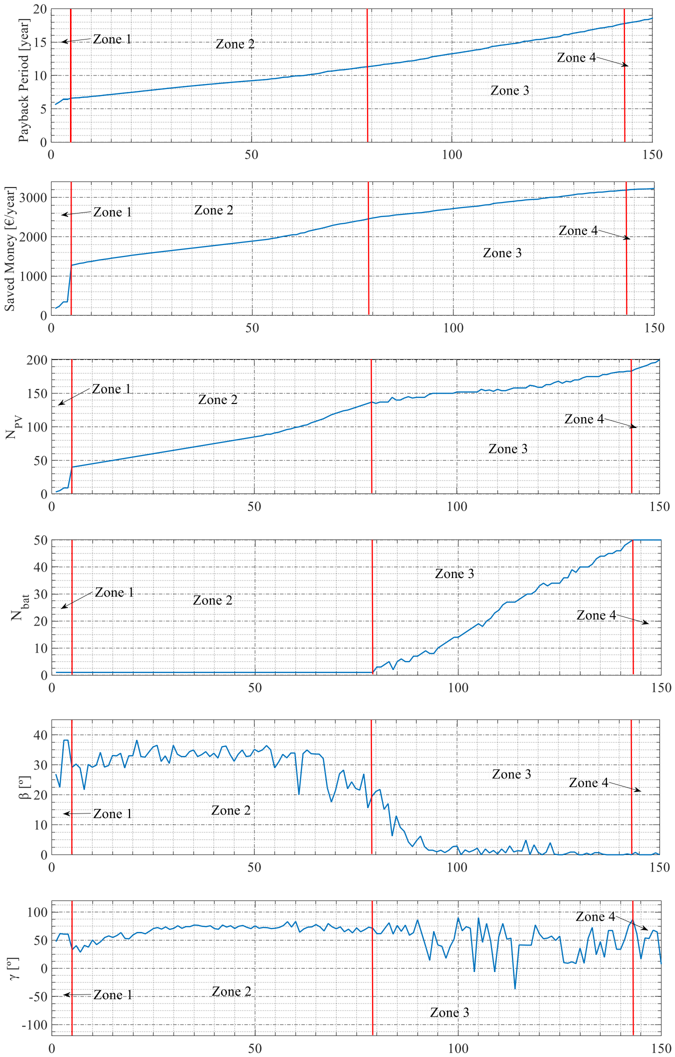


Fig. 15. Last generation of the simulated scenario.

From the graph above, it is possible to draw some conclusions about the characteristics of the system under analysis. It is possible to distinguish the existence of four zones where the behavior of the money saved annually as a function of the payback period varies. For a better understanding, not only of these zones, but also of the evolution of the decision variables along the population of the last generation, these elements are represented in ascending order of the payback period in figures 20-25.



Figs. 20-25. Objective functions and decision variables of all samples of last generation.

In first analysis, the number of photovoltaic panels installed is proportional to the payback period and the money saved annually, because the greater the number of panels, the more solar energy is produced and, consequently, the more money is saved. In addition, there is another parameter that contributes significantly to the evolution of the objective functions: the number of batteries installed. The greater the number of batteries, the greater the amount of stored energy prevenient from the panels, and consequently, the greater the amount of money saved annually, because when it is necessary, the energy stored in the batteries is given priority over the energy from the grid.

As noted earlier in this chapter, there are four zones that are represented in the figures 20-25. The individual analysis of each of these zones is then carried out:

1) Zone 1: This zone is the least relevant to analyze the results of this simulation. While the money saved annually, and the number of panels increase throughout this zone, the payback period remains constant, leading to the conclusion that installing 1 or 40 panels has little impact on the variation of this objective function, concluding that these samples are not good indicators of the actual behavior of these variables in this simulation.
2) Zone 2: The second zone defined is characterized by the zone where as the money saved annually grows at a certain rate, the payback period increases less significantly when compared with, for example, zones 3 and 4. This is relevant for the fact that it is the most suitable zone for defining the parameters of the installed system. It should be noted that all the samples of this zone predict the installation of only one battery, which leads to the conclusion that a system composed only of photovoltaic panels and one battery is economically more advantageous than a system with more than a battery, or none. Regarding the installation angles of the panels, the inclination with which the panels are installed is around 30º, while the azimuth is around 60º.
3) Zone 3: The samples that are within this zone are those which, in addition to providing for the installation of photovoltaic panels, also have batteries to aid in the supply of electricity to the exploration unit. The transition point between zones 2 and 3 corresponds to the set of samples from which it becomes more advantageous to install more batteries than to add only photovoltaic panels and a battery, as in zone 2. However, in terms of objective functions, and from the analysis of figure 23, it is clear that from this point on, the payback period increases more significantly than the money saved annually, leading to the conclusion that installing a system with the parameters of the third zone is not as economically advantageous as installing a system with the parameters of zone 2.
4) Zone 4: In this zone, as in the second one, the results obtained are the least adequate when compared with the solutions of the zones 2 and 3. It may be considered that a saturation point has been reached here. The number of batteries remain constant at the maximum value previously defined, the number of photovoltaic panels increases at a high rate and therefore, this is the zone where the payback period has the most accentuated growth, while the money saved annually has its least accentuated growth, becoming almost constant. In short, the results obtained in this zone are not of interest from the point of view of the investor because they are economically unviable.

Considering a set of values from zone 3 ($n_{PV} = 154$; $n_{bat} = 20$; $\beta = 1{,}92°$ and $\gamma = 79{,}7°$), which assumes the installation of batteries in complement to the photovoltaic panels, the implementation of this system is analyzed in terms of energy and finances. Although the samples from zone 2 are more advantageous from the ones from zone 3, since those are very similar to the same analysis made in the previous chapter I proceed to the analysis of a solution that assumes the installation of batteries.

Based on the graph of the figure 26, it is evident the energetic efficiency of this system in what concerns the months of lower consumption. As far as peak consumption is concerned, about half of the energy consumed is produced by the panels. This demonstrates the inefficiency of this system to meet the energy needs of the farm, more specifically in the night and dawn periods of the months corresponding to the peak of consumption.

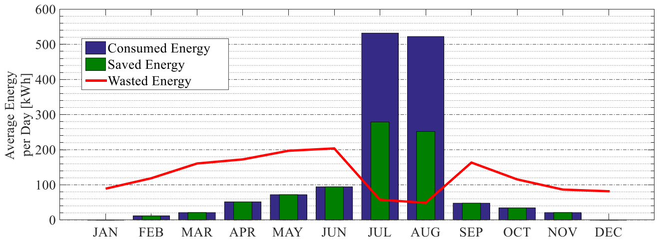


Fig. 16. Annual evolution of the saved energy, consumed energy and wasted energy.

As far as wasted energy is concerned, there are high levels of energy that are not used in the months of least consumption. However, as in the system composed only of photovoltaic panels, in the months of greater consumption the wasted energy reduces significantly in comparison to the other months of the year. In quantitative terms, of approximately 43,4 MWh consumed, about 27,2 MWh were saved, corresponding to about 62,7% of the total energy consumed per year.

In financial terms, for this case of a system consisting of photovoltaic panels and batteries, the investment required is € 38800, and at the end of the year the money saved amounts to € 2790, a much lower value that the investment made. This means that the payback period will be around 13,9 years.

IX. PHOTOVOLTAIC SYSTEM WITH SURPLUS SELLING

A. *Parameters*

After the analysis without considering the sale of excess energy produced to the grid, the simulation is made assuming the sale of the surplus at a price of € 0,041 / kWh. A significant improvement of the results is expected at the level of the payback period, since in previous simulations there is a large amount of energy produced that is wasted. As such, for this purpose, the objective functions will be the money saved annually (12) and the payback period (13). The decision variables are the same as in the last simulation, as can be seen in table 6.

TABLE VI. DECISION VARIABLES AND PARAMETERIZED LIMITS IN SIMULATION.

Variable	N_{PV}	N_{bat}	β [º]	γ [º]
Min	1	0	0	-90
Max	200	50	180	90

In addition to the decision variables and objective functions defined, the optimization was programmed to simulate 100 generations of samples with 150 elements per generation. No constraints were set on this simulation.

B. Results

Once the main parameters of the simulation were defined, the graph of the objective functions, shown in figure 27, was obtained. There, three zones with significantly different results are demarcated.

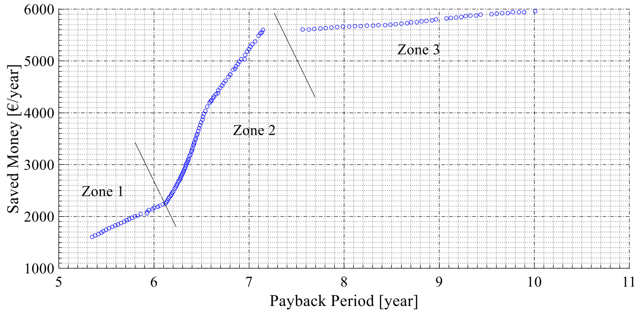
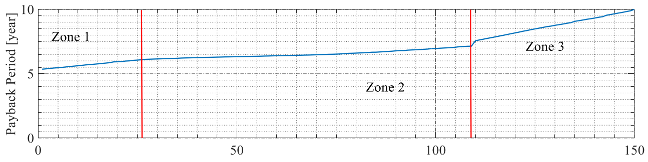
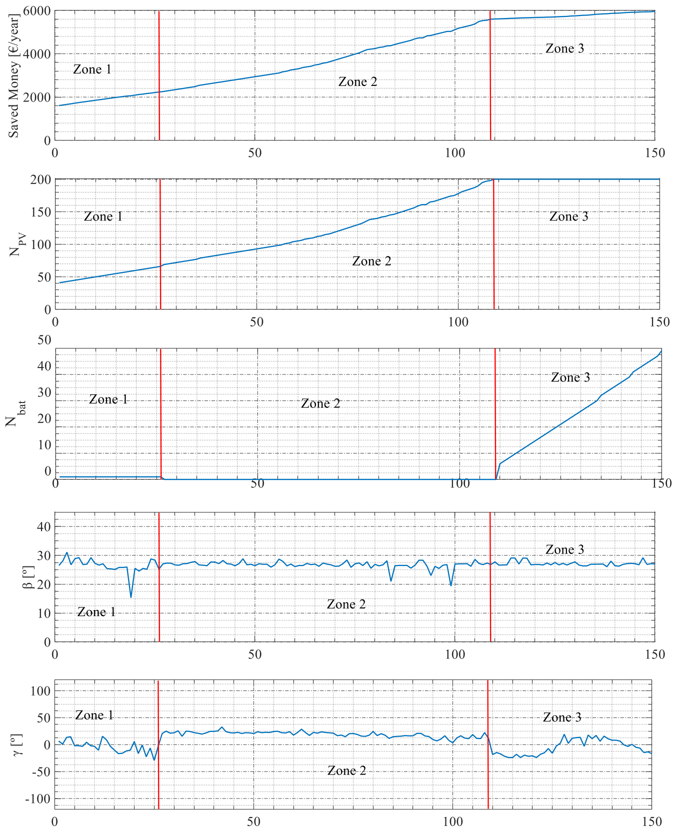


Fig. 27. Last generation of the simulated scenario

When analyzing the graph referring to the system that presupposes the sale of excess energy produced, it is possible to distinguish the existence of three zones whose behavior of the objective functions, one according to the other, varies significantly. The first zone is characterized by an objective function curve in which the money saved annually grows moderately and steadily as the payback period increases. However, the main difference between the zones marked in the figure 27 is that in zone 3 the annual saved money increases insignificantly when compared to the payback period, resulting in a curve with a very small slope. About zone 2, which concerns a zone where no batteries are to be installed in the designed system, the money saved annually increases considerably with the increase in the payback period, meaning that in this zone, when the payback period increases, it also grows the amount of energy saved and sold annually, culminating in a more economically advantageous zone.





Figs. 28-33. Objective functions and decision variables of all samples of last generation.

According to what was already described regarding the behavior of the variables in each zone, is perceptible a high difference in the transition from zone 2 to 3. It is noted that battery installation has a major impact on almost all other decision variables. Regarding the objective functions, it is verified that the return period has a more significant growth in the zone that assumes the installation of batteries than in zones 1 and 2.

The money saved annually has the opposite behavior. When the system consists only of photovoltaic panels and a battery, the money saved annually grows significantly with the increase of the number of panels installed. However, in zone 3, the money saved annually stabilizes as the number of batteries increase. About the angles with which the panels are to be installed, the inclination of these panels remains constant and close to 27º, while the azimuth orientation varies between -15º and +15º. It should be emphasized that this is a solution closer to that typical of installations of this kind in Portugal ($\beta = 30$º and $\gamma = 0$º), since, instead of wasting energy, as it presupposes the sale of surplus to the grid, it is more advantageous to direct the panels so that they absorb as much radiation as possible during the day, for a greater production of electricity. From these results it is already apparent that a solution with parameters concerning zone 2 is much more economically advantageous than a solution from zone 3, and more advantageous than the parameters related to zone 1.

Based on a sample from zone 2 ($n_{PV} = 195$; $n_{bat} = 0$; $\beta = 27{,}21$º and $\gamma = 11{,}54$º), in the figure 34 is shown a graph that allows the energetic analysis of a system with those parameters.

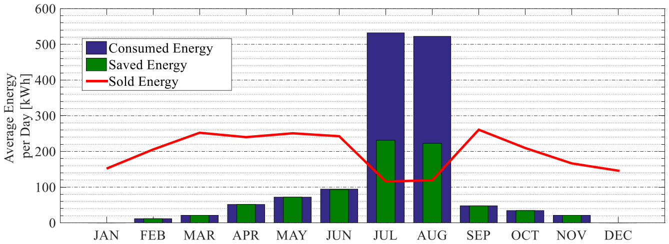


Fig. 34. Annual evolution of the saved energy, consumed energy and wasted energy.

From the figure above, it can be observed that a system with these parameters allows a total energy saving for the months of lower consumption. In the peak consumption months (July and August), a little less that 50% of the energy consumed during this period is saved. In what concerns the sold energy, it reaches its highest values in the months of lower energy demand, while in months of peak consumption it reaches its lowest values. These values of sold surplus result in a higher amount of money saved annually.

With this solution, the money invested is recovered after approximately 7 years, which is significantly more advantageous than the same solution, without the sale of surplus (payback period of 15,3 years).

X. CONCLUSIONS

From this study, several conclusions were drawn. In a first analysis, the installation of an autonomous photovoltaic system was studied. From this study, it was verified that the design of a self-sufficient system is not financially viable, due to the high return payback period. As this solution was not adequate, feasible alternatives have been studied. Two types of photovoltaic systems were studied from an economical perspective.

Regarding the photovoltaic system only composed of photovoltaic panels, it was concluded that the best results obtained with this solution concerns the installation of a maximum of 140 photovoltaic panels. Higher values than this lead to saturation of energy saved annually.

As for the simulation of the photovoltaic solar system composed of photovoltaic panels and batteries, it has been found that, in economic terms, the installation of batteries in considerable numbers is not economically advantageous for this system. However, the simple installation of one battery is more beneficial than the no installation of batteries. Through the simulation of this kind of system, it can be concluded that up to 140 photovoltaic panels installed, the simulation regards the installation of one battery which is the best solution for this kind of system.

Finally, with the simulation related to the implementation of a photovoltaic solar system that assumes the sale of surplus, it was concluded that, if it is possible to obtain the license to carry out this activity, this is the most advantageous solution. However, with this new variant, the results of this simulation differ from the previous ones. With these specifications, up to about 70 panels installed should be accompanied by a battery. Between 70 and 200 solar panels installed, batteries should not be included in the designated system, corresponding to the set of solutions of this simulation the best ones within the scope of this thesis.

REFERENCES

[1] Sucena Paiva, José P., “Redes de Energia Eléctrica: Uma Análise Sistémica,” IST Press, 2005.
[2] Luque, Antoonio and Hegedus, Steven, “Handbook of Photovoltaic Science and Engineering,” John Wiley & Sons Ltd, England, 2003.
[3] Duffie, John A. and Beckman, William A., “Solar Engineering of Thermal Processes,” John Wiley & Sons, Inc., Hoboken, New Jersey, 2013.
[4] Stine, William B., “Power from the Sun,”, 2001, «http://www.powerfromthesun.net»
[5] Maleki, Mousavi, Abbas, Seved, Hizam, H. and Gomes, Chandima, “Estimation of hourly, daily and monthly global radiation on inclined surfaces: Models re-visited,” Energies 10.1, 2017.
[6] «http://pt.weatherspark.com/y/32249/Clima-característico-em-Cartaxo-Portugal-durante-o-ano».
[7] “Diagnóstico Sócio-Cultural do Distrito de Santarém – Estudo 1”, Santarém, 1985.
[8] PVGIS (Photovoltaic Geographical Information System), «http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html»
[9] White, Frank M., “Fluid Mechanics – 7th Edition,” McGraw-Hill Series in Mechanical Engineering, 2009.