Design of a photovoltaic solar installation for the irrigation of the Vallada cultivation area (Valencia)

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November, 2021

Abstract: Of the 43 countries that make up Europe, Spain is ranked number 19 in terms of the percentage of GDP associated with the agricultural sector, with 2,61% in 2019. If this value is compared with that of the richest and most developed countries (Denmark, Sweden, Germany, United Kingdom, Norway, Italy, France) it is observed how Spain is the country that has a more developed agricultural sector, that is, it bases a greater portion of its wealth on the goods generated by this sector. In addition, for many years, around 2/3 of all the water consumed in Spain has been used for agriculture (in turn, around 20% of the water consumed is extracted from underground reserves, for which submersible well pumps, powered by the electrical network or by a generator set, are used). If these two factors are added to the fact that Spain is one of the countries with the lowest rate of precipitation it is concluded that, although it is always necessary to optimize the use of water, in the case of Spain the efficient and responsible use of water takes on even more importance.

This paper aims to present the consumption associated with a groundwater pumping installation based on the volumes of water required each hour of the year by the cultivation areas and the regulation strategy of the water storage tanks, as well as highlight both the potential economic savings and the reduction in polluting emissions achieved depending on the degree of self-sufficiency achieved by means of a photovoltaic installation. In addition, the convenience of installing a set of PATs to recover a part of the energy carried by water on its way through the different pipes is analyzed based on the results of a previous publication (Modesto Pérez Sánchez, Francisco Javier Sánchez Romero, P. Amparo López Jiménez and Helena M. Ramos).

Keywords: Renewable energies; photovoltaic energy; solar photovoltaic systems; pumping groups; Performance Ratio; emissions.

1. Introduction

Although the contribution of the agri-food sector to GDP and employment in the case of the Valencian Community is slightly lower than the Spanish average (around 1% in both cases), this sector is relevant and especially when it comes to exports abroad, since Valencian exports from the primary sector account for around 8,5% of the national total and, in turn, represent around 20,2% of the total exports of goods from the Valencian Community. Citrus fruits stand out from this agricultural sector, a crop with a great tradition in the region which accounts for a very important part of Valencian agri-food exports and which is one of the hallmarks of said autonomous community.

To carry out the irrigation of these cultivated areas, there are a multitude of possible options depending on the characteristics of the land, the crops, or the available water resources, among other factors such as the location of the plantation.

In this sense, it is of special interest to analyse the possibility of achieving a complete degree of energy self-sufficiency through a photovoltaic installation and of implementing it if it is feasible (and profitable), not only because of the economic benefits but also because of the considerable reduction in emissions that can be achieved. achieve with this type of installation throughout its useful life. Geographical location has a strong impact on the reliability obtained by a PV system since it determines the climate conditions. In this sense, ambient temperature and radiation directly affect the capacity of the modules to generate electrical energy; specifically, the higher the temperature the lower the generation, whereas the higher the irradiance the higher the generation.

Specifically, these are systems in which there is a direct conversion of sunlight into electricity without any heat engine to interfere. These devices are simple in design and require very little maintenance. Large photovoltaic installations can give outputs of tens of megawatts peak (MWp). This technology is characterized by having a multitude of practical applications, such as power source, water pumping, communications, satellites and space vehicles, reverse osmosis plants, etc [1].

T.D. Short and P. Thompson [2], S.S. Chandel, M. Nagaraju Naik and Rahul Chandel [3], and Vimal Chand Sontake and Vilas R. Kalamkar [4] are recent publications wich develop important and present aspects related to pv pumping systems.

2. Material and methods

2.1. Determination of the energy needs

As is logical, the first step to be able to size an installation that meets certain energy needs is precisely to know what the needs are that must be covered. In this sense, a series of data has been available from an Excel sheet and an EPANET file. This has made it possible to know what the flows are demanded in each of the irrigation sectors. In this way, knowing the water demands in each of these sectors as a whole, it is possible to determine the energy needs of the pumping systems throughout the year.

Once the flow to be supplied to each irrigation sector in each hour of the year is known, the required pumping parameters must be determined based on the characteristics of the pipes and the water extraction capacity of the wells. In this sense, both wells, the one that feeds Sector 1 and the one that feeds Sector 2, can provide a maximum flow of 0,1 m^3/s, and therefore the pumping system of each of them will not be able to extract an upper flow. On the other hand, to determine the height or pressure that these groups must provide, various factors are taken into account:

- The depth of the well
- The difference in height between the point of extraction of the water and the high point to which the water must be driven.
- The length of the pipes, as well as their roughness, diameter and material
- The pumped flow

Once the operating point corresponding to each sector is known (Q = 100,94 L/s and H = 126,14 m for Sector 1; Q = 98,74 and H = 63,97 m in case of Sector 2), the total power that is required at the input of both pump motors is obtained by eq. (2.1.1):

$$P_e = \frac{\gamma \cdot Q \cdot H}{\eta_h \cdot \eta_e \cdot 1000} = \frac{P_f}{\eta_h \cdot \eta_e} = \frac{P_f}{\eta_g} = \frac{P_p}{\eta_e} \qquad (2.1.1)$$

2.2. Obtention of the dimension of the pv installation

At this point, the energy needs at the entrance of the pumping groups are known. Next, it is necessary to know the energy resources available in the area.

To do this, it is necessary to go to the PVGIS web address. It is an online platform that provides free and open access to, among other things, hourly data of solar radiation and temperature.

In this way, both irradiance and temperature data are obtained for each hour of the year in the location where the projected photovoltaic installation would be executed. With this, it is possible to know the power that the photovoltaic generator is capable of delivering each hour, depending on the irradiance and the temperature. Precisely, the maximum power that a photovoltaic panel is capable of delivering based on these factors, in addition to its nominal power and the variation of said power with temperature, is given by eq. (2.2.1) and eq. (2.2.2):

$$P_{m\,mod} = P_{m\,mod\,(STC)} \cdot \frac{G_{loc}(\alpha,\beta)}{G_{STC}} \cdot \left[1 + \frac{\gamma_p}{100} \cdot \left(T_{cel} - T_{cel\,(STC)}\right)\right] \qquad (2.2.1)$$

$$T_{cel} = T_{loc} + \frac{NOCT-20}{800} \cdot G_{loc}(\alpha,\beta) \qquad (2.2.2)$$

Next, a performance of the inverter to be installed must be established, as well as the Performance Ratio (PR) of the installation. The value of these returns is initially estimated and, when the business models of the different components are selected and the losses can be more accurately calculated, the calculations are redone, obtaining the final energy balances (eq. 2.2.3):

$$P_{pv\,gen} = \frac{P_e}{\eta_{inv} \cdot PR} = \frac{P_{inv}}{PR} \qquad (2.2.3)$$

For the PR, the considered losses have finally been:

- Orientation and tilt losses: 2% (the panels face south, then the orientation is optimal, and the slope is almost identical to optimal)
- Shadow losses: 5%
- Cell temperature losses: 2,5% These losses were already considered before, so they are not included now
- Losses due to mismatch effect: 1,5%
- Losses due to dust: 1%
- Angular and spectral losses: 1,5%
- Losses due to non-compliance with nominal power: 5%
- Ohmic losses in the DC section: 1%
- Losses in the MPPT system: 1,5%
- Losses in the DC/AC converter: 2,5%. These losses were already considered before, so they are not included again.
- Ohmic losses in the AC section: 1%
- Other losses: 2,5%

In this way, knowing the power that can be delivered by a panel at each moment of the day, as well as the energy needs to be satisfied, it is possible to determine the number of panels that would need to be installed in the photovoltaic installation that feeds its corresponding irrigation sector (eq. 2.2.4):

$$N_T = \frac{P_{pv\,gen}}{P_{m\,mod}} \tag{2.2.4}$$

The distance that must exist between the rows of modules is given by eq. (2.2.5):

$$d = \frac{h}{\tan(61º - \Phi)} \tag{2.2.5}$$

Regarding the other main component, the inverter, first it is necessary to set the number of modules that can be connected in series to each one of them. To do this, the following eq. (2.2.6) & (2.2.7) establish the limits of the interval of this number of modules:

$$N_{S\,max} = \frac{V_{DC\,inv\,max}}{V_{OC\,mod\,(Tmin\,mod)}} \tag{2.2.6}$$

$$N_{S\,min} = \frac{V_{MPPT\,min}}{V_{M\,mod\,(Tmax\,mod)}} \tag{2.2.7}$$

And, at the same time:

$$V_{OC\,mod\,(Tmin\,mod)} = V_{OC\,mod} + \beta_V \cdot (T_{\min mod} - 25°C) \cdot V_{OC\,mod} \tag{2.2.8}$$

$$V_{M\,mod\,(Tmax\,mod)} = V_{M\,mod} + \beta_V \cdot (T_{\max mod} - 25°C) \cdot V_{OC\,mod} \tag{2.2.9}$$

Whereas the maximum number of modules that can be connected in parallel to the inverter is given by the expression eq. (2.2.10):

$$N_{P\,max} = \frac{I_{DC\,inv\,max}}{I_{SC\,mod\,(Tmax\,mod)}} \tag{2.2.10}$$

And, at the same time:

$$I_{SC\,mod\,(Tmax\,mod)} = I_{SC\,mod} + \alpha_I \cdot (T_{\max mod} - 25°C) \cdot I_{SC\,mod} \tag{2.2.11}$$

In addition to the maximum number of modules that can be connected in series and parallel, and related to this, it is necessary to set limits on both the maximum voltage and the open circuit voltage and the short-circuit current that can reach the inverter, and that they must respect the capacity values of this component established in their commercial datasheet:

$$V_{M\,string} = N_S \cdot V_{M\,mod} \in (V_{MPPT\,min}, V_{MPPT\,max}) \tag{2.2.12}$$

$$V_{OC\,string} = N_S \cdot V_{OC\,mod} < V_{M\,adm\,inv} \tag{2.2.13}$$

$$I_{SC\,sos} = N_P \cdot I_{SC\,mod} < I_{M\,adm\,inv} \tag{2.2.14}$$

For the cabling calculation, two sections are distinguished: the DC cabling and the AC cabling. In both cases, the criteria described in ITC-BT-40 (point 5) of the "*Reglamento Electrotécnico de Baja Tensión* (REBT)" have been used. These criteria are the maximum allowable voltage drop and the maximum allowable current.

- Criterion of the maximum admissible voltage drop

The calculation of the minimum necessary cable section in case of applying this criterion is obtained by the eq. (2.2.15), for the case of the cables that connect the photovoltaic modules to each other in series and those that connect the output of the different strings that make up the photovoltaic field with their corresponding junction boxes:

$$S_{vd\,DC\,st} = \frac{2 \cdot L_{DC\,st} \cdot I_{mp}}{\sigma_{T°C} \cdot \frac{e_{st}}{100} \cdot N_S \cdot V_{M\,mod}} = \frac{2 \cdot L_{DC\,st} \cdot I_{mp}}{\sigma_{x°C} \cdot \frac{e_{st}}{100} \cdot V_{M\,string}} \tag{2.2.15}$$

Once the section of the cables is calculated, it must be normalized to the immediately higher value.

Similarly, for the case of the wiring that connects the output of these junction boxes with the input of the inverters, in parallel, this formula acquires here the expression eq. (2.2.16) :

$$S_{vd\,DC\,inv} = \frac{2 \cdot L_{DC\,inv} \cdot N_P \cdot I_{mp}}{\sigma_{T°C} \cdot \frac{e_{inv}}{100} \cdot N_S \cdot V_{M\,mod}} = \frac{2 \cdot L_{DC\,inv} \cdot N_P \cdot I_{mp}}{\sigma_{x°C} \cdot \frac{e_{inv}}{100} \cdot V_{M\,string}} \tag{2.2.16}$$

Whereas for the wiring that distributes the current from the output of each inverter to the corresponding AC measurement and protection panel eq. (2.2.17) is applied:

$$S_{vd\,AC\,triph} = \frac{\sqrt{3} \cdot L_{AC} \cdot I_{out\,inv\,AC} \cdot \cos\varphi}{\sigma_{T°C} \cdot \frac{e_{AC}}{100} \cdot V_{net}} \tag{2.2.17}$$

e_{st} is the maximum allowable voltage drop between the photovoltaic generator and the connection point to the Public Distribution Network or to the indoor installation. The ITC-BT-40 and the IDAE specify that a value of 1,5% has to be adopted (V)

- Criterion of the maximum admissible current

This criterion, also called thermal criterion, expresses that the connection cables must be sized to allow the circulation of a current at least 25% higher than the value of the maximum intensity that could circulate through the considered cabling section, according to the provisions of the "*Norma UNE-HD 60364-7-712*". Therefore, this intensity is expressed by eq. (2.2.18) and eq. (2.2.19):

$$I_C = 1{,}25 \cdot I_{SC\ mod} \leq I_{adm} \tag{2.2.18}$$

$$I_{adm} = CF_1 \cdot CF_2 \cdot I_0 \tag{2.2.19}$$

Where $\boldsymbol{CF_1}$ is the correction factor corresponding to the bundling level of the cables. To determine the value of this factor, Table B.52.17 of the "*Norma UNE-HD 60364-5-52*" is used; $\boldsymbol{CF_2}$ is the correction factor for operating temperature other than 60 °C. The value can be taken from Table A.4 of "*Norma UNE-EN 50618*".

For the obtention of I_0, first of all, it is necessary go to Table B.52-1 of the "*Norma UNE-HD 60364-5-52*".

Then, according to the reference installation method used in the project, the number of conductors per cable and the type of insulation is used in these cables, the corresponding column of Table C.52-1 bis or Table C.52-2 of the "*Norma UNE-HD 60364-5-52*" is obtained. This column, according to the section of the cable previously obtained by the maximum admissible voltage drop criterion, provides the value of this parameter.

This criterion seeks to size the conductor so that it does not exceed the maximum admissible temperature that its insulation can withstand in normal operation, being said temperature equal to 70°C in the case that the insulation is thermoplastic (PVC), or 90°C if it is thermosetting type (XLPE or EPR) (this last is the case in this thesis).

As happened with the previous criterion, in this case the formulas used have certain modifications depending on the section of the cabling calculated. Thus, in the case of DC wiring between junction boxes and inverters:

$$I_{C\ jb-inv} = 1{,}25 \cdot N_P \cdot I_{SC\ mod} \leq I_{adm\ jb-inv} \tag{2.2.20}$$

$$I_{adm\ jb-inv} = CF_1 \cdot CF_2 \cdot I_{0\ jb-inv} \tag{2.2.21}$$

While in the case of AC wiring between the inverters and the AC measurement and protection panels there is eq. (2.2.22) and (2.2.23):

$$I_{C\ AC} = 1{,}25 \cdot I_{AC\ inv\ max} \leq I_{adm\ AC} \tag{2.2.22}$$

$$I_{adm\ AC} = CF_1 \cdot CF_2 \cdot I_{0\ AC} \tag{2.2.23}$$

The obtained sections were:

- Cables of 25 and 35 mm^2 in section, between strings and junction boxes. 54 cables (30 km) in S1 and 38 cables (17,7 km) in S2 of the first section and 24 cables (14,5 km) in S1 of the second section.
- 16,11 m of 70 mm^2 section cable (six cables), 5,37 m of 10 mm^2 section cable (two cables) and 5,37 m of 6 mm^2 section cable, between junction boxes and inverters.
- Six triphasic lines of three conductors of 185 mm^2 and a neutral of 95 mm^2 each (S1), and four triphasic lines of three conductors of 150 mm^2 and a neutral of 70 mm^2 each (S2).

There are also several protection devices which features must be calculated.

- Protection tubes: The outer diameter of the protection tubes depends directly on the number and section of the cables it contains. This correspondence is given by the ITC-BT-21
- C protection devices
  - Protection against overcurrents and short circuits (ITC-BT-22):
    - To satisfy the overcurrent protection conditions, given by eq. 2.2.24, 2.2.25 and 2.2.26:

$$I_d \leq I_{nf} \leq I_{adm} \tag{2.2.24}$$

$$I_{op\ g} \leq 1{,}45 \cdot I_{adm} \tag{2.2.25}$$

$$I_{op\ g} = \begin{cases} 1{,}6 \cdot I_{nf} & if\ I_{nf} \geq 16\ A \\ 1{,}9 \cdot I_{nf} & if\ 4\ A < I_{nf} < 16\ A \\ 2{,}1 \cdot I_{nf} & if\ I_{nf} \leq 4\ A \end{cases} \tag{2.2.26}$$

    - To satisfy the short circuits protection conditions, given by eq. 2.2.27, 2.2.28 and 2.2.29:

$$P_{f\ b} \geq I_{SC\ \max f} \tag{2.2.27}$$

$$I_{SC\ adm\ cond} > I_{op\ f\ 5} \tag{2.2.28}$$

$$I_{SC\ \min f} > I_{op\ f\ 5} \tag{2.2.29}$$

From the ITC-BT-22 the following eq. (2.2.30) is obtained, which allows to calculate this parameter:

$$I_{SC\ adm\ cond} = k \cdot \frac{S}{\sqrt{t}} \qquad (2.2.30)$$

Being k the coefficient that depends on the material of which the conductor is made and the insulation if has (see UNE 20460-4-43) and t the maximum duration of the short circuit, during which the equipment must guarantee the protection of the installation (5s).

On the other hand, $I_{op\ f\ 5}$ is the minimum current capable of making the fuse act in a time not exceeding 5s (A). It is therefore the fusing current in 5 seconds of the selected fuse; and $I_{SC\ min\ f}$ is the minimum short-circuit current that can be generated downstream of the fuse (A). Its value is calculated using the simplified expression found in the "*Guía BT Anexo 3*", eq. (2.2.31):

$$I_{SC\ \min f} = \frac{0{,}8 \cdot U}{Z_L} \qquad (2.2.31)$$

In which U, according to the "Guía BT Anexo 3", is the phase-neutral supply voltage is taken, which is 230 V.

- Protection against overvoltages. Surge arresters:

  ITC-BT-23 establishes that the device in charge of this type of protection must reduce overvoltages (transient) to a value that is admissible and endurable by the equipment it protects downstream. Based on this, the DC junction box has to include Type 2 surge protection devices, characterized by the following properties described in the mentioned standard.

- Protection against direct and indirect contacts. DC side grounding → (UNE-HD 60364-4-41; ITC-BT-08 ; ITC-BT-18, ITC-BT-24)

  The UNE-HD 60364-4-41: 2018 standard sets out the minimum specifications that a system that uses the IT installation scheme must meet for grounding. First, it is established that all the masses of the pv installation must be grounded, either individually, in groups or together; in this case it has been decided to connect these masses in groups. In the DC section the frames of the modules will be connected to earth via copper rods. Their configuration must be round, highly resistant, ensuring maximum rigidity to facilitate their introduction into the ground and preventing them from bending due to the force of the hits. An effort will be made to ensure that the grounding resistance of the set of 2 m long copper rods and the 35 mm^2 bare copper wiring that interconnects them is a maximum of 10 - 12 Ω. To do this, the calculus is done as it is shown in the following:

  To avoid incurring in a more extensive document, comment that the dimensioning of the protection elements on the AC side is very similar to those already described for the DC side (see the standards corresponding to each one in the previous point).

3. Case study

3.1. Description of the location area of the facilities

The land on which the irrigation network, the pumping systems and the ponds are located, as well as on which it is intended to project and locate the photovoltaic installation necessary for its partial or total self-sufficiency, is located in the municipality of Vallada, which in turn is located in the region of "La Costera", province of Valencia.

On the other hand, its economy is based on two fundamental pillars:

- Firstly, the municipality is dedicated to the furniture, wicker, rattan, reed and basketry industry, its main clients being other European countries.

- Secondly, agriculture also plays a fundamental role in the economy and the maintenance of jobs for the population. In this case, olive trees, cereals, almond trees and fruit trees predominate as dry crops. Citrus and different varieties of fruit trees occupy irrigated crops.

Figure 3.1.1. Aerial view of Vallada and its region

3.2. Available data and existing facilities

- Drip irrigation system.

- There are two branched networks of pipes. The first of them, the oldest, consists of the water extraction well known as "Pozo Canyoles I" that provides a maximum water flow of around 0,1 m^3/s that is pumped to a reservoir located at a height of 360 m and with a capacity of around 5000 m^3. The second, much more recent, consists of a water extraction point known as "Pozo el Tollo" that pumps a maximum flow of around 0,1 m^3/s to a reservoir located at a level similar to the previous one (371 m) but of much greater capacity, specifically 17,000 m^3. They are represented in Figure 3.2.1

- By default, both branched networks of pipes work independently, each one with its well and its reservoir, although if necessary it is possible to allow the communication of both basins, so that one of them can also supply water to the different irrigation points of the other pipe network.

- The pumps are submerged and therefore self-priming and not susceptible to the cavitation problem common in jet pumps.

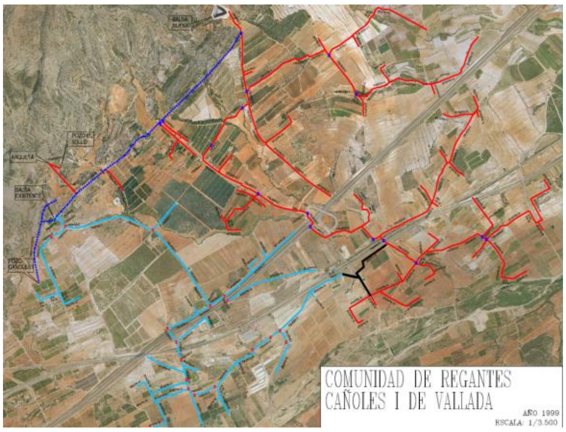

Figure 3.2.1. Existing hydraulic network

3.3. Considerations and operating strategy

When choosing the commercial models of both the panel and the inverter finally installed, a comparison was made between different models.

In the case of the panels, a comparison was made between 3 models based on 4 factors:

- Producible power
- Number of panels required
- Occupied surface
- Cost of the panels

On the other hand, when comparing commercial inverters (3 in total), it was taken into account:

- Number of investors required
- Inverters cost

The calculations have been carried out in accordance with current legislation.

Regarding the operating strategy considered for the regulation of the volume stored in the reservoirs and the buy-sell strategy of the energy, it has been the following: during peak hours, when the price of electricity consumed from the grid is higher (even though it depends on the company and the type of rate contracted), an attempt will be made to pump the maximum possible flow (0,1 m^3/s per well) by means of the energy provided by the photovoltaic installation if the remaining capacity of the corresponding water tank is sufficient, so that in off-peak hours, when the cost is much lower, the energy from the network is used in case it is necessary to pump more water.

However, and as a consequence of the particularities of the water needs and of the water pumping and storage systems of each sector, the strategy differs from one to the other.

In this way, with the hours in which solar radiation is available (the irradiance threshold from which it is usually considered that the received one is enough to allow the water pumping is usually between 200 and 400 W/m^2, so in this project, 300 W/m^2 has been taken as the minimum value to consider that the pumping can be carried out by photovoltaic energy) and the pumping flow of the installation of Sector 1, not only the water needs of the same can be supplied, but there is also a considerable number of hours per year in which, as no pumping is required, this solar resource can be used to generate electricity that would be poured into the grid (after conversion to alternating current) for sale, thereby generating profits while the tank is able to keep irrigation needs satisfied. On the other hand, it should be emphasized that it has been established, as a regulation strategy, not to pump during those hours in which the radiation was lower than the previously indicated minimum value, to let the tank empty and to pump again at those times when enough radiation is received until it reaches its maximum capacity, at which point it stops pumping again until its capacity is around 15% of its maximum. Therefore, in this sector, if so decided, it would be possible to supply the energy and water needs by pumping water from the well during a fraction of the annual hours in which sufficient irradiance is received without requiring the injection of electricity from the electrical network, being able to sell the energy surpluses.

In the case of Sector 2, regulation is not so simple. Due to the high water needs, in this case it is not only not possible to meet the energy and water demands not even pumping all the annual hours with sufficient radiation, but also during the months of highest consumption (May-September) it is required a certain contribution of electricity from the network to pump during the night hours. In this case, it has also been decided to pump using photovoltaic energy once 15% of the capacity of the corresponding reservoir has been reached and until it is filled, and on the other hand the energy from the network has been used when the stored volume was already scarce, 10% of capacity, during night hours.

The value of 15%, in both cases, has been set in order to ensure that the remaining capacity of the reservoirs was sufficient to supply the water needs for at least the next 6 hours (with a demand significantly higher than 0) in the event that solar radiation is not available in those hours (passage of a cloud or rainy day).

4. Results and discussion

4.1. Photovoltaic installation designed and degree of self-sufficiency achieved

In the case described, the results obtained have been the following:

Sector 1 (Canyoles I)

Q (L/s)	H (m)	η_g(%)	PR (%)	$P_{pv\ gen}$ (kW)
100,94	126,14	69,28	75	242,58

Table 1. Power to be installed in the pv generator of S1

Sector 2 (El Tollo)

Q (L/s)	H (m)	η_g(%)	PR (%)	$P_{pv\ gen}$ (kW)
98,74	63,97	69,54	75	119,88

Table 2. Power to be installed in the pv generator of S2

Based on the results of the previous section, it was decided to install around 70,8% of the total number of panels required in both sectors. Therefore, in Sector 1, 1560 panels will be installed and 6 inverters, and in Sector 2 a total of 760 panels and 4 inverters. This seeks, with a large but reasonable investment, to satisfy the energy needs without the need to purchase energy from the network in a high percentage of the necessary pumping hours and, at the same time, to obtain a profit in the years following the initial investment.

Furthermore, the total area required for each photovoltaic module is known, as well as the number of modules that will be installed for feeding each sector, so it is possible to calculate the surface required for their installation. The results of this simple calculation were reflected in the tables of the previous point. Their sum is 10277,60 m^2. The total cost of these panels, including the machinery and personnel required, is 330.112,80 €, whereas in case of the inverters this value is of 94.347,90 €.

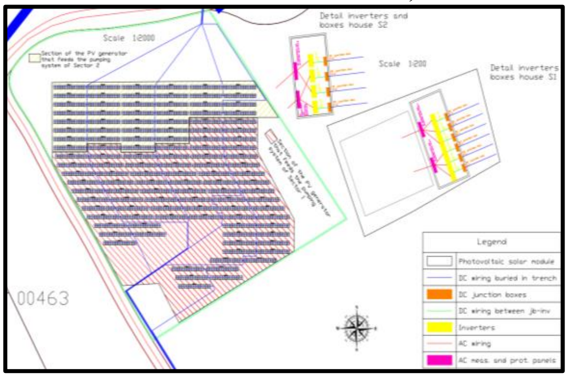

Figure 4.1.1. Final arrangement of the PV generator and other components and connections

4.2. Economic analysis

The following table lists the values used for the various variables that need to be taken into account to carry out the economic analysis of the project:

Parameter	Unit	Value
Investment (TBB)	€	1.410.752,56
Maintenance, replacements and insurance	€	4000
Useful life	Years	25
Production (first year)	kWh	1.385.509,74
Consumption	kWh	512.558,85
Consumption from pv energy	kWh	459.062,91
Surplus energy	kWh	926.446,84
CPI (for maintenance and insurance)	%	2,2
CPI (for sale and purchase price)	%	2
k	%	2,5
Annual power loss (%) first 10 years	%	1
Annual power loss (%) last 15 years	%	0,67
Cost of representation	€/kWh	0,00082
Generation access toll	€/kWh	0,0005
Sale price of energy (first year)	€/kWh	0,05
Purchase price of energy (first year)	€/kWh	0,0934

Table 3. Considerations for the cash flows and economic indicators (NPV, IRR and PP)

When determining the benefits, a distinction is made: on the one hand, the benefits that are obtained indirectly due to the annual economic savings associated with the reduction in consumption of electrical energy from the network and, on the other hand, the benefits due to the sale of the energy surpluses in the electricity market in those moments in which photovoltaic generation exceeds the consumption of the pumping groups. The corresponding expressions of these benefits are the following:

- Benefit associated to the reduction in the consumption of electrical energy from the network.

$$Saving_{month\ i}(€) = E_{prod\ month\ i}(kWh) \cdot price_{purchase}\left(\frac{€}{kWh}\right) \quad if\ E_{prod\ month\ i} < E_{cons\ month\ i} \qquad (4.2.1)$$

$$Saving_{month\ i}(€) = E_{cons\ month\ i}(kWh) \cdot price_{purchase}\left(\frac{€}{kWh}\right) \quad if\ E_{prod\ month\ i} > E_{cons\ month\ i} \qquad (4.2.2)$$

Here, the annual savings due to the use of the energy recovered by the PATs (around 4500 €/year) has been taken into account.

- Benefit associated to the sale of surpluses:

$$Benefits_{month\ i}(€) = \left(E_{prod\ month\ i}(kWh) - E_{cons\ month\ i}(kWh)\right) \cdot price_{sale}\left(\frac{€}{kWh}\right) \qquad (4.2.3)$$

Regarding the results of the NPV, IRR and PP, they are shown in the following table:

NPV (€)	**267.747,46 €**
IRR (%)	**4,0207%**
PP	**20,309**

Table 4. Results of the financial indicators of the economic analysis

The following graphs illustrate the energy flows in the hydraulic-photovoltaic installation, the savings and benefits obtained in the first year, the cash flows and the updated accumulated cash flows in the case of installing the designed photovoltaic system (≈70% of required modules):

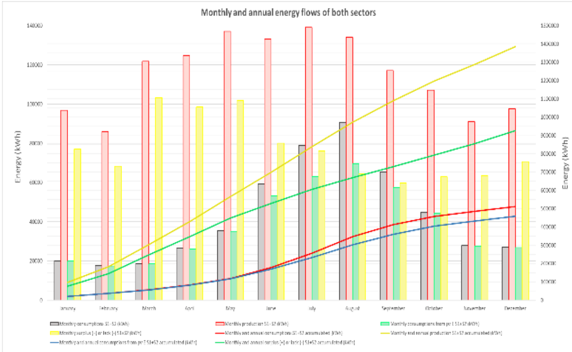

Figure 3.2.1. Monthly and annual energy flows

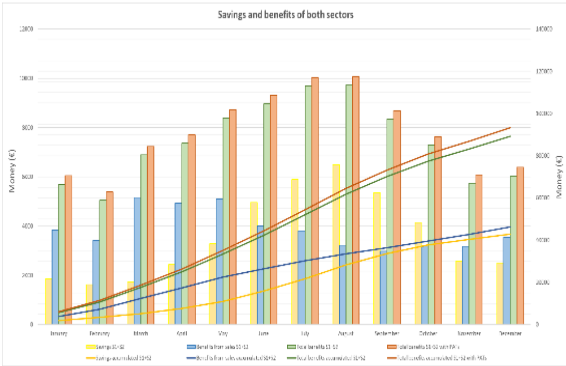

Figure 4.2.2. Monthly and annual savings and benefits

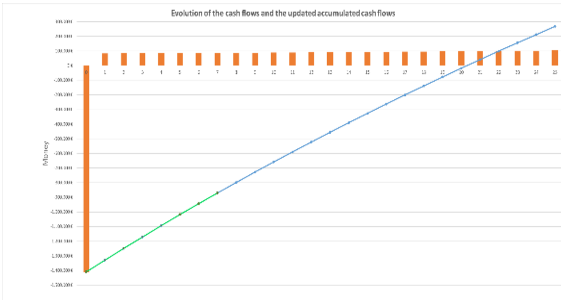

Figure 4.2.3. Evolution of cash and updated accumulated cash flows

The following conclusions can be drawn from the three previous graphs:

- In the first of them (Figure 4.2.1), it is observed how in every month the energy produced by the photovoltaic installation is higher than the consumption needs, which means that in all of them there is a surplus of energy that can be sold in the network and, therefore, from which benefits can be obtained. In turn, it is observed how in the months in which the water and energy needs are higher (June-October), despite the fact that the energy production of the installation is notably higher, as the energy needs increase to a much greater extent, the energy surpluses are lower. On the contrary, in those months in which less radiation is received, but the needs of the irrigation sectors are much lower

(November-May), despite the fact that energy production is lower, greater surpluses of energy are obtained that can be sold In the net. The self-consumption level is, in the first year:

$$S.C_{level} = \frac{Annual\ consumptions\ from\ pv\ E}{Annual\ consumption\ needs} = \frac{459.062{,}91}{512.558{,}85} \rightarrow S.C_{level} \approx 0{,}8956 = 89{,}56\% \quad (4.2.4)$$

- The second graph (Figure 4.2.2) is closely related to the first, since it reflects, in monetary terms, the different energy flows existing in the installation. In this way, it can be seen how in the months that were previously indicated as having higher energy production, but even higher energy demand (June-October), the benefits from savings are higher than the benefits from the sale of surplus energy, while that in the other months (November-May) a higher profit is obtained from the sale of surpluses than from savings due to the decrease in energy demand from the network.

- Finally, the last graph (Figure 4.2.3) reflects two facts: the first, that the cash flows are somewhat higher each year, going from about 83.360 € to 102.799 €, since although an annual power loss of the photovoltaic generator has been considered, and therefore a decrease in the energy that is obtained both for self-consumption and for sale and an increase in the demand for energy from the network, the established CPI allows the benefits to increase slightly each year (about 800 € per year); the second, that the cumulative updated cash flow becomes positive at the beginning of year 20, as previously indicated by the PP.

  As a last conclusion in the economic aspect, to emphasize that the financial parameters obtained would change taking into account the annual interest derived from the bank loan required for the partial or total financing of the investment (it should be remembered that the budget is closely of a million and a half euros, and that the Promoter is an irrigation society with about 20-25 members).

4.3. Environmental analysis

The execution of this project would not only entail a reduced environmental impact for the fauna, flora, people/populations or existing infrastructures, but also the environmental benefits that this would entail due to the reduction of polluting emissions associated with the generation of part of the electrical energy supplied by the network, and that of another form would be the only source of energy supply of the pumping groups, would be appreciable throughout the useful life of the project.

In this sense, it is possible to carry out an estimation of the amount of annual and total emissions and waste in the useful life of the project, which has been set at 25 years (hence the feasibility analyses have been carried out with this time horizon), that can be avoided by installing the photovoltaic plant designed in this document. For this, the latest report developed by the "*Observatorio de la Electricidad*", published in 2016, is used.

On the other hand, it is relevant to indicate that the value of each of the indices that relate the electricity consumption from the network with the emission of a specific pollutant has been reduced by 1% from the second year to the last. This has been done because, in anticipation that renewable energies continue to gain weight in the generation and injection of current in the network and that traditional energies will be able to slightly reduce the emissions associated with their electricity production, the energy consumption from the network will be associated with decreasing levels of polluting emissions.

At the same time, a relevant assumption has been taken into account: the water needs are assumed to be constant, that is, the variation in the environmental impact of electricity consumption is not being analysed if it varies for any reason, such as higher irrigation needs either by increasing the cultivated area or by substituting part of the area devoted to rainfed crops by crops that require greater water needs.

Therefore, knowing the electricity consumption that theoretically it is possible to save annually through electricity generation through the photovoltaic installation and with the above factors, the following results are obtained (Figure 4.3.1):

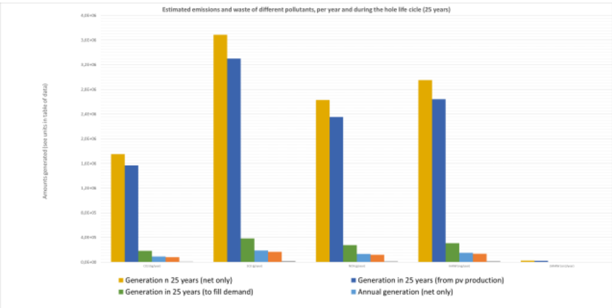

Figure 4.3.1. Potential emission savings over the estimated life of the installation

5. Conclusions

Photovoltaic energy has gained great weight in recent years, and its growth is expected to continue at a high rate, becoming the main (or second) renewable energy worldwide in the coming decades. Its applications are numerous (solar pumping, feeding of electric vehicles, etc.)

In the project that illustrates this master's thesis, the aim was to achieve the highest level of self-consumption by installing a photovoltaic generator that would supply the energy demand of two pumping groups. Finally, due to the available space and establishing a reasonable budget, it was decided to install a total of 2320 panels, which with a peak power in STC of 400 Wp gives rise to a photovoltaic installation of 928 kWp, so it is of a considerable size. This means that in the first year almost 90% of self-sufficiency is reached, which is progressively decreasing due to the loss of efficiency of the panels due to their degradation. At the same time, this quantity of panels means that great benefits are obtained, not only due to the savings in the purchase of energy from the network, but also due to the sale of surpluses in those moments when it is not necessary to pump water (or a part of the energy can be injected into the network). However, due to the large outlay that must be made in year 0, the benefits, although important, are not reached until the last five years of the installation's useful life. Based on the last mentioned, it is necessary to take into account several assumptions that have been taken into account (although trying to be as strict and objective as possible) in this project:

- The water and energy needs have been assumed to be constant throughout the useful life of the projected installation. In the future, the needs may increase, due to greater cultivation area or due to the substitution of rainfed crops for irrigated crops, they may be reduced or they may be practically the same.

- The irradiance levels used for the calculations of the power deliverable by the panels have also been considered constant.

- A multitude of parameters have been assumed in this project, such as the percentages of industrial profit and general expenses, the discount rate, the interest rate of the bank loan, the own funds that can be counted on to make the investment, the prices of purchase and sale of energy or the evolution of both the associated emissions of various pollutants when consuming energy from the network and the CPI of energy. On the other hand, to say that it has been tried to choose conservative values in many cases to obtain fewer misleading results.

It would be interesting to study other alternatives in which the percentage of self-consumption is lower, or also the possibility of increasing the capacity of the reservoirs to allow a greater volume of water to be stored and, perhaps with this, to be able to allocate a greater percentage of photovoltaic energy its sale in the electrical network.

On the other hand, although it is true that, in principle, the profitability of the project would be assured and that the reduction in pollutant emissions in successive years is undeniable, threats that may arise in the field of energy generation must also be taken into account. For example, it could be the case that the price of energy in the network is reduced, or increased less than expected, reducing savings, due to the improvement of the efficiency in the production of existing technologies or even the penetration of new energy sources, such as nuclear fusion, which could make the facility's profitability lower than expected.

6. References

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